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THEORETICAL BASES OF CHEMICAL TECHNOLOGY

DEPENDENCE OF EXTERNAL AND INTERNAL ENERGY-SAVING FOR RECTIFICATION OF BINARY MIXTURES

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The comparison of energy consumption for rectification of binary mixtures in one-column and two-column apparatuses was carried out with the use of vapor flow energy from the first column for heating the second column. It is shown that the expected two-fold reduction of the flow of heat energy is impossible due to the decrease of the internal energy-saving.

Keywords: *rectification, energy consumption, internal and external energy-saving, reflux ratio.*

Introduction

The energy consumption of the separation of liquid mixtures by distilling methods (distillation, rectification) and evaporation of salt solutions is stipulated by the necessity of evaporating one or more components of the separated mixture. The evaporation of **aqueous** solutions of salts and distillation processes with low relative volatility of the components (low separability of the mixture) are particularly energy-intensive.

In order to reduce the heat consumption upon evaporation the heat pump and multiple effect evaporation are often used [1–3]. The principle of heat pump is widely used also in distillation processes [4]. We have previously suggested [5] energy saving schemes for the distillation of binary mixtures. Besides, we calculated the energy saving and the reduced costs for these cases [6, 7]. We have not achieved the expected two-fold reduction of heating steam consumption in the boiler of the first column (upon distillation in a two-column assembly) due to the use of steam from the first column in the second column boiler [7].

In order to clarify the reasons for such a result we carried out the comparison of heat consumption upon the distillation of binary mixtures of one column, in two columns at equal pressures and in two columns at different pressures with the ability of using the steam as a heating agent in the second column boiler.

Experimental

When comparing the heat consumption for the separation of various schemes we evaluated the internal energy efficiency in fractionating columns that depends largely on reflux ratio. According to authors [8–10] internal energy efficiency is the degree of use of the steam flow from the boiler in the processes of heat and mass transfer on all the plates of the column. The value of the vapor flow through the column is determined by the specified requirements for the purity of the obtained separation products.

Internal energy efficiency in the upper part of a fractionating column is characterized by the ratio of the liquid flow L and steam flow D. If $\frac{L}{D}$ ratio is the same along the column height, it is equal to $\frac{R}{(R+1)}$, where R is reflux ratio.

The liquid flow in the lower part is always more intensive than the vapor flow due to the infeed. This allows the vapor flow to condense most completely on the plates due to the liquid flow from the upper plates. Energy saving here is maximal and is set to be equal to 1.

Taking into account the different number of plates in the upper and lower parts of the column the average internal energy *Эн** saving along the column can be calculated with the use of the following formula (if the initial mixture is fed into the column at the boiling point):

$$Э_н = \frac{R}{R+1}\frac{n_y}{n_y+n_0} + \frac{n_0}{n_y+n_0} \tag{1}$$

If a vapor-liquid mixture is fed into the column for separation (Ψ is the vapor fraction), a lesser vapor flow in the lower part of the column is required. The ratio of the vapor flow in the lower part D_H to the full flow D upon the feeding of the initial mixture in the vapor-liquid state depends on the vapor fraction Ψ in the liquid that is fed into the column:

$$\frac{D_H}{D} = \frac{D-\Psi L_1}{D} = 1-\frac{\Psi L_1}{(R+1)\Pi} = 1-\frac{\Psi(x_2-x_0)}{(R+1)(x_1-x_0)} \tag{2}$$

**Эн* means energy saving.

Equation (2) on the right is usable only for binary mixtures.

Therefore we can find the condition of the equal internal energy saving (vapor usage efficiency) in the product-concentrating column and stripping column:

$$\frac{R}{R+1} = 1 - \frac{\Psi(x_2 - x_0)}{(R+1)(x_1 - x_0)} \tag{3}$$

Equation (3) gives the vapor content in the initial binary system, upon which the same vapor flow condenses on each plate of the column:

$$\Psi = \frac{x_1 - x_0}{x_2 - x_0} \tag{4}$$

Note that the energy efficiency of the process is not maximal upon this vapor content, because not all the vapor flow necessary for the distillation “works” in the lower part of the column.

Thus, the average internal energy saving of a fractionating column *Эн* upon feeding the initial mixture with vapor fraction Ψ depends on the number of theoretical plates in the upper (n_y) and lower parts of the column (n_0) and can be calculated as follows:

$$Эн = \frac{R}{R+1}\frac{n_y}{n_y + n_0} + \left[1 - \frac{\Psi L_1}{(R+1)П}\right]\frac{n_0}{n_y + n_0} \tag{5}$$

Equation (5) is true for multicomponent mixtures as well. Note that if “cold” initial mixture is fed into the column ($t_x < t_1$), the value of Ψ is negative.

In the case of binary mixtures the second summand in the right part of equation (5) can be written as follows (taking into account the material balance of the column):

$$Эн = \frac{R}{R+1}\frac{n_y}{n_y + n_0} + \left[1 - \frac{\Psi}{(R+1)}\frac{x_2 - x_0}{x_1 - x_0}\right]\frac{n_0}{n_y + n_0} \tag{6}$$

Equations (5) and (6) can be used to evaluate internal energy saving (the efficiency of using the vapor flow in the fractionating column) at a given mixture separation value (x_1, x_2 and x_0) and the state of the initial mixture at the column inlet. It would appear reasonable that if internal energy saving increases, heat energy consumption for the separation process decreases.

In the case of a two-column system internal energy saving (the use factor of the vapor flows in both columns) can be calculated taking into account the fractions of the vapor flows in each column:

$$Эн = Эн_1\frac{D_1}{D_1 + D_2} + Эн_2\frac{D_2}{D_1 + D_2} \tag{7}$$

The calculation was performed with the use of Aspen Plus software, and the internal energy saving in the columns was calculated according to equations (1), (6) and (7).

Results and Discussion

When separating L_1 = 0.01 kmol/sec of benzene–toluene binary mixture of the composition x_1 = 0.5 kmol of the LBC (low-boiling component)/kmol of the mixture in a one-columned fractionating installation (Fig. 1) with the production of a distillate of the composition x_2 = 0.98 kmol of the LBC/kmol of the mixture and a bottom product of the composition x_0 = 0.02 kmol of the LBC/kmol of the mixture, we obtained results presented in Table 1.

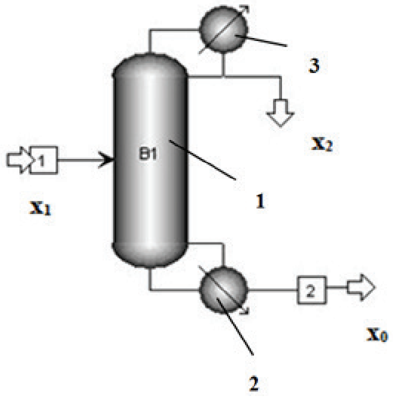

Fig. 1. Scheme of a one-column fractionating installation.
1 – column, 2 – boiler, 3 – condenser.

Table 1. Results of calculating the one-column installation upon the separation of benzene–toluene mixture

Reflux ratio, *R*	1.6023
Number of theoretical plates in the upper part, n_y	9
Number of theoretical plates in the lower part, n_o	9
Heat consumption in the boiler $Q_к$, kW	435
Internal energy saving, *Эн*	0.812

In order to choose the optimal scheme of the two-column installation with different pressures in the columns we compared two variants of separation in two-column fractionating installations with the same pressures (Fig. 2).

Flow L_1 =0.01 kmol/sec and the composition of the initial mixture (x_1 =0.5 kmol/sec), as well as the final compositions of the distillate x_2 = 0.98 and of the distillation residue x_0 = 0.02 are equal for both schemes.

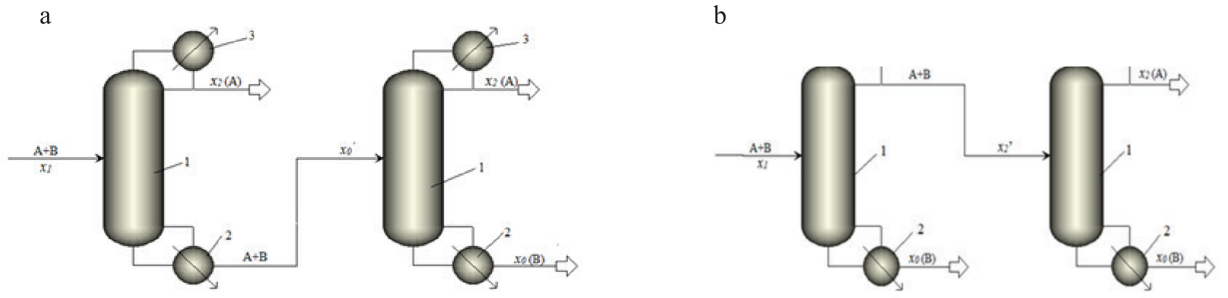

Fig. 2. Schemes of separation of benzene–toluene binary mixture:
a – two-column fractionating installation with intermediate concentration of the distillation residue x_0’;
b – two-column fractionating installation with intermediate concentration of the distillate x_2’.
1 – column, 2 – boiler, 3 – condenser.

In scheme “a” the distillation residue with intermediate concentration x_0' = 0.20 kmol of LBC/kmol of the mixture is subject to separation in the second column with the production of the required final products. In scheme “b” the distillate of composition x_2' = 0.85 kmol of LBC/kmol of the mixture is separated in the second column to give the required compositions of the final products.

Calculation of the number of theoretical plates and of heat consumption in the boilers was performed with the use of Aspen Plus software. The internal energy saving of each column was calculated according to equation (1), and the average internal energy saving – according to equation (7). The results of the calculations are presented in Table 2.

It can be seen from Tab. 2 that smaller total consumption is characteristic for the scheme “a”. Rectification in both columns according to the scheme “a” is carried out at large reflux ratios, which creates conditions for better internal energy saving (especially in the second column). Almost equal average internal energy savings are caused by the different extent of approach of the calculations that we carried out to optimal.

In order to estimate external energy saving upon the separation of the binary mixture in two columns with various pressures the scheme “a” was chosen as less expensive. The scheme of such energy-conservative installation is submitted in Fig. 3. Pressure in the second column is taken as atmospheric, and optimum pressure in the first one according to the calculations carried out earlier [6, 7] is taken as equal to 3 atm.

Table 2. Core indicators of the operation of two-column installations at atmospheric pressure

Indicator	Scheme “a” x_0' =0.20 kmol of LBC/kmol of mixture		Scheme “b” x_2' =0.85 kmol of LBC/kmol of mixture	
	1-st column	2-nd column	1-st column	2-nd column
Reflux ratio, *R*	1.603	4.85	0.84	0.84
The number of plates in the upper part, n_y	8	9	4	5
The number of plates in the lower part, n_0	5	6	9	10
Internal energy saving, *Эн*	0.763	0.897	0.832	0.818
Average internal energy saving, *Эн*	0.818		0.826	
Heat consumption, kW	314	212	325	268
Total amount of heat in the rectifying still, Q_Σ (kW)	526		593	

For the convenience of comparison of heat consumption with other variants of rectification here, as well as above, we divided the flow of the initial mixture L_1 = 0.01 kmol/sec with composition x_1 = 0.5 kmol of LBC/kmol of mixture with

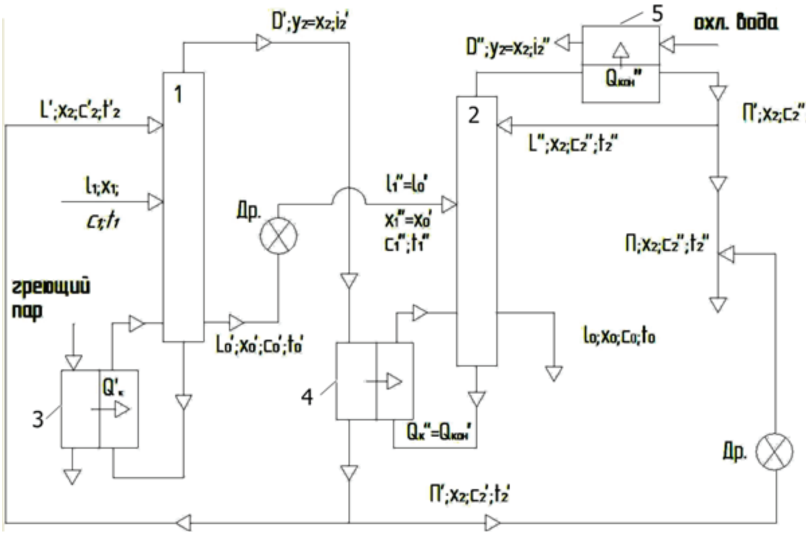

Fig. 3. Scheme of a two-colomn rectifying plant with different operating pressure:
1,2 – colomns, 3 – boiler, 4 – condenser boiler, 5 – condenser
*[греющий пар means heating strem; охл. вода (охлаждающая вода) means cooling water;
Др. (дроссель) means throttle flap].

the preparation of distillate of composition x_2 = 0.98 kmol of LBC/kmol of mixture and a bottom product of composition x_0 = 0.02 kmol of LBC/kmol of mixture. Concentration $x_0^{'}$ = 0.3155 kmol of LBC/kmol of mixture corresponds to equal heat abstraction $Q_{кон}^{'}$ in the condenser of the first column and the required heat supply $Q_к^{''}$ in the boiler of the second one [7]. The fraction of vapor Ψ in the vapor-liquid mixture entering the second column after throttling at the specified concentration and pressure in the columns is 0.265. Calculation of internal energy saving in this case for the second column is performed with the use of formula (6).

The result of calculating this energy-conservative variant of two-column rectification in comparison with the results of one-column rectification is shown in Table 3.

$$Эн_2 = \frac{3.29}{3.29+1} \cdot \frac{9}{9+10} + \left[1 - \frac{0.265}{3.29+1} \cdot \frac{0.98-0.02}{0.316-0.02}\right] \frac{10}{9+10} = 0.363 + (1 - 0.2003)\frac{10}{19} = 0.783$$

Table 3. Comparison of core indicators of rectification processes in one column and in two columns with external energy saving in recuperator 4

Indicator	One column	Two-column installation	
		1-st column	2-nd column
Reflux ratio, R	1.602	1.98	3.29
The number of plates in the upper part, n_y	9	10	9
The number of plates in the lower part, n_0	9	4	10
Amount of heat in the rectifying still, $Q_к$, kW	435	329	352
Internal energy saving, *Эн*	0.812	0.760	0.783
Average internal energy saving, *Эн*	0.812	0.760	

Conclusions

It is shown that the general heat consumption for the separation in case of two-column rectification is equal to 329 kW (the heat consumption of the second column, 352 kW, is provided with vapor from the first column). This is significantly less than the heat consumption in one column (435 kW). However, this decrease in heat consumption (1.32-fold) and, therefore, in the primary vapor consumption are much less than double decrease achieved in case of two-effect evaporating installation under the assumption of constancy of the latent heat of evaporation in the range of different pressures. This is explained as follows. Using external energy saving in the absence of any internal energy saving in the bodies of the evaporation plant provides reduction of the primary vapor consumption multiple of the number of the bodies. Using external energy saving in rectification decreases internal energy saving in the first column (it is estimated to be equal to 0.76 in comparison with 0.812 in case of one-column rectification). Nevertheless, the lowered internal energy saving in the second column (0.783) due to the supply of the vapor-liquid mixture into the column does not influence the general energy saving, because the heating of the second column is completely provided with the vapor flow from the first one.

Thus, the above analysis showed that using external energy saving in the given option of rectification is followed by a change in internal energy saving. The latter directly affects the heat consumption in the boiler of the rectifying column.

Conventional designations

D – vapor flow, kmol/sec; E – separation factor; L – liquid flow, kmol/sec; n – plate number; Q – heat flow, kW; R – reflux ratio; r – heat of evaporation, kJ/kmol; t – temperature, °C; x – concentration of the low-boiling component in the liquid, kmol/kmol of the mixture; y – concentration of the low-boiling component in the vapor, kmol/kmol of the mixture; $П$ – distillate flow, kmol/sec;

Indexes: 0 – bottom product, 1 – initial mixture, 2 – top product, у – укрепляющая колонна (product-concentrating column), о – отгонная колонна (stripping column), k - кипятильник (boiler), кон – конденсатор (condenser).

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