UDC 66.048.3

DISTILLATION OF BINARY TWO-PHASE MIXTURES WITH VARIOUS PHYSICO-CHEMICAL PROPERTIES: NORMAL MODE AND DEVIATIONS FROM IT*

L.A. Serafimov, K.A. Morozov@

Moscow Technological University (Institute of Fine Chemical Technologies),
Moscow, 119571 Russia
@Corresponding author e-mail: kamorozov@mitht.ru

In this article, normal continuous mode distillation is reviewed using an example of binary two-phase mixture distillation. In practice, there are often deviations from the normal mode. It has been proved that the deviation leads to an increase in energy consumption for the ongoing process. In the industry, columns separating binary mixtures are normally the finishing apparatus in the flow-sheet separation of multicomponent mixtures, which are obtained in the reactor as a result of main as well as by-reactions. The distillation of binary mixtures is relatively simpler than that of multicomponent mixtures. In this regard, the fundamental parts of monographs especially in the thirties-forties of the last century, started with the study of binary mixtures, although the main focus was multicomponent mixtures. The importance of analyzing this complex and highly energy-intensive process is to facilitate the choice of a mathematical model for the process and the determination on its basis variance. Variance is a set of independent variables that allow calculation of a process only after taking into account the number of independent equations related these variables. A case of deviation from the normal distillation regime where an under-heated liquid enters the column feed has been revised. This leads to an increase in energy consumption during distillation. Key indicators of the normal regime, relative to the level of feed and the temperature of the liquid are shown in the text.

Keywords: *normal distillation mode, design calculations, virtual modes of distillation, special modes of distillation, the minimum reflux ratio, the maximum boilup ratio.*

The presented work considers the normal mode of continuous rectification, as well as deviations from it often encountered in practice, with rectification of a binary two-phase mixture as an example. Analysis of these deviations proved that they result in an increase of power consumption for the process.

As a rule, industrial columns separating binary mixtures are completing devices in the flow diagram of the separation of multi-component mixtures obtained in a reactor as a result of target and side reactions. Rectification of binary mixtures is a simpler process than rectification of multicomponent ones. Therefore, most monographs, especially those written in 1930s and 1940s, begin with the consideration of binary rectification, although multi-component mixtures [1–13] are considered as well.

Choosing a mathematical model of the process and determining its variance [14, 15] on this basis is of great importance for the analysis of this complex and very power-intensive process.

---

* Original Russian Text © L.A. Serafimov, K.A. Morozov, 2016, published in Tonkie Khimicheskie Tekhnologii / Fine Chemical Technologies, 2016, Vol. 11, No 4, pp. 15-25.

Variance a set of independent variables allowing to start calculating the considered process after setting them with account of the number of independent equations that interrelate these variables.

The abstract concept of variance means the difference of the total number of variables of a chosen model and the number of equations interrelating these variables [16]. Equation systems of this kind obtained after choosing independent variables are often referred to as mathematically closed ones. Consequently, the complexity of a model is closely connected with the number of variables of a real process considered in it.

At the beginning of the 20th century two directions of rectification studies were formed. The first one uses an approximate model based on the concept of theoretical plate. The second direction takes into account the sufficiently large number of phenomena inherent in the real process of rectification. In this case the general mathematical model considers mass transfer, longitudinal mixing, drop entrainment, the relative direction of the contacting phases flow and other factors. Studies in this direction are still performed. However, in predesign studies [10–13] and in design works the concept of theoretical plate (or the concept of theoretical step) is preferred. As a matter of fact, the scientific practice has the established opinion that the processes proceeding in packed and film-type columns, i.e., in devices with differential change of contacting phases composition can be measured by the number of theoretical plates. However, it has been shown long ago that the trajectories of these processes are different, especially in the middle part of columns. This does not result in essential mistakes in practical work, in contrast to works on the theory of rectification.

Recall that the concept of theoretical step is based on the assumption that the vapor and liquid flows leaving a plate are in thermodynamic equilibrium. This determines the number of equations in the considered processes in addition to balance equations and allows equating variance as follows [17]:

$$\mathcal{F} = n + Q_1^{loss} + Q_2^{loss} + \xi_1 + \xi_2 + 10 \qquad (1),$$

where n is the number of the components to be separated; Q_1^{loss} (and Q_2^{loss} are heat losses on each plate; ξ_1 and ξ_2 are pressures on each plate in the rectifying and exhausting sections of the column.

Equation (1) includes intensive, extensive and constructive variables. Thus, it significantly differs from the known phase rule: the latter uses only intensive variables or both intensive and extensive ones.

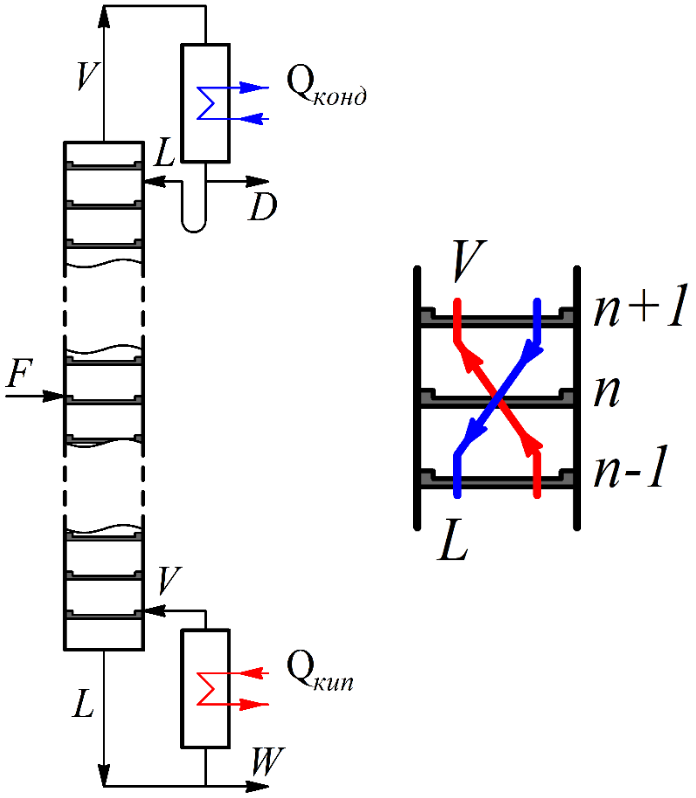
It is usual to consider two types of theoretical plates:

1) theoretical plates having a quite certain delay by the liquid phase;

2) theoretical plates represented on the chart as a convergence point of two inlet flows of various compositions and temperatures and two outlet flows of a liquid and vapor of various

compositions, but same temperature. Parameters of the inlet flows fulfil the Boshnyakovich [18] rule, and the outlet flows are thermodynamically equilibrium.

In general, the system (rectification column) is flowing, i.e., thermodynamically open. In the simplest case it has three external material streams: feed mixture (*F*), distillate (*D*), vat product (W) and two external power streams: the energy supplied to the boiler (Q_{boil}) and the energy removed in the condenser (Q_{cond}). As for the rest, the process goes adiabatically at a constant temperature and pressure in each section. Figure 1 presents the general view of an elementary two-section rectification plate column and its elements. Besides, the figure shows liquid (*L)* and vapor (*V*) flows in the column, the feed mixture, the distillate and the vat product, and also power flows.



a) b)

Figure 1. General view of a rectification column and its elements:
a) column, boiler, condenser;
b) scheme of flows on a plate
(see designations in the text).

[конд. means cond.; кип. means boil]

When using the concept of a theoretical plate, it is assumed that the liquid at each level is in the boiling state from the top plate to the boiler. Moreover, the distillate and vat product are also removed in the boiling state or in a state very close to boiling.

It is usual to distinguish the normal mode of rectification and various deviations from it forming a series of modes, which we will call "the modes with a deviation from the normal one" [4, 6]. Analogs of such modes in various forms exist in practice, which finally results in excessive energy consumption for the rectification process.

Apparently, Kirschbaum [4] and Sorel [5] should be considered as the authors of the concept "normal mode" of rectification, because this mode is closely related to the concept of theoretical plate. This term is found also in [6]. The normal mode means supplying the feed mixture and the state of all liquid flows as boiling liquids. In order to describe such mode the concept of a theoretical plate is usually used.

In our opinion, the characteristic of the normal mode is a little restricted when it is limited to supplying the mixture in the state of a boiling liquid. Apparently, modes where the feed stock is inlet in a certain aggregate state (liquid, vapor or liquid/vapor mixture flow) should be considered as normal ones. The point is that the feed mixture supply is an external factor with regard to the column operation. This factor determines to some extent the normal mode. Due to this deviations from the normal modes emerge and rise.

This work is devoted to the analysis of dynamic systems of continuous rectification of binary mixtures. These systems function in modes other than normal. Nowadays researchers show a certain interest in the matter [10–26].

We will base the analysis on the model of a theoretical plate, because it is the simplest one. The problem definition can be either design-oriented or test-oriented irrespective of whether an element of the column is considered in the form of a plate or in the form of a transfer unit. Besides, the number of independent variables is invariant with respect to the type of calculation irrespective of whether a discrete system or a continuous model is considered.

Table 1 presents data characterizing the invariance of the number of independent variables in the design-oriented and test-oriented problem definition. The choice of a rectification model determines the total number of variance of the considered system presented in Table 1.

Table 1. Independent variables in the design-oriented and test-oriented problem definition

Evaluated variable (designation)		The number of variables
Design-oriented problem definition	Test-oriented problem definition	
Feed mixture composition (x^F)		n – 1
Feed mixture amount (F)		1
Feed mixture pressure (P)		1
Feed mixture enthalpy (H)		1
Concentration of one component in the distillate (x^D)	Setting reflux ratio (R)	1
Concentration of one component in the vat (x^W)	Setting the general number of steps (N)	1
Concentration of one component at the feed level (x^F)	Setting the number of steps of two sections	1
Condensate excess coefficient (based on the determination of R_{min}) (σ)	Setting the ratios of outputs W/D, or W, or D	1

Heat losses into environment at each step, in the distillate and in the vat	$Q_1^{loss} + Q_2^{loss} + 2$
Pressure at each step, in the vat and in the condenser ($2\xi_i+2$ to take into account local resistance)	$\xi_1 + \xi_2 + 2$
Total: $F =$	$n + Q_1^{loss} + Q_2^{loss} + \xi_1 + \xi_2 + 10$

The compositions of all the points creating the trajectory of a dynamic system development are divided into compositions formed by the process course and compositions forming a singular point of the considered dynamic system. Actually, a simple rectification column has two sections. Each of them corresponds to its own dynamic system. Thus, the considered two dynamic systems form one joint discrete system. The joining occurs upon transition from one section (for example, the rectifying one) to another (the exhausting, lower one). The join points are simple points of trajectories break at a reflux ratio larger than minimum or special points with unilateral or bilateral infinity. In this case the number of separation steps approaches infinity, and the composition approaches a constant. Such points form a constant composition zone (CCZ) and are boundary ones for the two joint dynamic systems, or final points.

Note that the normal rectification mode postulates one singular point with bilateral infinity in the sections. As noted by Lewis, in this case differentiation is admissible in the vicinity of these points in the general discrete process. Note also that the compositions of these points are identical for identical independent variables, both in case of discrete and differential dynamic systems. In order to carry out further analysis of both the normal mode and modes differing from normal let us obtain the general equation of power consumption for the rectification of a binary mixture in the form of a ratio of power consumptions determined with the aid of minimum reflux ratio and the maximum vapor number. This approach is caused by the necessity of representing the mechanism of interaction of the independent variables.

It is known that if all compositions are associated with the first (highly volatile) component, the minimum reflux ratio for the normal mode is determined by the following equation:

$$R_{min} = \frac{V-D}{D} = \frac{L}{D} = \frac{x_1^D - y_1^F}{y_1^F - x_1^F}. \tag{2}$$

The maximum vapor number is determined by the following equation:

$$\Theta_{max} = \frac{L-W}{W} = \frac{V}{W} = \frac{x_1^F - x_1^W}{y_1^F - x_1^F}. \tag{3}$$

Figure 2 shows dependencies of the physical magnitudes represented by equations (2) and (3).

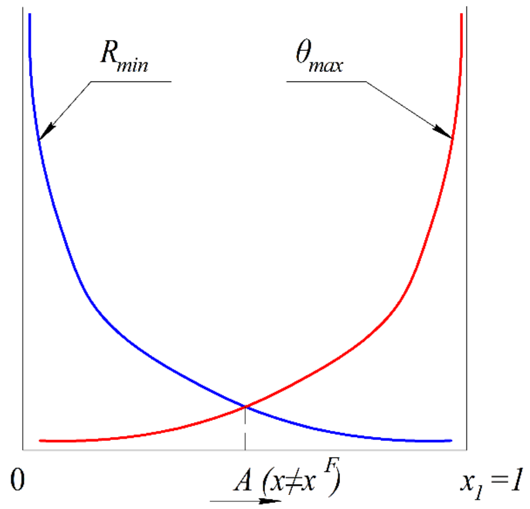


Figure 2. General view of R_{min} and Θ_{max} dependences on condition of precision fractional distillation of binary mixture ($x_1^D = 1, x_1^W = 0$).

Due to the shape of curves of R and Θ the value of R reaches its minimum as the concentration of the highly volatile component. increases. At the same time the value of Θ reaches its maximum. This determines the values of the lower indexes of the magnitudes. Point A where these curves cross corresponds to a case when the tangent to the binary mixture equilibrium curve is parallel to the chart diagonal XY.

Table 2 presents data on the values of R_{min} and Θ_{max} on condition of precision fractional distillation as functions of x_1^F (the feed mixture composition in the normal mode).

Table 2. Values of R_{min} and Θ_{max} as functions of the composition of benzene–toluene feed mixture in the normal mode[1]

x_1^F	y_1^F	R_{min}	Θ_{max}
0.010	0.023	76.006	0.778
0.100	0.208	7.340	0.927
0.200	0.376	3.556	1.139
0.300	0.511	2.311	1.419
0.400	0.622	1.698	1.799
0.500	0.714	1.336	2.336
0.600	0.790	1.100	3.150
0.700	0.855	0.934	4.512
0.800	0.910	0.812	7.247
0.900	0.958	0.719	15.471
0.990	0.996	0.653	163.647

Rectification of binary mixtures has a specific feature as compared to rectification of multicomponent ones: it allows precision fractional distillation for both final products.

---

[1] The results were obtained by student Chavapiva Maposa.

In this case equations (2) and (3) take the form:

$$R_{min} = \frac{1-y^F}{y_1^F - x_1^F}. \tag{4}$$

$$\Theta_{max} = \frac{x_1^F}{y_1^F - x_1^F}. \tag{5}$$

Let us assume that the amount of the feed mixture is 1 mol.

Then $D = x_1^F$, and $W = 1 - x_1^F$.

In this case the amount of vapors at the top of the column is determined by the following equation:

$$V = (R_{min} + 1) * D = \frac{1-x_1^F}{y_1^F - x_1^F} * x_1^F. \tag{6}$$

Similarly, the vapor flow at the bottom of the column is expressed by the following equation:

$$L = (\Theta_{max} + 1) * W = \frac{y_1^F}{y_1^F - x_1^F} * (1 - x_1^F). \tag{7}$$

If we designate the evaporation heats of the components as λ_1^D and λ_2^W, we obtain:

$$Q_{min}^D = \frac{1-x_1^F}{y_1^F - x_1^F} * x_1^F * \lambda_1^D; \tag{8}$$

$$Q_{max}^W = \frac{y_1^F}{y_1^F - x_1^F} * (1 - x_1^F) * \lambda_2^W. \tag{9}$$

Dividing equation (8) by equation (9) we obtain:

$$\frac{Q^D}{Q^W} = \frac{x_1^F}{y_1^F} * \frac{\lambda_1^D}{\lambda_2^W} = \frac{1}{K_1^F} * \frac{\lambda_1^D}{\lambda_2^W}. \tag{10}$$

Therefore, ratio $\frac{Q^D}{Q^W}$ depends on the partition coefficient of component 1 and the phase-transition heats of the first and second component.

Thus, in the normal mode, if the feed mixture is supplied as a boiling liquid, the energy coming to the boiler is equal to the energy leaving the condenser, for example, if a pure component or an azeotropic mixture undergo rectification.

According to the data of typical Figure 2 reflux R_{min} ratio decreases as the concentration of the highly volatile component in the feed mixture x_1^F increases.

Thus, one should use the minimum reflux ratio as a characteristic of the difficulty of separating a particular mixture with a certain care. This fact characterizes the complexity of the variables interaction mechanism even in binary mixtures, not to mention multicomponent ones.

It can be seen from Table 2 that energy content increases as the content of the highly volatile component increases. This means that the number of moles in the contacting streams grows as the column height increases. Moreover, the condenser and boiler loadings are different. Two factors play a role. First, the change of the feed mixture, namely, the increase of the content of the highly volatile component in the feed mixture, which is a condition of the design task, leads to an increase of the distillate amount. On the other hand, as a rule, the evaporation heat of the less volatile component at the same pressure is higher. Therefore, more energy is supplied to the boiler for evaporation. At the same time, the reflux ratio in this case decreases as the concentration of the less volatile component in the mixture increases. These comparisons prove, firstly, a certain role of vapor number, and, secondly, the complexity of the variables interrelation in the course of rectification.

The analysis of rectification in the normal mode could be continued, but we will concentrate further attention on a number of characteristic deviations from the normal mode.

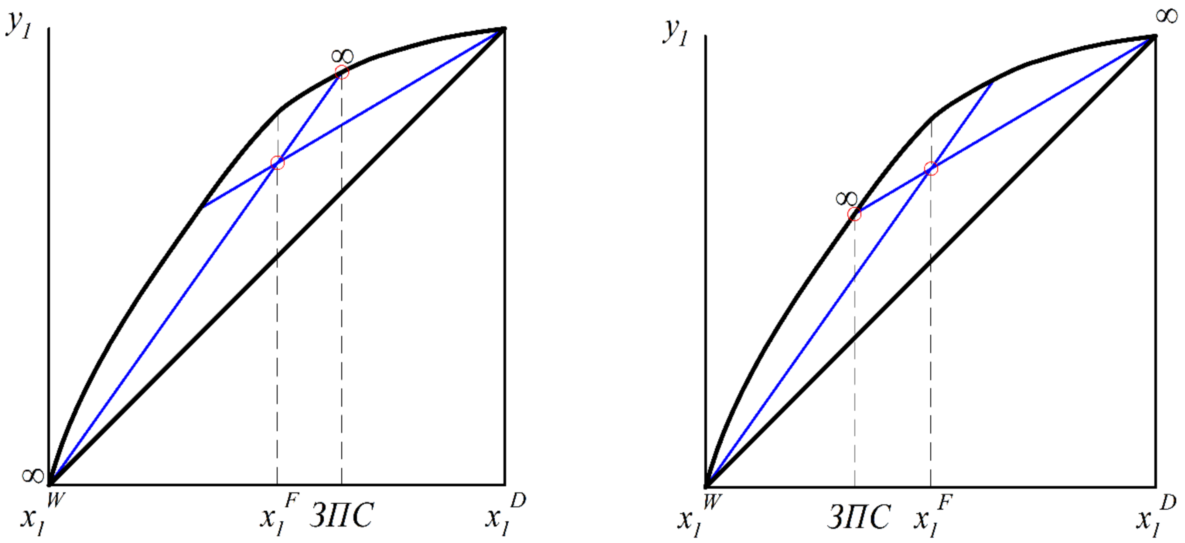
Let us first consider the level of supply of the feed mixture.

It has already been noted that the balance equations of each section have in extreme case a finite length from one singular point to another. In this case the abilities of the mathematical model, on the basis of which the study is conducted, are restricted to the considered mode. In the particular considered case one singular point is the point of the final product, and the second singular point is the crossing of the balance line with the phase equilibrium curve.

If the feed level is too high, the balance line of the column exhausting section is used, and if this level is too low, the balance line of its rectifying section is used. In addition, it is necessary to consider that both balance lines should be coordinated with the overall mass balance of the column. This fact is reflected on the x–y chart: both balance lines cross in a point that always corresponds to the feed mixture composition in this state. In the studied case this is the point of the feed mixture (Figure 3).

The singular point of the sections junction corresponds to the constant composition zone (CCZ) in the exhausting or rectifying sections of the column. This zone belonging to one section adjoins another section.

Varying the deviations from the normal mode at the expense of the feed mixture supply level gives two branches of the CCZ. They, in turn, converge to the feed mixture. Previously we had in mind that in each case described by us we meant a one-way infinity belonging to one of the two balance lines.



a) b)

Figure 3. Different cases of the feed mixture supply:

a) too high feed; b) too low feed.

[ЗПС means CCZ]

In the point corresponding to x_1^F, i.e., to the feed mixture composition, a two-way infinity presented in Figure 4 is realized.

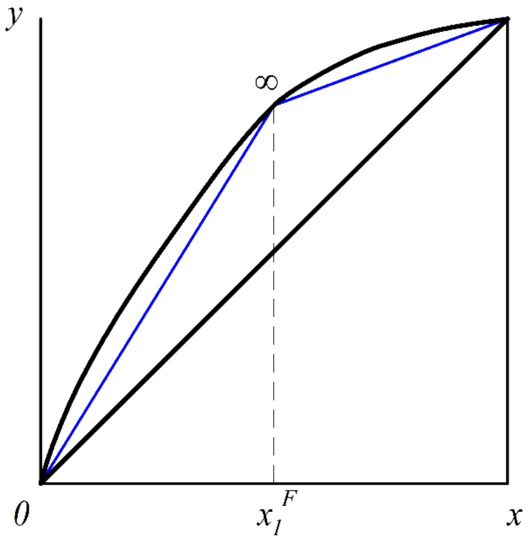


Figure 4. Minimal reflux ratio for the normal mode or binary mixtures rectification.

Note that the intersection point of the balance lines at various extents of farness from the normal mode migrates from the point located on the phase equilibrium curve to a point located on the chart diagonal. A continuum of points, each of which is characterized by a certain value of reflux ratio and a certain value of vapor number is formed on the phase equilibrium curve. Each point of the continuum corresponds to the minimum reflux ratio if one considers the rectifying section or to the maximum vapor number if one considers the exhaustive section. Crossing of the continuums corresponds to normal rectification.

Thus, too high or too low level of feed mixture supply results in too high energy necessary for the separation.

The normal mode of rectification corresponds to the minimum power consumption. If the feed mixture is supplied in another phase state, the obtained regularity remains.

It should be noted that, if differential type columns are considered, the following condition corresponds to the minimum reflux ratio:

$$x^{\text{ТП}} = x^{F}. \tag{11}$$

[ТП means FP]

Our study shows that if a discrete model is considered, optimality conditions are as follows:

$$x_{n-1} < x_n^F < x_{n+1}. \tag{12}$$

When solving the task in the testing mode, the level of the feed plate arrangement also follows criterion (12) given above. This corresponds to the normal mode of rectification. A study carried out in this direction showed that in general the highest efficiency of separation is observed at any values of reflux ratios and the number of plates, and also at any reasonable final compositions of the distillate and vat product, if the above criteria (11), (12) are followed. Figure shows 5 the dependence of the distillate and vat product composition on the feed level.

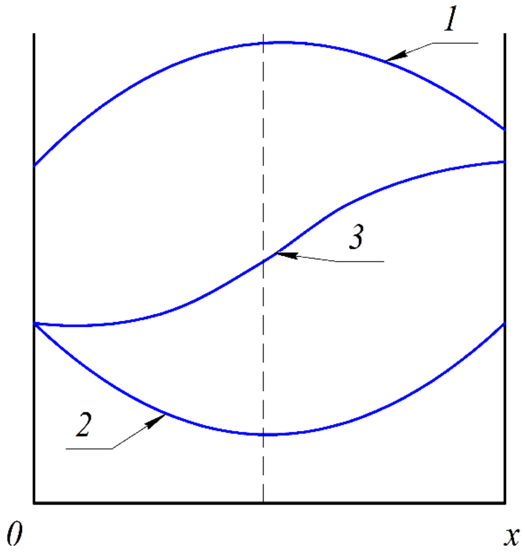


Figure 5. Dependence of compositions in a column on the feed mixture supply to different levels:

1) distillate composition;
2) vat composition;
3) composition on the feed plate.

In this case points are replaced with lines. Data of this kind were obtained in full-scale experiments [27]. A mathematical experiment was carried out in [17]. Thus, in both cases the correctness of criteria (11) and (12) for columns of various type was completely proved. In plate columns criterion (12) does not require equality of the mixture composition and the composition on the feed plate. The reason is that the dynamic system is discrete. In rare cases such coincidence can be observed.

A large number of deviations from the normal mode is due to the temperature of the feed mixture directed to rectification.

Table 1 presents state variables of the feed mixture. The matter of their change is considered in [17, 22–26]. As of today, two methods of solving this problem have been created. Both methods determine the intersection point of balance lines, which corresponds in the normal mode to supply of the feed mixture in a liquid state at its boiling temperature $x^F = const$. The intersection point is an invariant with respect to the reflux ratio and vapor number.

McCabe–Thiele method determines the geometric locus of intersection points of working and balance lines of column sections according to the following equation:

$$q = \frac{H^V - H^F}{H^V - H^L}. \tag{13}$$

In oil industry the stripping product fraction determined by the following equation is usually used:

$$e = \frac{H^F - H^L}{H^V - H^L}. \tag{14}$$

Obviously,

$$e + q = 1. \tag{15}$$

Work [17] presents a table of feed mixture aggregate states depending on the values of H^V, H^L and H^F. We think it is expedient to repeat it in the text (Table 3).

Table 3. Effect of binary feed mixture enthalpy on the values of e and q [17]

No	Feed mixture state	State of enthalpies	q	e	Mixture temperature
1	Heated to a temperature below boiling point	$H^F < H^L$	> 1	< 0	$T_F < T_{boil}$
2	Boiling liquid	$H^F = H^L$	1	0	$T_F = T_{boil}$
3	Vapor-liquid mixture	$H^L < H^F < H^V$	$0 < q < 1$	$0 < e < 1$	$T_{boil} < T_F < T_{cond}$
4	Saturated vapor	$H^F = H^V$	0	1	$T_F = T_{cond}$
5	Superheated vapor	$H^F > H^V$	< 0	> 1	$T_F > T_{cond}$

Figure 6 shows lines 1–8 described by equation (11) and corresponding to different aggregate states of the feed mixture of preset composition x^F. Supply of the feed mixture in an underheated state (positions 1, 2, 3 in Figure 6) and supply of the feed mixture in the form of superheated vapor (positions 7, 8 in Figure 6) are shown. Supply of the feed mixture in a mixed state as well as supply of underheated liquid are not considered in this work [17].

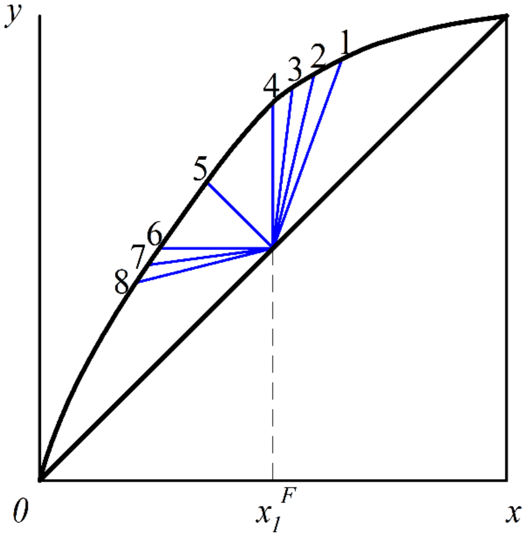


Figure 6. Arrangement of intersection lines of balance (working) lines upon varying feed mixture temperature:
1–3 – underheated liquid;
4 – liquid at boiling temperature;
5 – vapor-liquid mixture;
6 – vapor at condensation temperature;
7, 8 – superheated vapor.

When using the value of q, the equation of balance lines of sections intersections at composition x^F has the form (16):

$$y_1 = \frac{q}{q-1} * x_1 - \frac{x_1^F}{q-1}. \tag{16}$$

When passing to stripping product fraction e taking into account equation (15), we obtain:

$$y_1 = \frac{x_1^F}{e} + \frac{1-e}{e} * x_1 \tag{17}$$

or

$$e * y_1 = x_1^F + (1-e) * x_1. \tag{18}$$

Figure 7 presents the case when underheated liquid is supplied to the rectification column. In the normal mode and upon deviation bilateral infinities of the number of plates are observed. However, in this case power consumption increases despite the reduction of the reflux ratio. Therefore, predictably, the deviation from the normal mode will lead to an increase in energy consumption for separation.

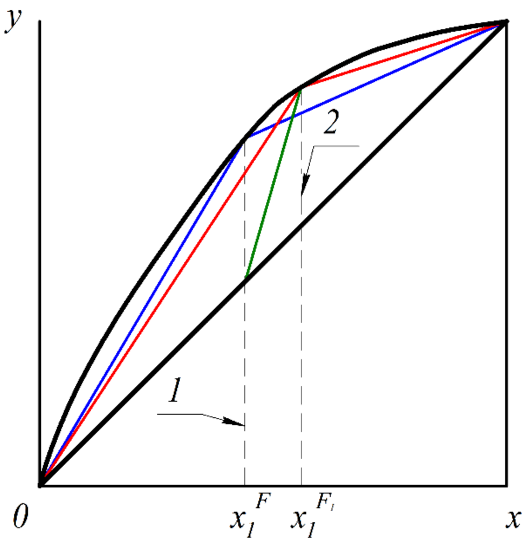


Figure 7. Supply of underheated liquid:

1) intersection of working lines in the normal mode;
2) intersection of working lines in case of underheated feed mixture.

Let us consider why this occurs without presenting calculation formulas. The matter is that supplying an underheated liquid to the feed plate results in partial condensation of vapor, and the liquid on the feed plate is heated to boiling. The condensed part of vapor in the form of condensate goes to the boiler and evaporates in it. Thus, a recycle is formed in the exhausting section of the column. This recycle is absent in the rectifying section. The problem is solved in the design option: the compositions of the distillate are not sensitive to reflux ratio under the statement of the problem, because precise fractionation is considered. Calculation shows that if the distillate contains the slow evaporating component, the same result is obtained: power consumption increases.

Figure 8 shows a recycle covering only the exhaustive section of the column. The existence of the recycle is one of the main reasons for power consumption increase in the considered process as compared to the normal mode.

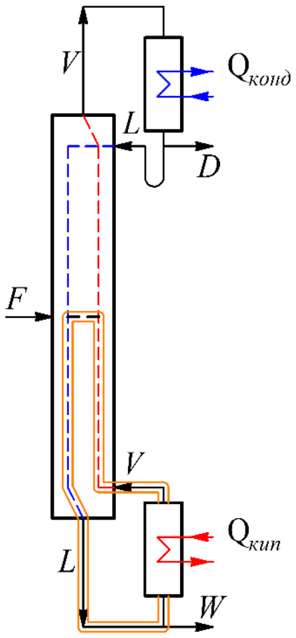


Figure 8. The formation of an internal recycle (marked as an orange contour, the solid line) in the flows of the vapor (the dashed red line on the right) and of the liquid (the dashed blue line at the left) in case of feed mixture supply in the form of an underheated liquid.
[конд. means cond.; кип. means boil]

Let us consider supply of superheated vapor as a feed mixture. In this case a recycle is formed in the rectifying part of the column (Figure 9), which results in an increase of consumption for the condenser (i.e., an increase of the coolant consumption).

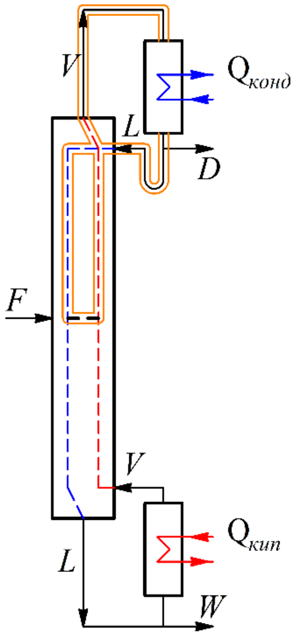


Figure 9. The formation of an internal recycle (marked as an orange contour, the solid line) in case of feed mixture supply in the form of a superheated vapor. [конд. means cond.; кип. means boil]

According to the rectification process variance, the choice of particular independent variables within the theoretical plate model is mathematically arbitrary. But technologically, this choice is of fundamental importance. For example, in some works temperature is preset instead of reflux composition. Because pressure in the column is already chosen, it is possible to vary only the reflux cooldown degree. In this case, in contrast to the normal mode of rectification, power consumption in the evaporator and, therefore, the vapor number are too high. So, a recycle of substance passing the condenser is formed, because a part of the vapor is condensed on the last plate (Figure 10).

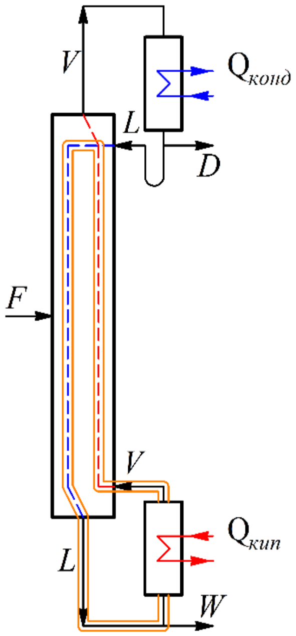


Figure 10. A scheme of the formation of a recycle (marked as an orange contour, the solid line) in case of cooled reflux supply into the column.
[конд. means cond.; кип. means boil]

Thus, fixing simultaneously the column pressure and the reflux temperatures results in a deviation from the normal mode and to an increase in energy consumption for rectification.

Accordingly, choosing temperature as an independent variable with fixed pressure results in modes with too high power consumptions, i.e., to modes differing from the normal one. In all cases of deviation from the normal mode forced recycles are observed. Of course, when solving the predesign task, one must consider the cost of heating and cooling agents required for rectification. In order to understand this it is necessary to compare the costs of rectification of air and of usual liquid products with temperature 0–100 °C.

Conclusion

In summary note that the choice within the model of theoretical plate as a standard of the normal mode characterized by supply of the feed mixture in the form of a boiling liquid allows to compare any different mode with it. Deviations are due to changes of the feed mixture aggregate state. However, a specific normal mode corresponds to each aggregate state. Let us consider Figure 6. Transition from one aggregate state to another in two-phase systems is characterized by transition from position 4 to position 6. In the first case the normal mode corresponds to supply of a boiling liquid, and in the second case, to supply of saturated vapor. Transition from the boiling liquid to the saturated vapor is followed by a sharp rise of power consumption for rectification [28] and considerably increases the separation cost. Thus, the power consumption of the considered process always increases irrespective of the mechanism of deviation from the normal mode. When passing to a finite number of theoretical steps of separation, different capital investments are required depending on the feed mixture composition. They are not of particular interest in case of binary rectification, but they are of prime importance in case of multi-component mixtures rectification, when it is necessary to compare power costs and investment costs of various separation options.

Owing to the performed analysis the thesis in monograph [29] can be improved as follows: the feed mixture should be supplied to the column in the aggregate state in which it comes leaving the previous device. An exception is the case considered by Lvov [28].

DESIGNATIONS:

x – mole fraction of a component in the liquid phase; *y* – mole fraction of a component in the vapor phase; *T* – temperature, °C; *P* – pressure, Pa; ξ – pressure on each plate; *D* – quantity of the distillate, mol/sec; *W* – quantity of the bottom product, mol/sec; *L* – liquid flow in the column, mol/sec; *V* – vapor flow in the column, mol/sec; $\mathcal{F}$ – variance; *R* – reflux ratio; Θ – vapor number; *K* – coefficient of distribution of a component between the vapor and liquid phases; λ – specific heat of full condensation of the vapor flow, J/mol; *Q* – amount of heat, J/mol; *q* – mole fraction of the liquid in the feed flow according to the McCabe–Thiele method; *e* – stripping product fraction; *H* – enthalpy, J/mol; *n* – the number of components in the mixture.

INDEXES:

1 – the low-boiling component; 2 – the high-boiling component; F – feed flow; D – distillate; W – vat flow; V – vapor flow; L – liquid flow; FP – feed plate; max – the maximum value; min – the minimum value; boil – the boiler (evaporator), boiling temperature; cond – the condenser (dephlegmator), condensation temperature; loss – heat loss; n – the number of a plate.

References:

1. Robinzon K.Sh. Osnovnye nachala drobnoj peregonki (Elements of Fractional Distillation): trans. from Engl. P.I. Kotljarov; ed. by. I. A. Krasuskiy. Khar'kov: Gos. in-t po proektirovaniju i str-vu kokso-him. ustanovok. Koksostroj, 1930. 177 p. (in Russ.)
2. Torman K. Peregonka i rektifikacija (Distillation and Rectification). Leningrad: Nauchnoe him. teh. izd-vo, 1931. 128 p. (in Russ.)
3. Tregubov A.M. Osnovnye nachala peregonki i rektifikacii (Elements of Distillation and Rectification). Baku-Moskva: Azneft' izdat., 1932. 158 p. (in Russ.)
4. Kirschbaum E. Destillier und Rektifiziertechnik. Berlin: Verlag von Julius Springer, 1940. 282 p.
5. Sorel E. Le Distillation. Paris: Encyclopedic Scientifique, 1960. 220 p.
6. Gel'perin N.I. Distilljacija i rektifikacija (Distillation and Rectification) Avtoriz. trans. from Ger. (Kirshbaum) with add. M.-L.: Goshimizdat, 1947. 312 p. (in Russ.)
7. Bagaturov P. A. Kurs teorii peregonki i rektifikacii. (Course Theory of Distillation and Rectification). Gosudarstvennoe nauchno-tehnicheskoe izdatel'stvo neftjanoj i gorno-toplivnoj literatury, 1954. 480 p. (in Russ.).
8. Zharov V.T., Serafimov L.A. Fiziko-himicheskie osnovy distilljacii i rektifikacii (Physico-Chemical Foundations of Bath Open Distillation and Distillation) L.: Khimiya, 1975. 240 p. (in Russ.).

9. Aleksandrov I.A. Peregonka i rektifikacija v neftepererabotke (Distillation and Rectification in Oil Refining). M.: Khimiya, 1981. 352 p. (in Russ.)

10. Komissarov Ju.A., Gordeev L.P., Vent D.P. Nauchnye osnovy processov rektifikacii. (Scientific Foundations of Processes of Distillation) / Ed. by. L.A. Serafimov in 2 books. M.: Khimiya, 2004. V. 1. Binarnye smesi (Binary mixtures). 270 p. V. 2. Rektifikacija mnogokomponentnyh smesej (Distillation of Multicomponent Mixtures). 415 p. (in Russ.)

11. Petlyuk F.B., Serafimov L.A. Mnogokomponentnaja rektifikacija. Teorija i raschet. (Distillation of Multicomponent Mixtures. Theory and Calculation). M.: Khimiya, 1983. 304 p. (in Russ.)

12. Frolkova A.K. Razdelenie azeotropnyh smesej (The separation of azeotropic mixtures). M.: Vlados, 2010. 139 p. (in Russ.)

13. Reshetov S.A. Predsintez shem rektifikacii mnogokomponentnyh azeotropnyh smesej. (The Initial Development of the Rectification Schemes of Multicomponent Azeotropic Mixtures) M.: Vlados, 2014. 192 p. (in Russ.)

14. Serafimov L.A., Cheljuskina T.V. // Theor. Bases of Chem Technol. 2014. V. 48. № 3. P. 274–281. (in Russ.)

15. Serafimov L.A., Cheljuskina T.V., Frolkova A.K. // Vestnik MITHT (Fine Chem. Tech.), 2014. V. 9. № 5. P. 21–29. (in Russ.)

16. Gilliland E.R., Reed E.F. // Ind. Eng. Chem. 1942. V. 34. № 5. P. 551–557.

17. Khakhin L.A. Razrabotka jentropijnoj ocenki raboty rektifikacionnyh kolonn i funkcional'nykh kompleksov (Development of Entropy Evaluation of the Distillation Columns and Functional Complexes): abstract of PhD dissertation. M.: MITHT, 2008. 218 p. (in Russ.)

18. Boshnyakovich F. Tekhnicheskaja termodinamika (Engineering Thermodynamics): trans. from Ger. in 2 books. Moskva-Leningrad: Gosjenergoizdat. V. 1. 1955. 438 p. V. 2. 1956. 255 p. (in Russ.)

19. Zakharov M.K., Rodinskaja N.V. // Vestnik MITHT (Fine Chem. Tech.). 2006. V. 1. № 2. P. 62–66. (in Russ.)

20. Zakharov M.K. // Khimicheskaya Tekhnologiya. 2008. V. 9. № 4. P. 177–182. (in Russ.)

21. Zakharov M.K. // Vestnik MITHT (Fine Chem. Tech.). 2009. V. 4. № 1. P. 60–63. (in Russ.)

22. Zakharov M.K., Dovbish A.A. // Vestnik MITHT (Fine Chem. Tech.). 2010. V. 5. № 6. P. 9–12. (in Russ.)

23. Zakharov M.K. // Vestnik MITHT (Fine Chem. Tech.). 2012. V. 7. № 3. P. 22–24. (in Russ.)

24. Zakharov M.K., Starostin Ju.A., Nazarov D.G. // Vestnik MITHT (Fine Chem. Tech.). 2011. V. 6. № 6. P. 23–29. (in Russ.)

25. Zakharov M.K., Abbasi Mohand, Zvereva E.N. // Vestnik MITHT (Fine Chem. Tech.). 2013. V. 8. № 2. P. 34–38. (in Russ.)

26. Abbasi Mohand Kadir Baki. Jenergosberezhenie v processah rektifikacii binarnyh i mnogokomponentnyh smesej (Energy Efficiency in the Processes of Distillation of Binary and Multicomponent Mixtures): abstract of the PhD dissertation. M.: MITHT, 2014. 122 p. (in Russ.)

27. Serafimov L.A. Napravlennoe izuchenie fazovogo ravnovesija i raschet rektifikacii neideal'nyh mnogokomponentnyh smesej (Directed Study of Phase Equilibrium and Calculation of Rectification of Non-Ideal Multicomponent Mixtures): abstract of the PhD dissertation. M.: MIHM, 1961. 262 p. (in Russ.)

28. L'vov P.V. Nekotorye voprosy rektifikacii binarnyh i mnogokomponentnyh smesej (Some Questions of Distillation of Binary and Multicomponent Mixtures). M.: AN SSSR, 1960. 107 p. (in Russ.)

29. Platonov V.M., Bergo B.G. Razdelenie mnogokomponentnyh smesej (Separation of Multicomponent Mictures). M.: Khimiya, 1963. 368 p. (in Russ.)