

NOTICE WARNING CONCERNING COPYRIGHT RESTRICTIONS:
The copyright law of the United States (title 17, U.S. Code) governs the making of photocopies or other reproductions of copyrighted material. Any copying of this document without permission of its author may be prohibited by law.

**Underwood's Method for
Side Strippers and Enrichers**

by

Neil A. Carlberg, Arthur W. Westerberg

EDRC 06-55-89

**Underwood's Method
for
Side Strippers and Enrichers**

Neil A. Carlberg
Arthur W. Westerberg

Department of Chemical Engineering
and
Engineering Design Research Center (EDRQ)
Carnegie Mellon University
Pittsburgh, PA 15213

November 1988

Abstract

Insight into complex column heat flow facilitates extension of Underwood's method to columns with sidestream strippers and sidestream enrichers. This presentation is much simpler than previous ones. The same insights show that even though these configurations are more energy efficient, they require a larger temperature range for operation than analogous simple column sequences.

Introduction

When designing a distillation column, it is imperative that the minimum reflux ratio is known. This parameter is critical; it determines a lower limit to column operation. The reflux ratio sets the internal flow rates of the column which, in turn, determine the utility consumption and column diameter. At some point as the reflux ratio decreases, one or more of the operating lines of the column will intersect the equilibrium surface. These intersection points are known as pinch points. An infinite number of trays are required to pass through a pinch point. Thus, the pinch points determine a minimum value for the reflux ratio. Normally, a column is operated just slightly above this minimum value.

To find the minimum reflux ratio rigorously, a set of simultaneous nonlinear mass and energy balances and equilibrium relationships must be solved. This approach is often difficult. In order to find a solution quickly several shortcut methods have been developed. The most notable of these shortcut calculations is the classic method of Underwood (1946,1948). For separations with constant relative volatility and constant molar overflow, an algebraic construct is used to obtain a simple solution procedure.

Although Underwood only considers simple columns, the analysis can be extended to complex column configurations. Recent works address the issue of shortcut methods for complex columns.

Glinos and Malone present the correct algorithm for analyzing a column with a sidestream stripper (1985a,1985b) and a column with a sidestream enricher (1985a). The side stripper analysis is developed for a ternary mixture; the generalization to the n component case is assumed to hold, but is not proved. The authors base their results on estimating the location of the pinch point in the side column. A step in their development assumes that the composition of the liquid return stream from the side column is at the pinch composition. While true for the ternary case, this assumption is not always true, and in fact, as it will be shown, not necessary to make. For complex columns the overall minimum reflux is achieved only when each column is at its respective minimum. The authors observe and use this fact but do not prove it. In a later paper Glinos and Malone (1988) formulate several design rules as to when to favor various

complex column configurations. The criteria for these design rules is the overall reboil rate. It will be shown, however, that the temperature range over which a complex configuration operates is also an important design consideration.

Hdkowski and Krolkowski present a method to find the minimum energy requirements for a side stripper and side enricher (1987). They restrict their analysis to ternary mixtures, and the development is very complex algebraically. Underwood's method is used as a basis for an optimization procedure. The appropriate vapor flow rate is minimized subject to internal mass balances and pinch point constraints. By choice of the proper objective function, they minimize the overall reflux. An analytical solution is obtained by observing the effect of the decision variables on the objective function. The authors then compare complex columns to the equivalent simple column sequences on an energy usage basis. Because the analysis is limited to ternary mixtures, their results are not generalized to an n component mixture. With the complexity of the algebra involved in their derivation, such an extension would not be easy.

There is a much cleaner and more general approach to obtain these results for multicomponent columns. This is a principle contribution of this work. This paper presents a straightforward generalized multicomponent Underwood analysis for several complex column configurations. First, the side stripper and side enricher are analyzed using Underwood's basic principles. Insight into complex column heat flow allows for the formulation of a simple solution strategy. This strategy is readily extended to multiple side strippers and side enrichers. Finally, complex columns are compared to analogous simple column sequences. By using the same heat flow insights, it will be shown that complex columns are more energy efficient, but suffer from larger temperature drops across the whole configuration.

Simple Columns

A simple column is defined as a column with one feed and two product streams (Figure 1). The column is equipped with one condenser and one reboiler. The reflux ratio for a simple column is defined as

$$R = \xi \tag{1}$$

and the reboil ratio is defined as

(2)

Components that appear in both of the product streams are said to distribute. In a similar manner,

components which appear exclusively in only one of the product streams are termed non-distributing. When splitting feeds, it is convenient to designate key components. Components are ranked in a list according to their relative volatility from the lightest to the heaviest. The lightest component which distributes is designated as the light key. The heaviest component which distributes is designated as the heavy key. If the key components are adjacent to each other, and if they appear largely in only one product stream, then the split is said to be sharp. For non-sharp splits, components between the keys will appear in both product streams.

Before the analysis can begin, a brief discussion on column specifications is needed. The overall goal of the separation system will be to isolate pure component products. Thus, sharp splits are assumed throughout the discussion. It will be assumed that the composition and thermal condition of the feed are specified. No restriction will be placed on the quality of the feed. Additionally, the product streams must be specified in some fashion. For this discussion the composition of all of the product streams will be given. Once the specifications are made, minimum reflux may be determined.

There are only two assumptions underlying Underwood's method: constant relative volatility and constant molar overflow. For this situation the method gives an exact solution. To derive the Underwood equations for a simple column, mass balances are written around tray n in the rectifying section

$$V y_{n+1,i} = L x_{n,i} + D x_{D,i} \quad (3)$$

and tray m in the stripping section

$$\bar{V} y_{m+1,i} = \bar{V} x_{m,i} - B x_{B,i} \quad (4)$$

At minimum reflux the operating lines will intersect the equilibrium surface. This situation, known as the pinch condition, requires an infinite number of stages. After considerable manipulation, the mass balances (written at the pinch conditions) are transformed into the well known equations

$$\sum_i \frac{\alpha_i d_i}{\alpha_i - \phi} = D (R_m + 1) \quad (5)$$

$$X \frac{\alpha_i b_i}{\alpha_i - \psi} \gg S_m B \quad (6)$$

Here d_i and b_i are the molar flow rates of component i in the distillate and bottom stream; ϕ and ψ are the Underwood roots for the rectifying and stripping sections. A detailed derivation of these equations is given in Underwood's original papers.

$$D_1 - V_1 - L_1 = \sum_{i=2}^n B_2 \quad (13)$$

$$x_{D1i} = \frac{x_{D2}i^{D_2} + x_{B2}i^{B_2}}{D_2 + B_2} \quad (14)$$

Since the Underwood equations are derived from mass balances, it is irrelevant that the primary column has a net product stream. Thus, the primary column can be considered to be a simple sharp column with product streams D_1 and B_1 . The reflux and reboil ratios for the primary column are defined as

$$R_1 = \frac{L_x}{D_2 + B_2} \quad S_1 = \frac{\bar{V}_1}{B_1} \quad (15)$$

The Underwood equations for the primary column are thus

$$\sum_i \frac{\alpha_i f_i}{\alpha_i - \phi} = F(1 - q_1) \quad (16)$$

$$\sum_i \frac{\alpha_i \Lambda_i}{\alpha_i - \phi} = D_1 (R_{1m} + 1) \quad (17)$$

$$\sum_i \frac{\alpha_i b_{1i}}{\alpha_i - \phi} = -S_{1m} B_1 \quad (18)$$

For the remainder of the discussion only the common roots are needed. The solution scheme for the primary column is the same as the simple sharp column outlined earlier.

The key to understanding the analysis of the secondary column is to determine the quality of the net feed to the secondary column. The quality of the net stream D_j is defined as

$$q_2 = \frac{\bar{L}_2 - L_2}{D_1} = \frac{\bar{L}_2 - L_2}{B_2 + D_2} \quad (19)$$

By substituting

$$\bar{L}_2 = L_2 - L_x \quad (20)$$

into Equation 19, the quality of the feed to the secondary column can be expressed in terms of the reflux ratio of the primary column

$$q_2 = \frac{-L_x}{B_2 + D_2} = -R_1 \quad (21)$$

Since q_2 will always be negative, the net stream can be considered superheated. Thus, the secondary

column is a simple sharp column with a superheated feed D_1 . The Underwood equations for the secondary column are thus

$$X_i^{\wedge} = 010-f2> - \wedge(R^{\wedge}l) \quad (22)$$

$$\sum_i \frac{\alpha_i d_{2i}}{\alpha_i - \eta} = D_2 (R_{2m} + D) \quad (23)$$

$$\sum_i \frac{\alpha_i b_{2i}}{\alpha_i - \eta} = -S_{2m} B_2 \quad (24)$$

Here, the Underwood root for the side stripper is denoted by r_1 .

When analyzing the secondary column, it is desirable to use as small a minimum reflux in the primary column as possible to find T_1 . This can be argued qualitatively by examining the heat flow within the configuration. The overall energy balance of the configuration when the feed and products are at their boiling points is

$$Q_{R1} + Q_{R2} \sim Q_{Ci} \quad (25)$$

Deviation from the bubble point condition can be handled by adding an appropriate constant heat term to the equation above. Note that Q_{C2} sets the utility consumption for the entire configuration. Equation 10 shows that as the reflux ratio of the primary column increases, the primary column neboil ratio must also increase. Equation 21 indicates that the quality of the net stream D_1 decreases and becomes more superheated as the primary column reflux increases. As shown before, as the feed to a column becomes more superheated, the condenser duty of that column increases and the reboiler duty decreases. For the cold utility consumption, Q_{C2} will increase as the primary column reflux increases. There is a tradeoff with hot utility consumption. As the primary column reflux increases, Q_{R1} will increase and Q_{R2} will decrease. From Equation 25 and noting that Q_{C2} increases, $Q_{R\pm}$ will increase by a quantity larger than Q_{ra} will decrease. Furthermore, the increased hot utility consumption will occur at a wanner (and more expensive) temperature, dearly, this tradeoff is not favorable. Therefore, minimum reflux in the primary column is desired when analyzing the secondary column. This argument is also shown analytically in Appendix A.

The solution procedure given by Glinos (1985a) is now fully justified for the side stripper. It is as follows:

1. Solve Equation 16 for $oc^{\wedge} > 4 > OL_{HKI}$.
2. Find the minimum reflux in the primary column, $/?_{1/n}$, with Equation 17.

3. Solve Equation 22 for $\alpha_{LK2} > \eta > \alpha_{HK2}$.
4. Set R_1 to some constant times R_{1m} .
5. Find the minimum reflux in the secondary column, R_{2m} , with Equation 23.
6. Set R_2 to some constant times R_{2m} .

Column with Sidestream Enricher

Consider the column with the sidestream enricher pictured in Figure 5. The configuration has three product streams, one condenser, and two reboilers. Again, the composition of all of the product streams is specified.

The analysis of the side enricher case is very similar to the side stripper. The configuration shown in Figure 5 is transformed into its topological equivalent shown in Figure 6. The primary column will sharply split the mixture into two parts. The light key and lighter components will appear in the distillate stream D_1 . The heavy key and heavier components will pass to the secondary column where they will be split accordingly into the two product streams D_2 and B_2 .

The net product stream B_1 is defined as

$$B_1 = \bar{L}_1 - \bar{V}_1 = D_2 + B_2 \quad (26)$$

$$x_{B1i} = \frac{x_{D2i} D_2 + x_{B2i} B_2}{D_2 + B_2} \quad (27)$$

The primary column can be considered to be a simple sharp column with the product streams D_1 and B_1 . Accordingly, the reflux and reboil ratios for the primary column are defined as

$$R_1 = \frac{L_1}{D_1} \quad S_1 = \frac{\bar{V}_1}{D_2 + B_2} \quad (28)$$

The Underwood equations for the primary column are

$$\sum_i \frac{\alpha_i f_i}{\alpha_i - \phi} = F(1 - q_1) \quad (29)$$

$$\sum_i \frac{\alpha_i d_{1i}}{\alpha_i - \phi} = D_1 (R_{1m} + 1) \quad (30)$$

$$\sum_i \frac{\alpha_i b_{1i}}{\alpha_i - \phi} = -S_{1m} B_1 \quad (31)$$

The secondary column can be considered to be a simple column with a subcooled feed. The quality of the net stream B_x is given by

$$(1 - q_2) = \frac{V_2 - \bar{V}_2}{-B_1} = \frac{V_2 - \bar{V}_2}{D_2 + B_2} \quad (32)$$

Since

$$\bar{V}_2 = \bar{V}_x + V_2 \quad (33)$$

Equation 32 may be rewritten as

$$(1 - q_2) = \frac{\bar{V}_1}{D_2 + B_2} = -S_1 \quad (34)$$

Since $q_2 = S_1 + \dots$ stream will be subcooled. The Underwood equations for the secondary column are

$$\sum_i \frac{S_i b_i}{\alpha_i - \theta} = B_1 (1 - q_2) = SiBi \quad (35)$$

$$\sum_i \frac{S_i}{\alpha_i - \theta} = D_2 (q_2 + 1) \quad (36)$$

$$\sum_i \frac{\alpha_i b_i}{\alpha_i - \theta} = -S_1 B_2 \quad (37)$$

Here, θ represents the Underwood root for the side enricher.

When determining the Underwood root for the secondary column, as small a reboil ratio as possible in the the primary column should be used. The overall energy balance for the side enricher when the feed and products are at their bubble points is

$$Q_{R2} = Q_{C1} + Q_{C2} \quad (38)$$

Thus, Q_{R2} sets the utility consumption for the configuration. Equation 10 shows that as the reboil ratio of the primary column increases, the reflux ratio of the primary column must increase. From Equation 34, the feed to the secondary column, will become more subcooled as the reboil ratio in the primary column increases. If the feed to a column becomes more subcooled, the reboiler duty will increase and the condenser duty will decrease. Thus, by arguments similar to the side stripper case, the smallest possible value for the secondary column reboil ratio will be obtained when S_x is at a minimum. This argument is given analytically in Appendix A.

The solution procedure, as originally given by Glinos (1985a), for the side enricher may now be outlined:

1. Solve Equation 29 for $a_{LKI} > \Phi > a_{HKI}$.
2. Find the minimum reboil ratio in the primary column, S_{1m} , with Equation 31.
3. Set S_x to some constant times S_{1m} .
4. Solve Equation 35 for $a_{zja} > y > a_{HK2}$.
5. Find the minimum reboil ratio in the secondary column, S_{2mf} with Equation 37.
6. Set S_2 to some constant times S_{2m} .

Multiple Side Strippers and Side Enrichers

The analysis given above can be easily extended to columns with multiple side strippers or side enrichers. Initially the same sort of topological transformation is necessary to make the problem more manageable. The generalized transformation for multiple side strippers is shown in Figure 7; the generalized transformation for multiple side enrichers is shown in Figure 8.

The solution procedure for multiple side columns is much the same as the solution procedure for single side columns. Each column is treated as a simple sharp column with the appropriate feed quality and product streams. Initially, the Underwood root for the first column is calculated, and with this quantity either the reflux or reboil ratio is found. The appropriate parameter is used to determine the Underwood root in the next column, and so on. The process is continued until the reflux or reboil ratio is found in the last column.

A special case is the column with a side stripper and side enricher (Figure 9). This configuration presents a unique opportunity for heat integration. Heat may be passed from the condenser of the side enricher to the reboiler of the side stripper if a sufficient temperature driving force is present between the two streams. Since all of the columns operate sharply, these two streams will contain different species. This fact guarantees that the condenser of the side enricher will be hotter than the reboiler of the side stripper. A quick bubble point calculation will determine if a sufficient driving force is present.

Utility Consumption

The question to ask is how do complex columns compare against simple column sequences in terms of utility consumption. The answer is that complex columns are more energy efficient but have larger temperature ranges than simple column sequences. Basically, complex columns are more favorable with respect to first law effects and less favorable with respect to second law effects. Thus, if there is an

adequate temperature driving force, complex columns will be favored; if not, simple columns are more favorable from a utility point of view. This fact can be easily shown by examining the heat flow within each configuration.

Consider the side stripper and its analog, the indirect sequence. The condenser and reboiler duties for simple column sequences will be denoted with a prime superscript. The primary column of each configuration performs the same separation. Thus, the reboiler heat duty on the first column of each configuration must be equal ($Q_{R1} = Q_{R1}'$). The same separation is performed in the secondary column of each configuration. Since the feed to the secondary column of the side stripper is superheated, Q_{R2} must be less than Q_{R2}' . Thus, the side stripper will necessarily consume less hot utilities than the indirect sequence

$$Q_{R1} + Q_{R2} < Q_{R1}' + Q_{R2}' \quad (39)$$

Since the heat into each configuration must balance the heat removed, the side stripper must also consume less cold utilities than the indirect sequence

$$Q_{C1} < Q_{C1}' + Q_{C2}' \quad (40)$$

Therefore, the side stripper must consume less utilities overall relative to the indirect sequence.

By similar arguments the side enricher must consume less utilities than its analog, the direct sequence. The condenser duty on the first column of each configuration must be equal ($Q_{C1} = Q_{C1}'$). Since the feed to the secondary column of the side enricher is subcooled, Q_{C2} must be less than Q_{C2}' . Thus, the consumption of cold utilities for the side enricher must be less than the direct sequence

$$Q_{C1} + Q_{C2} < Q_{C1}' + Q_{C2}' \quad (41)$$

Likewise, the consumption of hot utilities for the side enricher must also be less than the direct sequence

$$Q_{R2} < Q_{R1}' + Q_{R2}' \quad (42)$$

Therefore, the side enricher must consume less utilities overall relative to the direct sequence.

In complex configurations vapor streams flow between columns. Any column supplying vapor must be at a pressure slightly higher than a column receiving it. If not, a compressor is necessary to transport the vapor. Such a compressor would be expensive to install and operate and should not generally be considered in the design. Thus, all of the columns in a complex configuration will operate at roughly the same nominal pressure. Therefore, with complex configurations the temperature difference between the hottest and coldest streams is fixed. In simple column sequences liquid streams flow between columns.

Relatively inexpensive pumps or valves can be used to adjust the pressure of each column as desired. Thus, simple column sequences are decoupled in terms of pressure. The pressure of the columns may be adjusted so as to minimize the difference between the hottest and coldest streams. Thus, complex columns consume less utilities than simple column sequences but require a larger temperature range for operation.

The following example illustrates these principles. A six component mixture is to be separated into three product streams. The feed and product specifications are given in Table 1. The feed is a saturated liquid, and the products are removed at their bubble points. The side stripper and side enricher were analyzed using the procedures given above. For comparison, the direct and indirect sequence were also analyzed. Since reboiler and condenser duties are proportional to vapor flow, these values are reported for each configuration in Table 2. In both instances, the complex columns consumed less utilities than their simple column analogs. The side enricher had the lowest utility usage of all of the configurations. The pressure of the simple columns was adjusted so as to minimize the operating temperature difference. The column pressures and product temperatures are listed in Table 3. The T-Q diagram for each configuration is illustrated in Figure 10. These figures also show typical hot and cold utilities. Complex columns must operate closer to the utility temperatures, and hence require a larger capital investment for heat transfer area. Thus, complex columns are less favorable with respect to the second law.

Nomenclature

variables

B	total molar flow rate of bottoms stream
b_i	molar flow rate of component i in bottoms stream
D	total molar flow rate of distillate stream
d_i	molar flow rate of component i in distillate stream
F	total molar flow rate of feed stream
f_i	molar flow rate of component i in feed stream
L	rectifying section liquid flow rate
\bar{L}	stripping section liquid flow rate
P_k	total molar flow rate of product stream k
P_{ft}	molar flow rate of component i in product stream k
Q_c	condenser heat duty

Q_R	reboiler	heat duty
q		thermal quality of feed stream
R		reflux ratio
R_m		minimum reflux ratio
S	reboil	ratio
S_m		minimum reboil ratio
T_c		condenser temperature
T^{\wedge}	reboiler	temperature
V	rectifying	section vapor flow rate
\bar{V}		stripping section vapor flow rate
x_{Di}		mole fraction of component i in distillate stream
x_{Bi}		mole fraction of component i in bottoms stream
a_i	relative	volatility of component i
$\langle t \rangle$		primary column Underwood root
$r $		side stripper Underwood root
y		side enricher Underwood root
subscripts		
HK		heavy key
LK		light key

Appendix A

In the development given above, it was shown using heat flow arguments that the reflux (or reboil) of the secondary column will increase with the reflux (or reboil) of the primary column. The following is an analytic approach to the same proof.

Consider the side stripper. To show that the secondary column reflux increases with the primary column reflux, it is sufficient to show that the derivative dR_2/dR_1 is always greater than zero. This derivative can be expressed using the chain rule as

$$\frac{dR_i}{dR_x} = \frac{\alpha_i d_{1i}}{(\alpha_i - \eta)^2} \quad (43)$$

Expressions for each term are found by taking the appropriate derivative on Equation 22 and Equation 23 respectively

$$\frac{d\eta}{dR_1} = \left(\sum_i \frac{\alpha_i d_{1i}}{(\alpha_i - \eta)^2} \right)^{-1} \quad (44)$$

$$\frac{dR_2}{dR_1} = \frac{\alpha_i d_{2i}}{(\alpha_i - \eta)^2} \quad (45)$$

Thus, the derivative in question can be expressed as

$$\frac{dR_2}{dR_1} = \frac{\sum_i \frac{\alpha_i d_{2i}}{(\alpha_i - \eta)^2}}{\sum_i \frac{\alpha_i d_{1i}}{(\alpha_i - \eta)^2}} \quad (46)$$

Since the relative volatilities and distillate flow rates are all positive quantities, this expression will always be positive. Therefore, R_2 will always increase with increasing R_x in a side stripper.

The development for the side enricher is much the same; the derivative in question is dS_2/dS_1 . This derivative can be expressed using the chain rule as

$$\frac{dS_2}{dS_1} = \frac{dS_2/dS}{dS_1/dS} \quad (47)$$

The terms in the derivative come from Equation 35 and Equation 37

$$\frac{d\psi}{dS_1} = - \left(\sum_i \frac{\alpha_i b_{1i}}{(\alpha_i - \psi)^2} \right)^{-1} \quad (48)$$

$$\frac{dS_2}{dS_1} = \frac{\sum_i \frac{\alpha_i b_{2i}}{(\alpha_i - \psi)^2}}{\sum_i \frac{\alpha_i b_{1i}}{(\alpha_i - \psi)^2}} \quad (49)$$

Therefore,

$$\frac{dS_2}{dS_1} = \frac{\sum_i \frac{\alpha_i b_{2i}}{(\alpha_i - \psi)^2}}{\sum_i \frac{\alpha_i b_{1i}}{(\alpha_i - \psi)^2}} \quad (50)$$

Again, this expression will always be greater than zero. Thus, S_2 will always increase with increasing S_1 in a side enricher.

Acknowledgement

This work was funded by DOE Grant DE-FG-85ER13396 in the form of student support. Computer facilities were provided by NSF Grant CDR-8522616. The NSF Grant provides funds for the EDRC, an Engineering Research Center.

Table 1: Example Problem - Feed and Product Specifications

	component	f_i	p_u	p_{2i}	p_{3i}
A	ethanol	30.0	29.85	0.15	0.00
B	i-propanol	30.0	0.15	29.85	0.00
C	n-propanol	15.0	0.00	14.925	0.075
D	2-butanol	15.0	0.00	0.075	14.925
E	i-butanol	5.0	0.00	0.00	5.00
F	n-butanol	5.0	0.00	0.00	5.00

all flow rates in kg-mol/hr

Table 2: Example Problem - Column Heat Duties

	$D_1(R_1 + 1)$	S_1B_1	$D_2(R_2+1)$	S_2B_2
Side Stripper	—	424.8	688.2	263.4
Indirect Sequence	424.8	424.8	388.6	388.6
Side Enricher	67.6	---	365.8	433.4
Direct Sequence	67.6	67.6	390.7	390.7

Table 3: Example Problem -- Column Temperatures and Pressures

	Pressure (atm)		Temperature (K)			
	P_1	P_2	T_{C1}	T_{R1}	T_{C2}	T_{R2}
Side Stripper	1.00	1.00	---	377.2	351.5	359.5
Indirect Sequence	1.00	1.25	356.0	377.2	357.3	365.3
Side Enricher	1.00	1.00	351.5	---	359.5	377.2
Direct Sequence	1.40	1.00	360.3	373.5	359.5	377.2

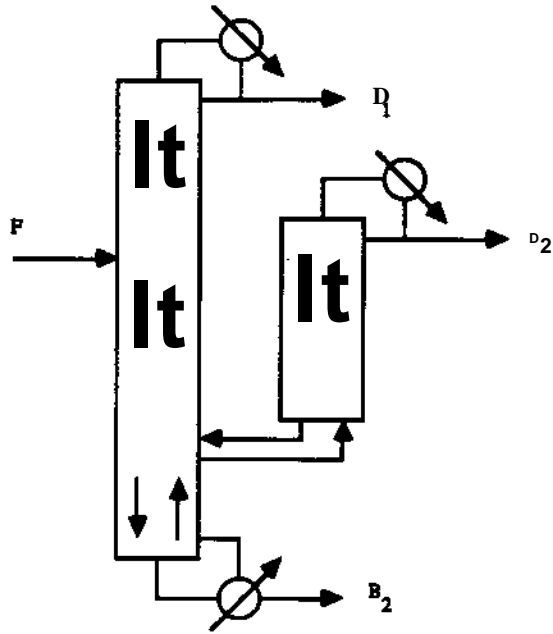


Figure 5: Column with Sidestream Enricher

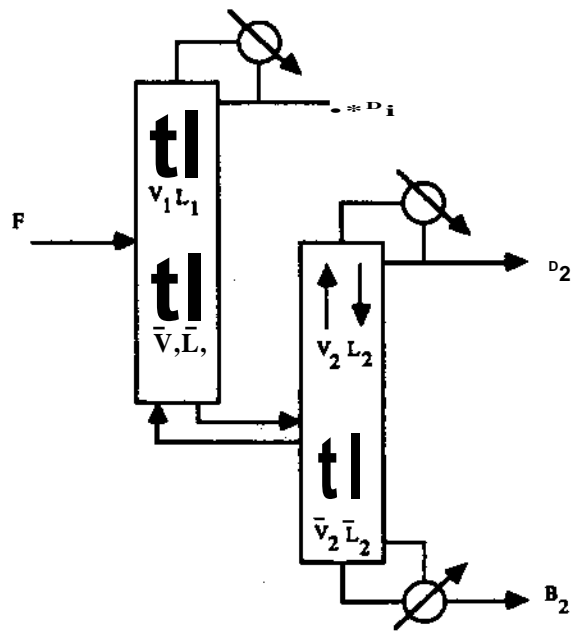


Figure 6: Equivalent Side Enricher Configuration

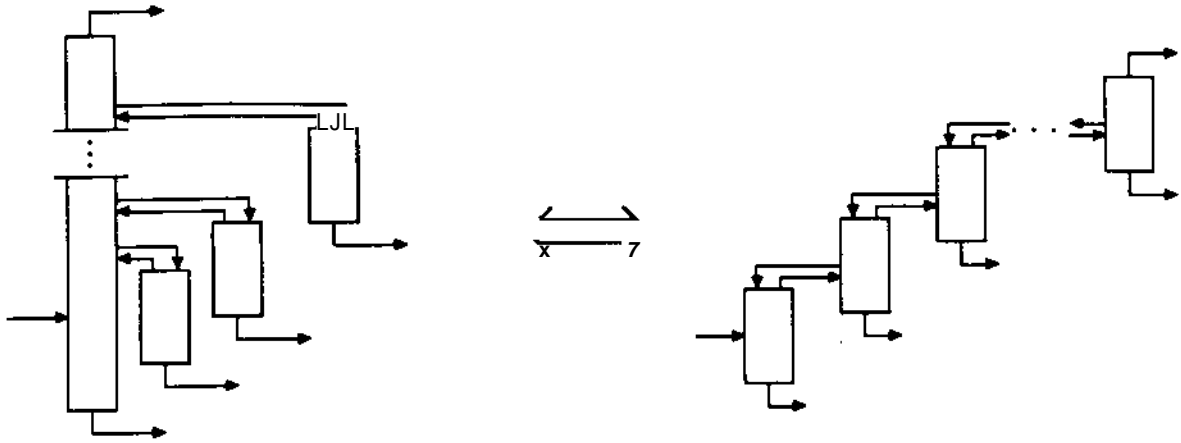


Figure 7: Multiple Side Stripper Transformation

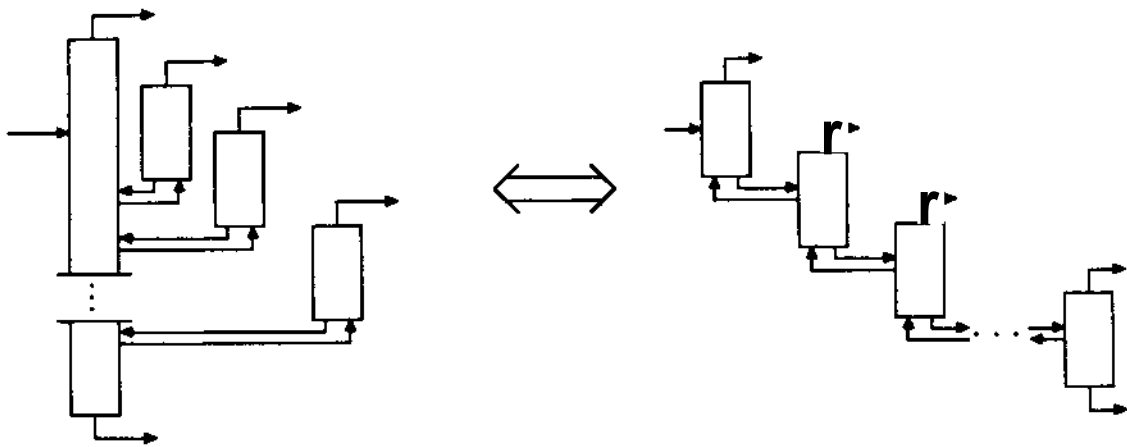


Figure 8: Multiple Side Enricher Transformation

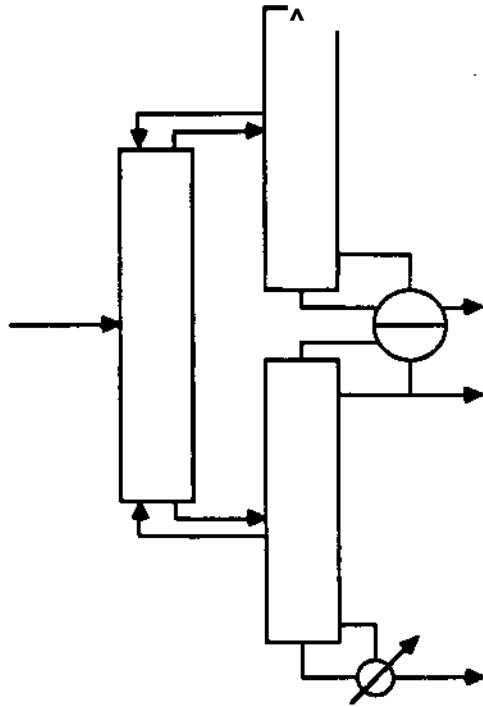


Figure 9: Column with Side Stripper and Side Enricher

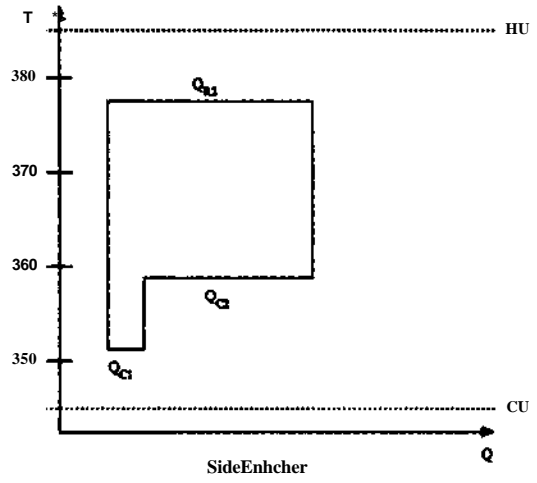
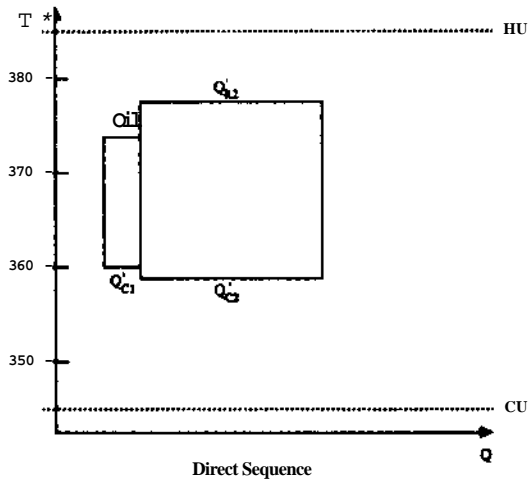
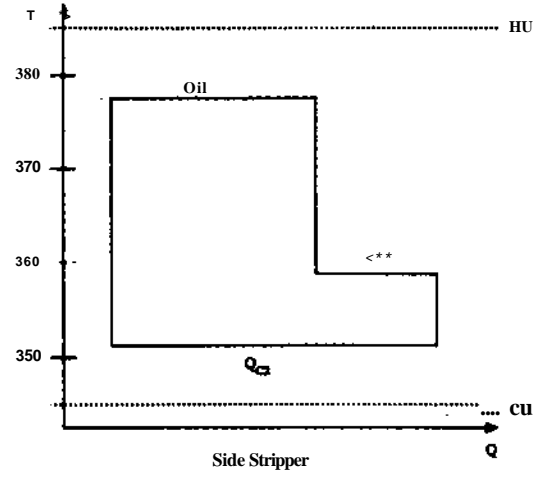
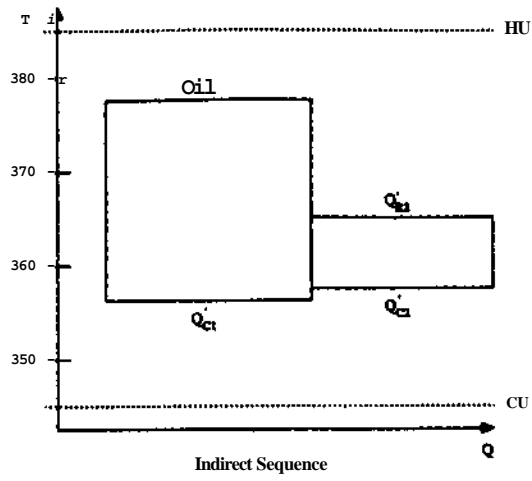


Figure 10: Example Problem -- T-Q Diagrams

References

- Andreovich, M.J.; Westerberg, A.W. A Simple Synthesis Method Based on Utility Bounding for Heat-Integrated Distillation Sequences. *AIChE Journal*, **1985**,31(3), 363.
- Fidkowski, Z.; Rrolkowski, L. Minimum Energy Requirements of Thermally Coupled Distillation Systems. *AIChE Journal*, **1987**,33(4), 643.
- Glinos, K. *A Global Approach to the Preliminary Design and Synthesis of Distillation Trains*. PhD Thesis, Univ of Massachusetts, **1985**.
- Glinos, K.; Malone, M.F. Minimum Vapor Flows in a Distillation Column with a Sidestream Stripper, *I&EC Process Des Dev*, **1985**,24, 1087.
- Glinos, K.; Malone, M.F. Optimality Regions for Complex Column Alternatives in Distillation Systems. *Chem Eng Res Des*, **1988**,66,229.
- Underwood, A.J.V. Fractional Distillation of Multicomponent Mixtures -- Calculation of Minimum Reflux Ratio. / *Inst Petrol*, **1946**,32, 614.
- Underwood, A.J.V. Fractional Distillation of Multicomponent Mixtures. *Chem Eng Progress*, **1948**, 44, 603.
- Terranova, B.E.; Westerberg, A.W. Temperature-Heat Diagrams for Intercolled/Interheated Distillation Columns. *Manuscript in preparation*, **1988**.