NOTATION

a = constant defined in Equation (11)
a_p = specific area of particles, cm^{-1}
a_1, a_2, a_3, a_4 = constants defined in Equation (10)
b = constant defined in Equation (11)
b_1, b_2, b_3, b_4 = constants defined in Equation (10)
c_0 = inlet fluid phase concentration
c_1 = outlet fluid phase concentration
c_1^* = equilibrium fluid concentration at the interface fluid/solid
d_a = stirrer diameter
d_T = sorber diameter
D = fluid diffusivity
f_1, f_2 = functions defined in Equations (8a) and (8b)
H = Heaviside function
K_f = film mass transfer coefficient, cm s^{-1}
K = separation factor
N_f = number of mass transfer units
N = speed of the stirrer
q_1 = solid phase concentration
Q = capacity of the solid
Re = Reynolds number, defined as $\rho N d_a^2/\mu$
Sc = Schmidt number
Sh = Sherwood number
t = time
t_{st} = stoichiometric time
U = flow rate
v_R = volume of solid in the sorber
v_s = volume of fluid in the sorber
V = volume of the sorber
x_1 = dimensionless fluid phase concentration
y_1 = dimensionless solid phase concentration

Greek Letters

ϵ = void fraction of perfectly mixed sorber
θ = dimensionless time variable
θ_{Bp} = dimensionless breakthrough time
λ_1, λ_2 = eigenvalues of the Jacobian
ρ = fluid density
ξ = capacity parameter
τ = space time
μ = fluid viscosity

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A Thermodynamic Approach to Heat Integration in Distillation Systems

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Starting from a conventional distillation system without heat integration, a series of bottlenecks from the viewpoint of energy conservation is sequentially found by a thermodynamic analysis using a heat availability diagram, and modified systems are evolutionally synthesized as the result of debottlenecking. The present approach has made possible a unified interpretation of various energy integrated distillation systems with multieffect columns, intercondensers/interreboilers, heat pumps, etc.

SCOPE

Distillation is a well-established method of separating multicomponent mixtures and is widely used in the petroleum refining, petrochemical, and other process industries. Distillation systems, however, are highly energy intensive and always consume a large amount of energy to achieve the objective. In view of energy conservation, it is impor-

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tant to establish a systematic method of reducing external energy inputs by the effective use of heat energy in the distillation system. There are a number of publications which have described various methods for achieving the present goal without a thorough analysis of their interrelationships. As described by Rathore et al. (1974), the problem of synthesizing distillation systems consists of two key subproblems. One is the selection of the basis and sequence of separation, and the other is the determination of a heat exchanger network for energy recovery. The former has been solved by various methods such as algorithmic methods, decomposition, heuristic methods, and evolutionary procedures. The latter has been studied by applying the methods of mathematical programming and modern control theories, followed by employing heuristics and specific characteristics of the problem. The present study is concerned with synthesizing energy integration systems in distillation, whose separation sequence is given beforehand. In general, when conserving energy in the distillation systems, the following items should be taken into consideration:

1. Reduce the amount of energy input for each distillation column by selecting optimal distillation performance such as reflux ratios, *q* value, and so on.

2. Reduce the amount of energy input to the distillation system by materializing energy integration.

3. Change the energy level of heat sinks and sources, one or both, required in the distillation system by varying operating conditions such as pressure or temperature.

In the present study, the last two steps are iteratively repeated after the first step is specified in advance. The method taken in the heat exchange system synthesis (Umeda et al., 1978) is extended to energy integration in the distillation system for a given separation sequence. By using the present method, a unified approach to energy conservation techniques for distillation systems can be established.

CONCLUSIONS AND SIGNIFICANCE

Starting from a conventional distillation system without heat integration, a method of energy conservation is found by a thermodynamic analysis using heat availability concept. A heat availability diagram which expresses available energy of the system is constructed by plotting a Carnot efficiency $(1 - To/T)$ against heat load Q and is used to find the status of utilization of heat load and available energy associated with the heat load.

This analysis alleviates the bottlenecks encountered at pinch-points associated with the temperature difference on the diagram. A pinch-point shows a thermodynamic constraint on heat recovery. As the results of the debottlenecking procedure consisting of three basic operations on the diagram, modified systems are evolutionally synthesized. Loss of available energy corresponding to the system decreases monotonically along the procedure.

The approach outlined in this paper has made possible a unified interpretation of various energy integrated distillation systems. The advantage of the aproach is its simplicity, ease of use, and clarity of thermodynamic characteristics of the generated systems. This leads to significant reduction of design cost.

THERMODYNAMIC ANALYSIS OF A DISTILLATION SYSTEM

System Definition

The essential elements of conventional distillation consist of a distillation column, a reboiler, and a condenser. Owing to other process requirements, it is common practice for feed preheaters or product coolers, or both, to be installed also. For the convenience of thermodynamic analysis, a distillation system is defined as being composed of two subsystems as shown in Figure 1. One is the column internal subsystem, and the other is the heat exchange subsystem consisting of a reboiler, a condenser, interreboilers, intercondensers, and other equipment for heat or energy supply, removal, and interchange which are involved in the system as the result of heat integration.

For comparing the results derived from the heat integration, temperatures of input and output process streams at the system boundary are assumed to be the same as the ambient absolute temperature. This requires the feed preheater and the product coolers to be within the system. Streams associated with the distillation system can be classified into two groups: heat sink and source streams. The heat sink streams are the feed stream, the column bottom liquid stream to be reboiled, and other heat absorbing streams including cooling media. The heat source streams are the column overhead vapor stream to be condensed, the product streams, and other heat supplying streams including heating media.

Heat Availability Diagrams

The necessity of thermodynamic analysis of process systems has long been recognized and is becoming very strong. In addition to system analysis using the first law of thermodynamics, much attention has been given to evaluating the energy quality by analysis based on the second law of thermodynamics. Among several ways of applying the second law, the practical usefulness of available energy concept has also been recognized in the present authors' experience. As far as the authors know, however, practical methods of systematic use of the available energy concept for the analysis and synthesis of distillation systems with heat integration have not yet been published. A method of thermodynamic analysis for the distillation system has been developed as an extension of the authors' previous work which is presented elsewhere (Itoh et al., 1979).

The relative utility of energy levels can be expressed as available energy. The thermodynamic availability study (Haywood, 1974) is related to the maximum possible work output or minimum possible work input when a system or fluid is taken by some steady flow process from a given

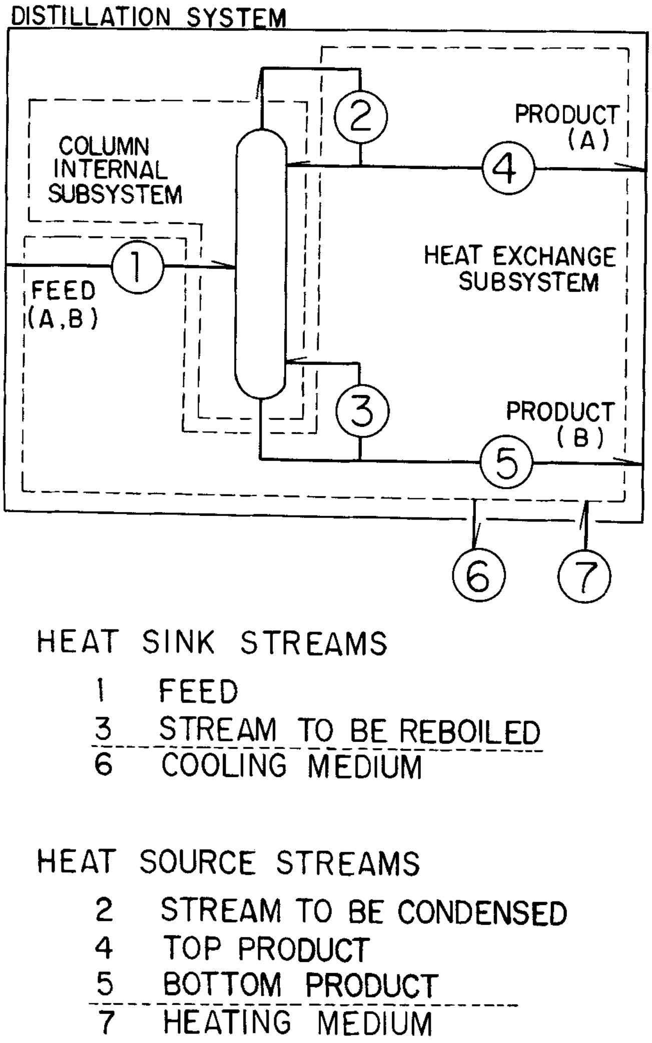


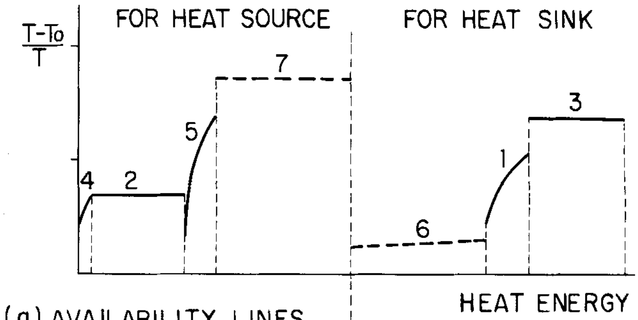
Fig. 1. A binary distillation system.

specified state 1 to a second specified state 2. Maximum work output could be obtained if the process is completely reversible. Real processes are irreversible, and maximum work output or minimum work input cannot be realized. In the distillation system, the major irreversible processes are the heat transfer process through heat exchangers and the heat energy interchange within the column. It is important to recognize that temperature decrease is directly concerned with the degradation of heat. It is possible to make graphical presentation of the available energy by plotting the Carnot efficiency against heat energy on what is called a heat availability diagram. Available energy change of a heat sink or source stream supplying or removing heat Q through the steady flow process from a state 1 to another state 2 is obtained by

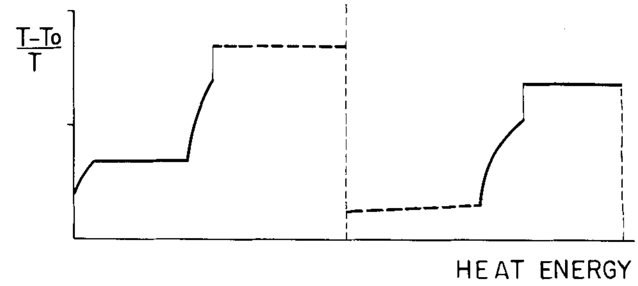
$$\int_{\text{State 1}}^{\text{State 2}} (1 - To/T)\, dQ$$

On the heat availability diagram, the area under each line between the two states corresponds to the available energy change for heat sink or source streams.

Figure 2 shows the heat availability diagram for the distillation system (Figure 1). Figure 2*a* shows the heat availability lines for heat sink and source streams. Figure 2*b* can be derived by collecting the stream segments with the same temperature level and making corresponding composite lines. A detailed explanation of constructing the composite lines has been given elsewhere (Umeda et al., 1978). The distillation system shown in Figure 1 does not recover any heat. The feed stream and the reboiler are heated by the heating media, and the condenser and the products streams are cooled by the cooling media. To find out the conditions of heat exchangeability, the composite heat sink line is set up under the other composite line in such a way that a heat balance relationship between the two lines is satisfied. The heat can be transferred through a heat exchanger by matching the heat source stream with the corresponding heat sink stream. The result of this operation is shown in Figure 3*a*. By



(a) AVAILABILITY LINES FOR STREAMS



(b) CONSTRUCTION OF COMPOSITE LINES

Fig. 2. Heat availability diagram.

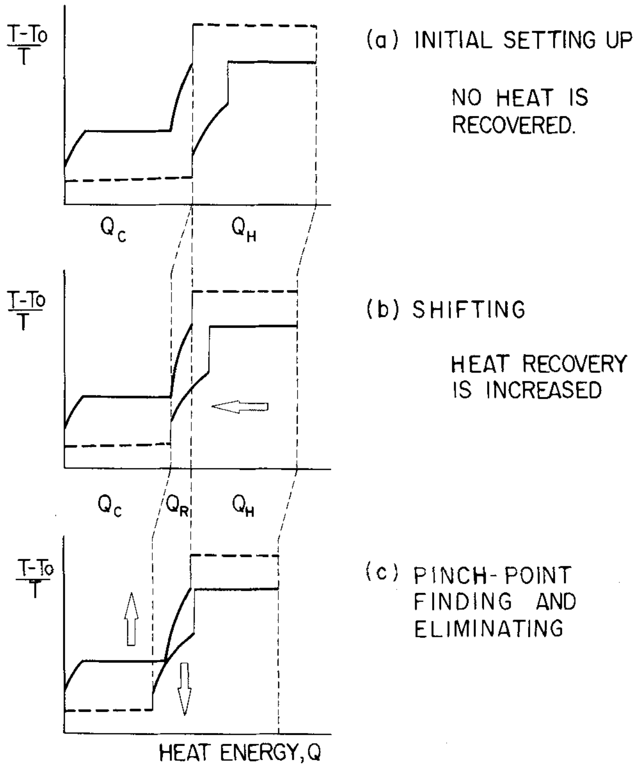


Fig. 3. Minimization of available energy loss.

comparing the areas under the respective composite lines, it is found that the total available energy of heat source streams is greater than that of heat sink streams.

The enclosed area between the composite lines corresponds to the loss of available energy due to irreversibility associated with heat transfer in the heat exchange subsystem. Though, in the preceding paragraphs, the description of the heat availability diagrams is limited to binary component systems, one can construct heat availability diagrams for multicomponent systems in the same way as described above. When a process becomes reversible, there is no loss of available energy. This fact is shown when the composite lines contact at all points. The minimization of available energy loss is achieved by minimizing the area between the composite lines.

Minimization of Available Energy Loss

For a given distillation system, the area corresponding to the loss of available energy can be decreased by changing the operating variables or distillation. Lowering column pressure, for example, decreases eventually the loss of available energy according to the reduction of reflux flow. It can also be decreased by lowering the temperature level of the heating media or raising that of the cooling media.

In addition, the loss of available energy is decreased by changing the system. The area enclosed by the composite lines can be decreased by shifting the composite heat sink line to the left on the diagram. As shown in Figure 3*b*, shifting the composite heat sink line to the left results in increasing heat recovery Q_R and decreasing the amounts of heat supply Q_H and heat removal Q_C. If the two lines contact, no more heat can be recovered without modifications of the system. The point where the two lines contact is named a pinch-point. Since there is no temperature difference at the pinch-point, as shown in Figure 3*c*, the heat exchanger area is infinite. Thus, the pinch-point gives a thermodynamic constraint on heat recovery. Further heat recovery can be realized by eliminating the pinch-point.

As pointed out in Figure 3*c*, pinch-point elimination can be achieved by the following operations:

1. For the composite line of heat source streams, raising the temperature level of the left-side segment above the pinch-point.
2. For the composite line of heat sink streams, lowering the temperature level of the right-side segment below the pinch-point.

Changing the temperature level is performed in practice by varying operating conditions such as pressures or temperatures of the heat sink or source streams. After the pinch-point is eliminated, the composite heat sink line can be shifted. These steps are iteratively implemented. From the economical viewpoint, the maximum degree of heat recovery is determined by a minimum approach temperature between the two composite lines. A smaller temperature difference will require larger heat exchanger area, and the minimum approach temperature is a key decision variable which should be determined so as to minimize an objective function expressing the economic criterion. The above stated procedure for eliminating the pinch-point on the heat availability diagram is also applicable to multicomponent distillation systems.

PROBLEM OF HEAT INTEGRATION

As previously described, it has been assumed in the present study that a separation sequence for the distillation system is given beforehand, and physical properties of components, operating, or design variables associated with the distillation system are also specified in advance. The problem of heat integration relates to the synthesis of the heat exchanger subsystem, and the problem is defined as the determination of a heat integration scheme so as to minimize the loss of available energy. From a practical viewpoint, this minimization is related strongly to economic criteria such as fixed and operating costs. If a temperature difference between the composite lines increases, the corresponding heat exchanger area decreases, and it is recognized that there is a trade off relationship between these costs.

As an economic criterion, the following objective function expressing the annual cost is defined:

$$\Phi = \alpha[\sum_i \phi_{Di} + \sum_j \phi_{Ej} + \sum_k \phi_{S\cdot R\cdot k}] + \sum_l \sum_k \psi_l \Psi_{kl}$$

The first three terms on the right-hand side are the fixed costs of distillation, heat exchange, and heat supply or removal systems, respectively. α is a key factor on the decision making under the trade off relationship. The last term is the operating cost of the heat supply or removal system. The unit costs ψ_l are given constants for each kind of utility.

METHOD OF PROBLEM SOLVING

A careful analysis of utilizing the heat availability diagram described in the preceding sections reveals that the following three basic operations on heat integration regarding streams excluding heating and cooling media play an essential role in synthesizing heat exchange systems:

1. An operation f_P is to change the pressure of a column or vapor streams which causes a temperature change on the composite lines or their segments. The operation of f_P for the composite lines leads to decreasing the loss of available energy in the high temperature region and increasing it in the lower temperature region. Although this operation requires an increase in the amount of energy input, it is compensated by following operation f_E, described below.
2. An operation f_T is to change the temperature of a segment of the composite lines without pressure change. The operation of f_T for the segment of composite line requires an increase in the complexity of the system due to the installation of interreboilers and/or intercondensers.
3. An operation f_E is to shift the composite heat sink line to the left. This makes it possible to recover heat.

By repeating iteratively each set of operations (f_P and f_E) and (f_T and f_E) on the composite lines or on their segments, a series of heat integration systems is evolutionally synthesized as the results of eliminating the pinch-points that occur in every repetition. The loss of available energy corresponding to these systems decreases monotonically along the repetitive operations. In solving practical problems, it is also necessary to change the operating variables of distillation as already described in the previous section. It is assumed in the present study that these additional efforts are made to decrease the loss of available energy during the repeated application of the operations, for they cause no change in the system structure. Although the usefulness of a heat availability diagram has been proven, it is difficult to know directly the exact values of approach temperatures between the composite lines. This is due to the fact that the ordinate expressing the Carnot efficiency $(1 - To/T)$ is nonlinear. If the ordinate of the heat availability diagram is replaced by temperature and it is plotted against the amount of heat, a T-Q diagram is obtained and the above difficulty can be overcome. The heat availability line on the T-Q diagram becomes a straight line for a given average specific heat, and the monotonicity of the heat availability line on the heat availability diagram can also be held in the T-Q diagram.

Though the area enclosed by the composite lines on the T-Q diagram does not give an exact value for the loss of available energy, within a certain allowable range the loss of available energy can be approximated by a linear relationship between the heat sink and source lines, for the following relationship is satisfied:

$$Q\left(1-\frac{To}{T1}\right)-Q\left(1-\frac{To}{T2}\right)=\frac{QTo}{\tilde{T}^2}(T2-T1)$$

where $\tilde{T}$ is geometric mean of $T1$ and $T2$, which are the temperature of heat source and sink streams, respectively (Timmers, 1969).

Application of The Basic Strategy and Some Rules

The basic operations f_P, f_T, and f_E can effectively be utilized to find heat integration schemes for the distillation system. The results of possible applications of the operation are summarized in Figure 4. On the right-hand side of the figure, nine energy conservation techniques are shown. These are systematically derived from the applications of the operations on the heat availability diagrams. For example, a distillation system with overhead vapor recompression is synthesized by applying once an operation f_P to raise only the overhead vapor stream pressure. Successive applications of these operations to the conventional distillation system give thermodynamically more efficient energy integrated systems such as those with intercondensers, interreboilers, and multieffect distillation colums. Although these distillation systems with heat integration are already known, interrelationships among these systems are made clear by the present approach. The iterative repetition of the operations can graphically be shown in Figure 5, where a set of T-Q diagrams is shown with the operations applied in every step. Starting from the original distillation system without any heat integration, two distillation systems are synthesized. One is a multieffect distillation system and the other is a distillation system with an interreboiler and an intercondenser.

Owing to the complexity of the heat integration problem, it may be effective to develop some heuristic rules for specifying the order of applying the operations f_P and f_T and for simplifying the systems. By taking the characteristics of operations f_P and f_T into consideration, it may be concluded that it is preferable to apply the sets of operation [firstly (f_P, f_E) and secondly (f_T, f_E)] to segments of composite lines, and then the set of operation (f_P, f_E) is applied to the whole composite line in the last stage of repetition. This heuristic rule may contribute to creating simpler systems. Other heuristic rules such as the elimination of unnecessary smaller heat exchangers are also applied to simplify the heat integrated systems. A detailed description can be found in the authors' previous work (Umeda et al., 1978). In solving real problems, it is necessary to take many other factors such as safety, flexibility, and operability into consideration. Since the modification of generated systems requires the designer's judgment on these factors to solve what are called multiobjective problems, it will be more efficient to make interactive use of computers.

Procedure of Heat Integration

For a given separation sequence of a distillation system without heat integration, the procedure for heat integration is given as follows. The first step is to make a T-Q diagram for the system and to calculate various economic items. The second step is to find a pinch-point of the system using a shifting operation f_E. The third step is to eliminate the pinch-point using the heuristic rule for selecting either operations f_P or f_T. Process designers can change the heuristic rule if necessary. The fourth step is to improve the system including the operating conditions and to modify the composite lines of the improved system. The fifth step is to minimize the loss of available energy of the improved system using operation f_E and the heuristic rule to simplify the improved system. Thermodynamic efficiencies and economic items are also calculated for the next step. The sixth step is to evaluate the improved system by economic and operability criteria. If it is necessary for the system to be further improved, return to the third step. If the system is evaluated as the optimal system, the procedure is terminated.

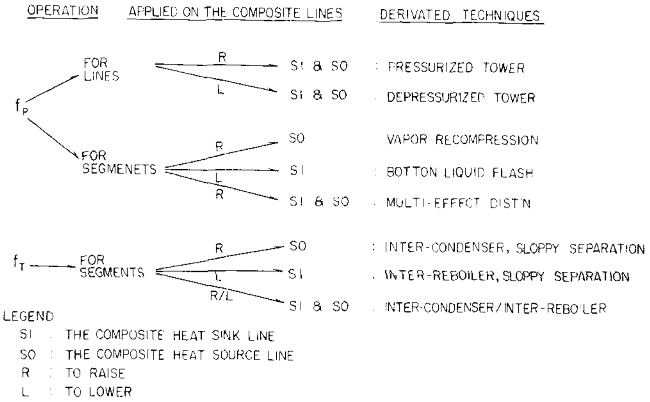


Fig. 4. Possible systems generated by one-step operation on a binary distillation system.

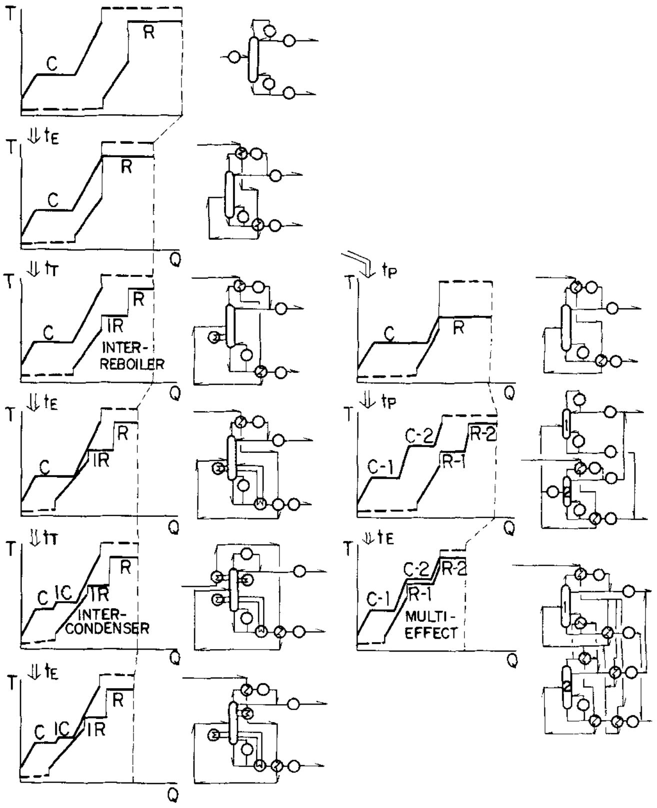


Fig. 5. Iterative repetition of the operations.

ILLUSTRATIVE EXAMPLE

To demonstrate the effectiveness of the present method, a complex system with five components (Rathore et al., 1974) was selected. The process flow scheme and the cor-

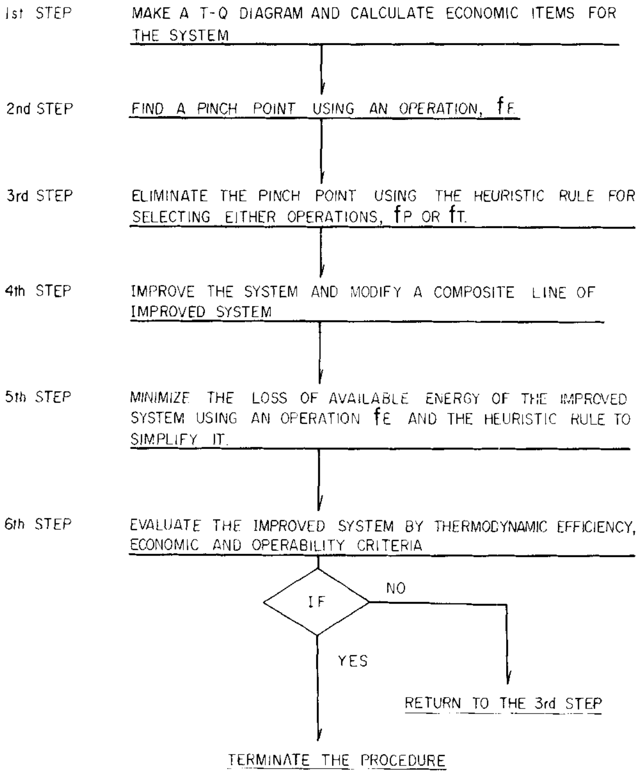
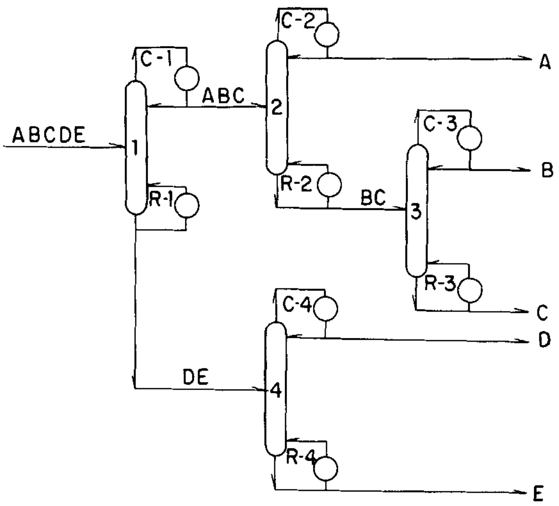


Fig. 6. A five-component distillation system.

responding T-Q diagram are shown in Figures 6, 7a, and 7b. Some results of applying the proposed method are shown in Figures 8a and 8b, where a higher degree of heat recovery is recognized. The amount of heat supply through the heating medium has been reduced approximately from 25 to 16 MM Kcal/hr. These results have been obtained by applying the operations, f_P, f_T, and f_E, several times. It is possible to make further modifications as described in the preceding sections.



FEED RATE : 907.2 KG-MOL/HR
FEED COMPOSITION :

A	PROPANE	0.05
B	i-BUTANE	0.15
C	n-BUTANE	0.25
D	i-PENTANE	0.20
E	n-PENTANE	0.35

KEY COMPONENT RECOVERIES :
98% FOR BOTH KEYS IN ALL COLUMNS
OPERATING PRESSURES:
6.8 ATM, ALL COLUMNS

Fig. 7. Illustrative examples.

DISCUSSION

The present approach described so far is applicable to the analysis and synthesis of heat integration in general processing systems (Umeda et al., 1979a). Although the

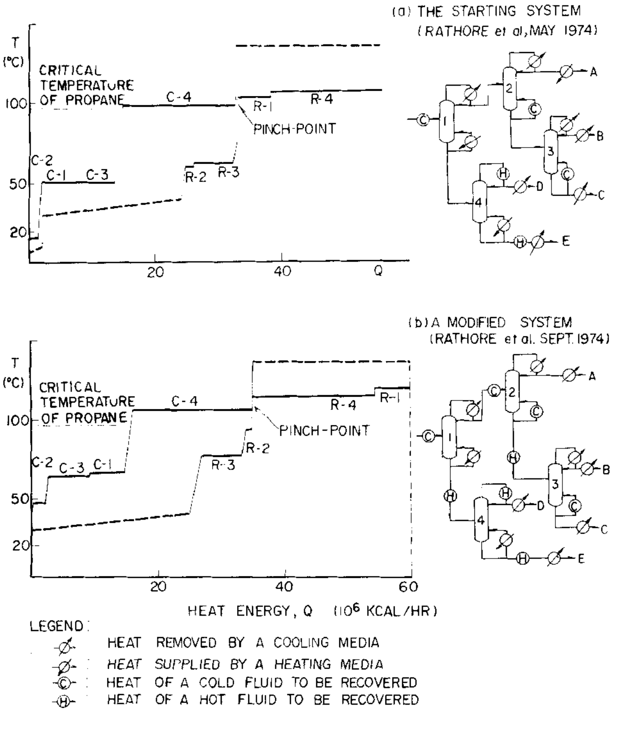


Fig. 8. Illustrative examples.

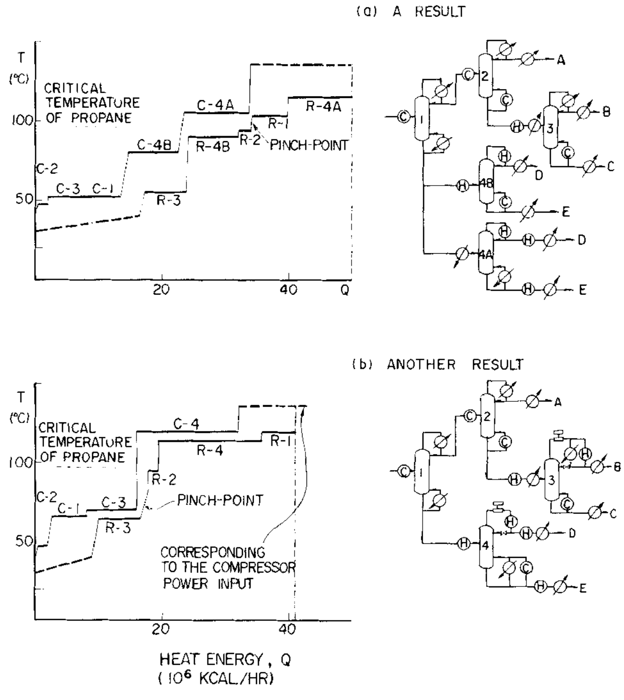


Fig. 9. Illustrative examples.

present study is limited to generating systems whose degree of heat integration increases gradually and will approach a reversible state, the stopping criteria for the repetitive application of the operations f_T, f_P, and f_E should include other factors from practical considerations such as the operability and reliability of the heat integrated system, as well as the economic criteria. In the practical application of the present method, the final decision of choosing the most appropriate system among the synthesized systems is dependent on engineering judgments. As a more rational approach, it is possible to deal with the problem under consideration as a multiobjective problem. The result by this rational approach will be presented elsewhere (Umeda et al., 1979*b*). The advantage of the present approach is its simplicity, ease of use, and clarity of the thermodynamic characteristics of the generated systems.

In addition to the problem of synthesizing the heat integration systems for energy conservation, it is also an important subject to improve the degree of energy utilization associated with the distillation. There exists the loss of available energy in the column internal subsystem. A detailed description on this subject is given elsewhere (Itoh et al., 1979).

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NOTATIONS

f_E = operation to shift the composite heat sink line to the left
f_P = operation to change the pressure of a column or vapor streams which causes a temperature change on the composite lines or their segments
f_T = operation to change the temperature of a segment of the composite lines without pressure change
Q = heat energy, Kcal/hr
Q_c = amount of heat removal, Kcal/hr
Q_H = amount of heat supply, Kcal/hr
Q_R = amount of heat recovery, Kcal/hr
T = absolute temperature of a stream, °K
To = absolute temperature of the atmosphere, °K

Greek Letters

α = factor associated with the annual fixed cost
ϕ_{Di} = investment cost of i^{th} distillation system
ϕ_{Ej} = investment cost of j^{th} heat exchange system
$\phi_{S \cdot R \cdot k}$ = investment cost of k^{th} heat supply or removal system
Φ = economic objective function expressing annual cost
Ψ_{kl} = amount of l^{th} kind of utility in k^{th} heat supply or removal system
ψ_l = unit cost of l^{th} kind of utility

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Transient Behavior of Moving-Bed Coal Gasification Reactors

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The transient response of dry ash and slagging moving-bed coal gasification reactors is analyzed for small step changes in feed conditions. The approach to the new steady state for perturbations about the optimum in the Lurgi gasifier has a time scale of about 10 hr. Transients in the slagging gasifier can result in a decrease in the coal bed height, which occurs on a time scale of several hours. There is a rapid initial response in both types of reactors in product gas temperature and heating value.

SCOPE

The gas produced from moving-bed coal gasifiers is to be used in downstream processes. Thus, an understanding of the transient behavior of a moving-bed gasifier is important, since any performance change in the gasifier will directly affect the performance of downstream units and hence of the overall system. This understanding is particularly important for the projected use in a combined cycle power generation process, in which individual units are closely coupled.

We have shown through steady state analyses of moving-bed gasifiers published previously that in order to

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