Energy Requirements of Nonconventional Distillation Systems

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Many shortcut procedures for distillation column sequencing have been elaborated, but complex column alternatives are usually not included. Glinos and Malone (1984, 1985) developed exact and approximate formulas for minimum reflux calculations and for some conventional and complex distillation systems separating an ideal solution. Similarly, exact expressions for calculations of minimum vapor flow rate were obtained by Fidkowski and Królikowski (1986a,b, 1987) for conventional sequences, systems with prefractionator, and thermally coupled distillation systems. These expressions are valid only for ideal ternary solutions. Conventional systems include direct and indirect sequence, systems with prefractionator—three tower systems and separation complexes. Among thermally coupled systems Petlyuk's system, the side stream stripper, and the side stream rectifier were discussed. Columns in particular systems may be connected by liquid stream, vapor stream, or both, which gives thirty possible structures of columns for ternary separation (Fidkowski and Królikowski, 1990). Comparison of particular systems shows that the thermally coupled system (TCS) Figure 1, and the separation complex (SC_L^V), Figure 2, require the least amount of energy (at minimum reflux conditions) for almost all of these systems. The only exceptions are single columns with a side stream, which may be especially profitable in some cases. Analytical comparison of these two promising systems, TCS and SC_L^V, is the aim of the present work.

The comparison is made under the assumptions given below. These assumptions are somewhat restrictive, but they enable one to express an objective function of each system in the form of simple analytical formulas, which are very convenient for screening calculations.

Separation of a ternary solution into almost pure components is considered. Constant values of relative volatilities and constant molar overflow in distillation columns are assumed. Components A, B, C are ranked in decreasing order of relative volatilities: $\alpha_A > \alpha_B > \alpha_C$. The term "almost pure components" is used to point out that products of separation can be treated as pure compounds; concentrations of the other components are so small that they do not practically affect the minimum reflux ratio value. In order to compare all the considered distillation systems at the same conditions, a boiling liquid state of each system feed and product was assumed. An objective function is defined as the sum of a minimum vapor flow rates in the system that are required for a given separation. Minimum reflux is calculated by Underwood's classic method (Underwood, 1948).

The sum of minimum vapor flows was positively tested as a substitutional objective function of a distillation sequence (Tedder and Rudd, 1978). Knowledge of its values for particular systems enables one to determine a subset of potentially optimum separation structures, by elimination of systems exhibiting significantly high minimum vapor flow. Therefore the synthesis task may be considerably reduced at an early stage.

The sum of minimum vapor flows in a complex system is usually not a single value (for a given separation task), but it is a function of some process parameters (e.g., ratio of prefractionator products) (Fidkowski and Królikowski, 1986a,b, 1987). Therefore minimum values of vapor flow rates at minimum reflux, V^{opt}, should be compared.

Let us define the following relation **R** between systems S1 and S2:

$$\mathrm{S1}\ \mathbf{R}\ \mathrm{S2} \qquad \text{if} \qquad V^{opt}(\mathrm{S1})\ \mathbf{R}\ V^{opt}(\mathrm{S2}) \tag{1}$$

for all possible values of feed composition (A, B, C) and relative volatilities (αA, αB, αC). **R** is one of the following relations: $<$, $\leq$, $=$.

Douglas (1988) compared thermally coupled system with a separation complex in which two prefractionator products were

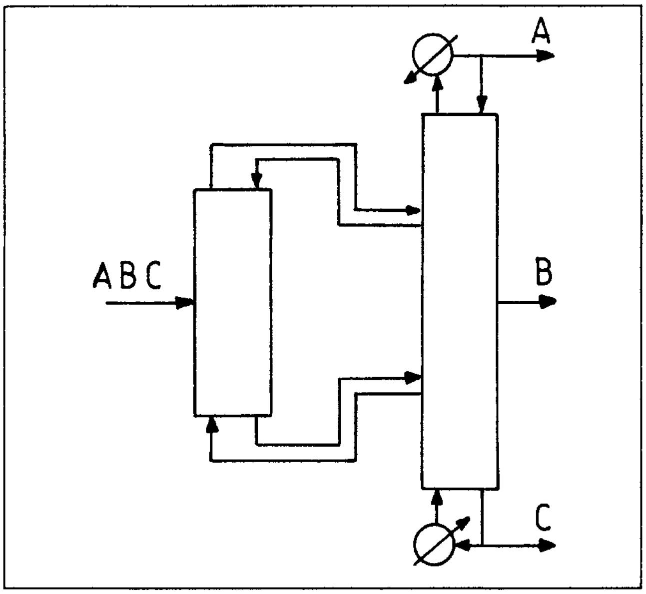

Figure 1. Thermally coupled system of distillation columns.

at the boiling liquid state (SC_L^L). He showed that the TCS always requires less energy than SC_L^L. However this result was obtained in a somewhat intuitive way, without any exact mathematical proof. As was shown (Fidkowski and Królikowski, 1986b):

$$SC_L^V < SC_L^L \tag{2}$$

so the problem of comparison of TCS with SC_L^V still remains unsolved.

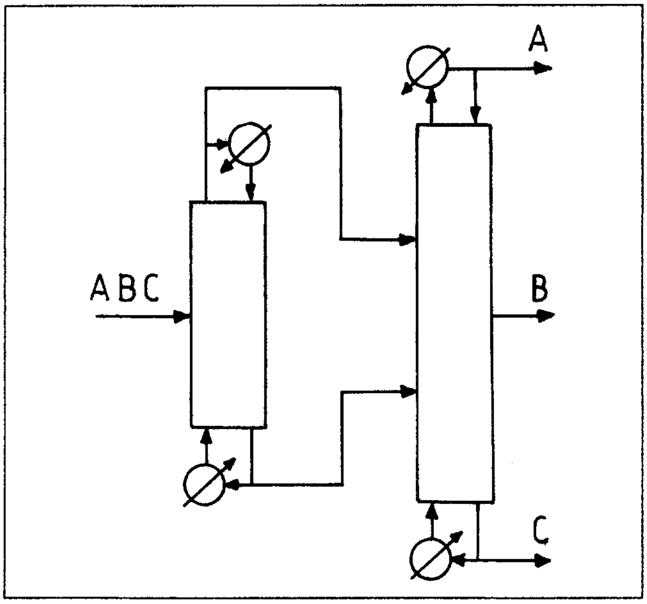

Figure 2. Separation complex.

Minimum vapor flow rates for the TCS and SC_L^V are given by the formulas (Fidkowski and Królikowski, 1986b):

$$V^{opt}(\mathrm{TCS}) = \max\left\{\frac{A\alpha_A}{\alpha_A-\phi_1}, \frac{A\alpha_A}{\alpha_A-\phi_2}+\frac{B\alpha_B}{\alpha_B-\phi_2}\right\} \tag{3}$$

$$V^{opt}(SC_L^V) = \frac{A\alpha_A + B\alpha_B + C\alpha_C}{\alpha_A - \alpha_C} + \max\left\{\frac{(A + B\beta_P)\alpha_B}{\alpha_A - \alpha_B}, \frac{B\alpha_B(1-\beta_P) + C\alpha_C}{\alpha_B - \alpha_C}\right\} \tag{4}$$

where ϕ_1 and ϕ_2 are the roots of Underwood's equation (Underwood, 1948):

$$\frac{A\alpha_A}{\alpha_A - \phi} + \frac{B\alpha_B}{\alpha_B - \phi} + \frac{C\alpha_C}{\alpha_C - \phi} = 0 \tag{5}$$

satisfying the inequality:

$$\alpha_A > \phi_1 > \alpha_B > \phi_2 > \alpha_C \tag{6}$$

One can show from Eq. 4 that for β_p defined as

$$\beta_P = \frac{\alpha_B - \alpha_C}{\alpha_A - \alpha_C} \tag{7}$$

the following formula is satisfied:

$$\frac{A\alpha_A}{\alpha_A - \phi_1} + \frac{B\alpha_B\beta_P}{\alpha_B - \phi_1} = \frac{A\alpha_A}{\alpha_A - \phi_2} + \frac{B\alpha_B\beta_P}{\alpha_B - \phi_2} = \frac{A\alpha_A + B\alpha_B + C\alpha_C}{\alpha_A - \alpha_C} \tag{8}$$

The aim of the following considerations is to find the relation **R** (if any) between $V^{opt}(\mathrm{TCS})$ and $V^{opt}(SC_L^V)$. On the basis of Eqs. 4, 5, and 6 we can write

$$\frac{A}{\alpha_A - \phi_1} + \frac{B}{\alpha_B - \phi_1}\frac{\alpha_B}{\alpha_A} > 0 \tag{9}$$

and

$$\beta_P < \frac{\alpha_B}{\alpha_A} \tag{10}$$

which gives

$$\frac{A}{\alpha_A - \phi_1} + \frac{B\beta_P}{\alpha_B - \phi_1} > 0 \tag{11}$$

Multiplying this inequality by a positive factor

$$\frac{(\alpha_A - \phi_1)\alpha_B}{\alpha_A - \alpha_B}$$

one can obtain

$$\frac{B\alpha_B\beta_P}{\alpha_B - \phi_1} + \frac{(A + B\beta_P)\alpha_B}{\alpha_A - \alpha_B} > 0 \tag{12}$$

Adding to both sides of the last inequality the expression

$$\frac{A\alpha_A}{\alpha_A - \phi_1}$$

and utilizing Eq. 8 we have

$$\frac{A\alpha_A + B\alpha_B + C\alpha_C}{\alpha_A - \alpha_C} + \frac{(A + B\beta_P)\alpha_B}{\alpha_A - \alpha_B} > \frac{A\alpha_A}{\alpha_A - \phi_1} \tag{13}$$

It is evident that in consequence the following inequality is also satisfied

$$\frac{A\alpha_A + B\alpha_B + C\alpha_C}{\alpha_A - \alpha_C} + \max\left\{\frac{(A + B\beta_P)\alpha_B}{\alpha_A - \alpha_B}, \frac{B\alpha_B(1 - \beta_P) + C\alpha_C}{\alpha_B - \alpha_C}\right\} > \frac{A\alpha_A}{\alpha_A - \phi_1} \tag{14}$$

On the other hand, from Eqs. 5 and 6

$$\frac{B\alpha_B}{\alpha_B - \phi_2} + \frac{C\alpha_C}{\alpha_C - \phi_2} < 0 \tag{15}$$

This inequality remains still satisfied if its positive component is multiplied by $(1 - \beta_p)$

$$\frac{B\alpha_B}{\alpha_B - \phi_2}(1 - \beta_P) + \frac{C\alpha_C}{\alpha_C - \phi_2} < 0 \tag{16}$$

Multiplying this inequality by the negative factor

$$\frac{\alpha_C - \phi_2}{\alpha_B - \alpha_C}$$

we obtain

$$\frac{B\alpha_B(1 - \beta_P) + C\alpha_C}{\alpha_B - \alpha_C} + \frac{B\alpha_B(1 - \beta_P)}{\alpha_B - \phi_2} > 0 \tag{17}$$

Then the expression

$$\frac{A\alpha_A}{\alpha_A - \phi_2} + \frac{B\alpha_B}{\alpha_B - \phi_2}$$

is added to both sides of the last inequality

$$\frac{A\alpha_A}{\alpha_A - \phi_2} + \frac{B\alpha_B\beta_P}{\alpha_B - \phi_2} + \frac{B\alpha_B(1 - \beta_P) + C\alpha_C}{\alpha_B - \alpha_C} > \frac{A\alpha_A}{\alpha_A - \phi_2} + \frac{B\alpha_B}{\alpha_B - \phi_2} \tag{18}$$

Taking into account Eq. 8, we have

$$\frac{A\alpha_A + B\alpha_B + C\alpha_C}{\alpha_A - \alpha_C} + \frac{B\alpha_B(1 - \beta_P) + C\alpha_C}{\alpha_B - \alpha_C} > \frac{A\alpha_A}{\alpha_A - \phi_2} + \frac{B\alpha_B}{\alpha_B - \phi_2} \tag{19}$$

It is obvious that in consequence the following inequality is also satisfied

$$\frac{A\alpha_A + B\alpha_B + C\alpha_C}{\alpha_A - \alpha_C} + \max\left\{\frac{(A + B\beta_P)\alpha_B}{\alpha_A - \alpha_B}, \frac{B\alpha_B(1 - \beta_P) + C\alpha_C}{\alpha_B - \alpha_C}\right\} > \frac{A\alpha_A}{\alpha_A - \phi_2} + \frac{B\alpha_B}{\alpha_B - \phi_2} \tag{20}$$

Finally, Eqs. 14 and 20 give

$$\frac{A\alpha_A + B\alpha_B + C\alpha_C}{\alpha_A - \alpha_C} + \max\left\{\frac{(A + B\beta_P)\alpha_B}{\alpha_A - \alpha_B}, \frac{B\alpha_B(1 - \beta_P) + C\alpha_C}{\alpha_B - \alpha_C}\right\} > \max\left\{\frac{A\alpha_A}{\alpha_A - \phi_1}, \frac{A\alpha_A}{\alpha_A - \phi_2} + \frac{B\alpha_B}{\alpha_B - \phi_2}\right\} \tag{21}$$

Notice that expressions in this inequality refer to objective functions of considered systems, Eqs. 3 and 4, and

$$V^{opt}\,(\mathrm{SC}_{\mathrm{L}}^{\mathrm{V}}) > V^{opt}\,(\mathrm{TCS}) \tag{22}$$

The last inequality is satisfied for all the positive values of A, B, C and α_A, α_B, α_C; then

$$\mathrm{TCS} < \mathrm{SC}_{\mathrm{L}}^{\mathrm{V}} \tag{23}$$

One can conclude that the least value of minimum vapor flow at minimum reflux conditions (taking into account all distillation systems listed above) is achieved in TCS. It should be pointed out that this result is valid only for a ternary ideal solution.

Notation

A, B, C = flow rate of component A, B, C in feed, kmol/s
S1, S2 = systems
$\mathrm{SC}_{\mathrm{L}}^{\mathrm{V}}$ = separation complex, Figure 2
TCS = thermally coupled system (Petlyuk's system), Figure 1
V = vapor flow rate and objective function, kmol/s
α = relative volatility
β_p = defined by Eq. 6
ϕ_1, ϕ_2 = roots of Underwood's equation, Eq. 4

Subscripts

A, B, C = component A, B, C

Superscripts

opt = optimum

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