CWM.

1. Xanthan gum (a natural polysaccharide) can be used as a stabilizer. If xanthan gum is used alone, the required amount of addition is 0.015–0.02 wt%. This addition causes 2.0–2.5 wt% decrease of coal concentration to keep the CWM viscosity almost constant.

2. Goethite (FeOOH) is only effective for static stability. Combined use of 0.5 wt% goethite and 0.005 wt% xanthan gum is recommended to establish good static stability without remarkable viscosity increase. The amount of additives is economical.

3. Attapulgitic clay is an effective stabilizer for CWM. Combined use of 0.1 wt% attapulgitic and 0.005 wt% xanthan gum gives perfect static stability. This combination of additives may be one of the most economical choices of CWM stabilizer. For dynamic stability, around 0.5 wt% of attapulgitic is needed.

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Nomenclature

c_w	= coal concentration	[wt%/slurry]
D	= cumulative undersize	[—]
d	= particle diameter	[μm]
H	= depth of hard-pack	[mm]
$\dot{\gamma}$	= shear rate	[s^{-1}]
η	= apparent viscosity at $\dot{\gamma} = 31.1 \text{ s}^{-1}$	[Pa·s]

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MULTICOMPONENT PRODUCTS SEPARATION PROCESS SYNTHESIS WITH SEPARATION SHARPNESS

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Key Words: Separation Process Synthesis, Separation Sequence, Separation Sharpness, Nonsharp Separation, Multicomponent Product

Introduction

The synthesis of optimal separation processes has been one of the most important subjects in process synthesis, and these separation processes are classified into two groups. One is that in which the products are pure substances, and various synthesis methods, such as heuristic,⁶⁾ evolutionary^{5,7,8)} and algorithmic¹⁾ methods, have been proposed. On the other hand, no proper method has been proposed for the other group (multicomponent products), into which the introduction of stream dividers and nonsharp separators is essential in reducing the separation cost. In this

synthesis problem there exists information feedback among the separation sequence, the ratios of the stream division, and the degrees of separation sharpness, so it is troublesome to synthesize an optimal process. Assuming that the recovery of the key components at each separation breakpoint is unity (sharp separation), Muraki and Hayakawa⁴⁾ and Muraki *et al.*²⁾ in preliminary research into this synthesis problem, developed two-stage evolutionary methods in which the separation sequence and the ratios of stream division are searched separately.

The degrees of separation sharpness are also important design variables in synthesizing a multicomponent products separation process because these degrees have considerable influence on separation cost. If

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optimal degrees of separation sharpness and the ratios of stream division can be determined when the separation sequence is known, then it is possible to adopt the two-stage strategy mentioned above. In this study, a rational procedure is developed to search these ratios and degrees for the separation process of two multicomponent products under a given separation sequence, and the proposed procedure is illustrated through a five-component distillation separation process synthesis problem.

To simplify the synthesis problem, it is assumed that:

- A1: One separation method is selected.
- A2: The order of physical or chemical properties upon which separation is based does not change.
- A3: The maximum number of separators is $m - 1$. (m is the number of species in the raw materials.)
- A4: A mass separating agent is removed in the separator immediately following the one into which it is introduced.

These assumptions are the same as those of separation process synthesis with sharp separation.^{2,4)} To reduce the calculation load, it is assumed further that the reflux ratio is 1.1 times the minimum reflux ratio, and that the operating pressure is adjusted so that the cooling water (305.15 K) can be used at the condenser. The total annual cost, which consists of capital and operating costs, is adopted as the objective function, and the design data and equations and the cost data and equations are the same as those in the study of distillation separation process synthesis.³⁾

1. Design Variables

In the case of sharp separation, the ratios of the stream division can be searched by manipulating the MAD⁴⁾ (material allocation diagram). The introduction of nonsharp separation causes a complicated interaction between these ratios and the degrees of separation sharpness. Consider the relation between them through a five-component distillation separation process synthesis problem (separation sequence S_1 - S_4 - S_3 - S_2), defined in Table 1 where the relative flow rate indicates the ratio of the flow rate of the product to that of the raw material for each individual species.

Figure 1 shows the function of nonsharp separation on the MAD graphically where species are numbered in the order of physical or chemical properties upon which the separation is based, and S_i is the separation which separates a multicomponent feed stream into two product streams (for example, distillate and residue streams of the distillation) between species C_i and C_{i+1} . Two variables are necessary to specify the nonsharp separation, and it is defined in this study that $X_{i,1}$ ($X_{i,2}$), the shadowed portion, is the recovery

Table 1. Example problem definition

(a) Flow rate (kmol/h)					
	C_1	C_2	C_3	C_4	C_5
Raw material	100	80	200	160	100
Product 1	20	24	160	80	10
Product 2	80	56	40	80	90

(b) Relative flow rate					
	C_1	C_2	C_3	C_4	C_5
Raw material	1.00	1.00	1.00	1.00	1.00
Product 1	0.20	0.30	0.80	0.50	0.10
Product 2	0.80	0.70	0.20	0.50	0.90

(c) Antoine's coefficients			
Component	A	B	C
C_1	6.82973	813.20	248.00
C_2	6.74808	882.08	240.00
C_3	6.83029	945.90	240.00
C_4	6.78967	1020.012	233.097
C_5	6.85221	1064.63	232.00

Antoine's equation: $\log(p/133.3) = A - B/(T - 273.15 + C)$

Fig. 1. Nonsharp separation.

fraction of C_i (C_{i+1}) in the residue (distillate) stream. The flow rates of the species in the product streams can be computed from these two variables if those in the feed stream are known. This means that those in the outflowing streams from the separation process can be also computed from these degrees and ratios if the configuration of the separation process is known.

It is necessary to determine a configuration suitable for nonsharp separation. This study derived it by manipulating the MAD⁴⁾ based on the assumption of sharp separation, and a flow chart of this example problem is shown in Fig. 2, where D_n represents the n -th stream divider. Based on this configuration, five linear equations for stream dividers and five nonlinear equations of the material balance for individual species of product 1 or 2 are set up respectively. For example, a linear equation for D_1 is

$$d_{1,1} + d_{1,2} = 1$$

and species 1 exists in three outflowing streams, so a nonlinear equation for that species of product 1 is

The number of variables is eighteen (eight degrees and ten ratios), so the degrees of freedom are eight. The ratios of the stream division can be determined by solving this set of equations if the degrees of separation sharpness are given. This means that this separation process is optimized by adjusting the degrees of separation sharpness, which are selected as the design variables in this study.

It is necessary for the search of degrees of separation sharpness to determine the ratios of stream division by solving these equations whenever these degrees are renewed, but it is troublesome because some of the equations are nonlinear. It is not always possible to determine these ratios directly by solving the equations mentioned above for the different configurations.

If f_i is defined as the relative flow rate of subproduct i , then equations of the material balance become linear.

where

$$\mathbf{p}_1 = (p_{1,1}, p_{1,2}, p_{1,3}, p_{1,4}, p_{1,5})$$

It is necessary to search the degrees of separation sharpness in order to minimize the objective function. The number of design variables of this optimization is

Fig. 2. Flow chart.

Fig. 3. MAD and decomposed subproducts.

Table 2. Compositions of subproducts

Subproduct number	C_1	C_2	C_3	C_4	C_5
1	1	1	1	1	1
2	$1 - X_{1,1}$	$X_{1,2}$	0	0	0
3	$X_{1,1}$	$1 - X_{1,2}$	1	$1 - X_{4,1}$	$X_{4,2}$
4	0	$(1 - X_{1,2})X_{2,1}$	$1 - X_{2,2}$	$1 - X_{4,1}$	$X_{4,2}$
5	0	$(1 - X_{1,2})X_{2,1}$	$(1 - X_{2,2}) \times (1 - X_{3,1})$	$X_{3,2}$	0

Nine initial base points, each composed of eight variables, are generated by random numbers. As mentioned above, whenever these degrees are renewed, the relative flow rates of subproducts are obtained, and the objective function is evaluated. **Table 3** shows the optimal degrees of separation sharpness and the relative flow rates of the subproducts. It is clear from the results that these degrees vary with the separation breakpoints, and that the relative flow rates differ with those obtained under the assumption of sharp separation.

A useful method is proposed for synthesizing an optimal separation process of a given separation sequence, into which stream dividers and nonsharp separators are introduced. No method has been published in which the degrees of separation sharpness

Table 3. Optimization results

(a) Degrees of separation sharpness							
$X_{1,1}$	$X_{1,2}$	$X_{2,1}$	$X_{2,2}$	$X_{3,1}$	$X_{3,2}$	$X_{4,1}$	$X_{4,2}$
0.064	0.228	0.284	0.110	0.018	0.498	0.100	0.212
(b) Relative flow rates of subproducts							
	f_1	f_2	f_3	f_4	f_5		
Nonsharp	0.099	0.108	0.001	0.003	0.798		
Sharp	0.100	0.100	0.200	0.200	0.300		

are considered. There exists a complicated interaction between the ratios of stream division and the degrees of separation sharpness. It is found from analysis of the relation between them that the degrees of separation sharpness are the design variables in this synthesis problem, and that a set of equations, some of which are nonlinear, must be solved to determine the ratios of stream division whenever the degrees of separation sharpness are renewed. It is troublesome to solve these equations. Decomposing the product into subproducts based on the MAD manipulation, and considering the relative flow rates of the subproducts as the variables, equations of the material balance can be reformed into linear ones, and the number of variables is always equal to that of species. Then the calculation load can be largely reduced. The Complex method is adopted to search the optimal degrees of separation sharpness because these variables are constrained implicitly and explicitly. The proposed

method is illustrated through a five-component two-product distillation separation process synthesis problem.

Nomenclature

B	= blender or blending	[—]
C_i	= species i	[—]
D_n	= n -th stream divider or division	[—]
$d_{n,k}$	= fraction of k -th stream at D_n	[—]
f_i	= relative flow rate of subproduct i	[—]
m	= number of species in the raw material	[—]
P_1, P_2	= product	[—]
$p_{j,i}$	= relative flow rate of species i in product j	[—]
p	= pressure	[Pa]
S_i	= separator, separation or separation breakpoint between C_i and C_{i+1}	[—]
T	= temperature	[K]
$X_{i,1}$	= recovery fraction of C_i in the residue at S_i	[—]
$X_{i,2}$	= recovery fraction of C_{i+1} in the distillate at S_i	[—]

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