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COMPLEX MODEL OF THE EFFICIENCY OF RECTIFICATION PLATES. 8. COMPARISON WITH OTHER MODELS WITH RESPECT TO EXPERIMENTAL DATA

V. V. Pavlechko and É. I. Levdanskii UDC 66.048.375

A complex model is compared with the Murphree and Hausen models for the cases of concurrent and cross motion of vapor and liquid phases. Use is made of results of experimental studies involving separation of an acetic acid-water mixture and industrial data on rectification of furfurol and ethanol. It is proved that the efficiencies in the complex and Murphree models coincide as the coefficient of phase equilibrium m approaches unity but when this coefficient increases, the first model and the Hausen model coincide. The possibility of using the Murphree model at $m \to 1$ and the Hausen model at $m \to \infty$ is shown.

A complex model of the efficiency of mass exchange [1–3] is the most general one and includes the known Murphree [4] and Hausen [5] models as the limiting cases [6]. In the present work, the interrelationship of these models is considered with the use of experimental and industrial data on rectification columns without analyzing the reasons for the high or low efficiency of the latter.

In the case of concurrent motion of the vapor phase and liquid, the efficiency of mass exchange in the general form is expressed by the formula [1]

$$E_{\text{con}} = \frac{(1-h)\dfrac{L}{mV} + 1 - h_1}{\dfrac{x_n - \dfrac{y_{n-1}}{m}}{x_n - x_{n-1}} - h\dfrac{L}{mV} - h_1} \,. \tag{1}$$

In particular cases where the distances h and h_1 acquire different values, the efficiency can be expressed in various ways. In the complex model, these distances depend on the coefficient of phase equilibrium [6]:

$$h = h_1 = \frac{1}{m+1} \tag{2}$$

and the efficiency is expressed by the formula

$$E_{\text{con}} = \frac{y_n - y_{n-1} + m(x_n - x_{n-1})}{mx_n + x_{n-1} - \dfrac{y_n}{m} - y_{n-1}} \,. \tag{3}$$

In the Murphree model, in analysis of the efficiency in the vapor phase and liquid these distances acquire, respectively, the values $h = 0$, $h_1 = 1$, and $h = 1$, $h_1 = 0$ [1], while formula (1) has the form of the following relations:

$$E_{\text{con1}} = \frac{y_n - y_{n-1}}{mx_{n-1} - y_{n-1}} \,, \tag{4}$$

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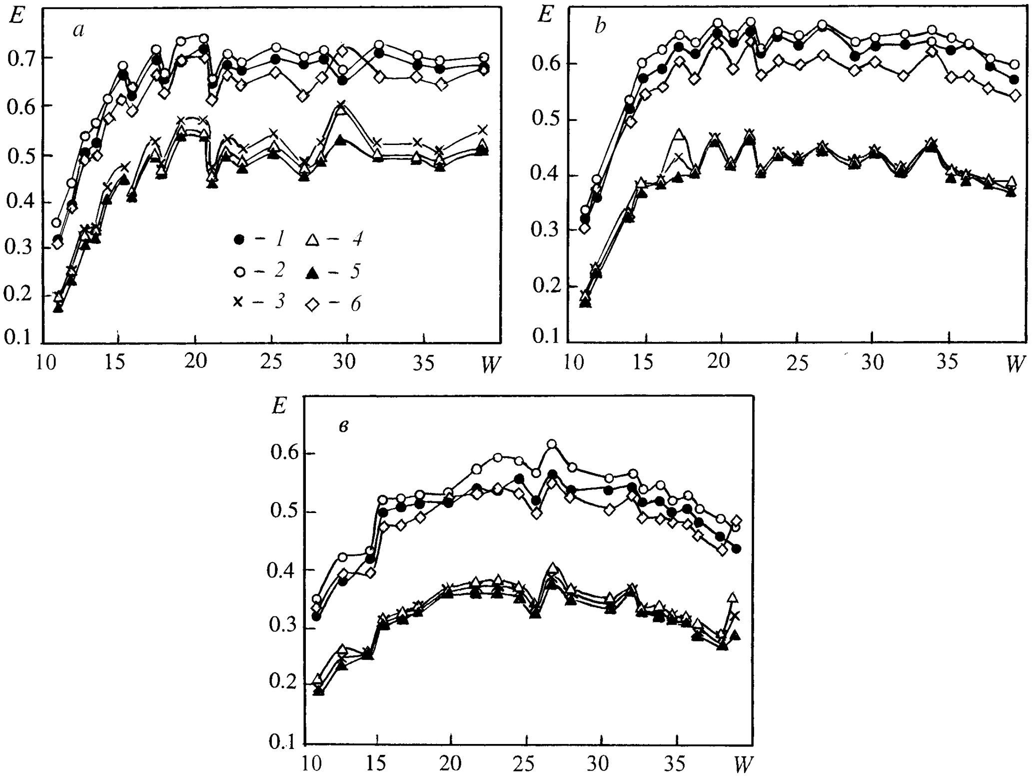

Fig. 1. Efficiency of the contact element vs. vapor velocity at different angles of inclination of the vanes [a) $\alpha = 30^{0}$; b) 37.5; c) 45]: 1, 2) graph-analytic efficiencies according to the Hausen model, respectively, in the vapor phase and liquid; 3) efficiency according to the complex model; 4, 5) efficiencies according to the Murphree model, respectively, in the vapor phase and liquid; 6) calculated efficiency of the Hausen model.

$$E_{\text{con2}} = \frac{x_n - x_{n-1}}{x_n - \dfrac{y_n}{m}} . \tag{5}$$

In the Hausen model, where $h = h_1 = 0$, the efficiency is presented by the expression

$$E_{\text{con3}} = \frac{y_n - y_{n-1} + m\,(x_n - x_{n-1})}{m x_n - y_{n-1}} . \tag{6}$$

The above formulas (3)–(6) have been employed in analysis of the experimental data on separation of an acetic acid-water mixture [7].

Experiments were carried out on an experimental column 200 mm in diameter with three plates arranged at a distance of 450 nm. On each plate one contact element [7, 8] consisting of eight vanes inclined at a certain angle toward the horizon was mounted. A liquid to the contact elements was fed from a higher-lying plate via the central branch pipe while vapor was fed from the underlying plate. Sampling was carried out under steady operation conditions of the apparatus without liquid recirculation to the stages on complete return of reflux, i.e., at $L = V$. An analysis of the samples for the quantitative content of acetic acid was accomplished by titration of the mixture by a solution of sodium hydroxide. The vapor velocity changed from 11 to 40 m/sec. The angle of inclination of the swirler vanes amounted to 30, 37.5, and 45^{0}, and the length of the contact elements was 50, 72, 102.5, 129, and 150 mm, respectively.

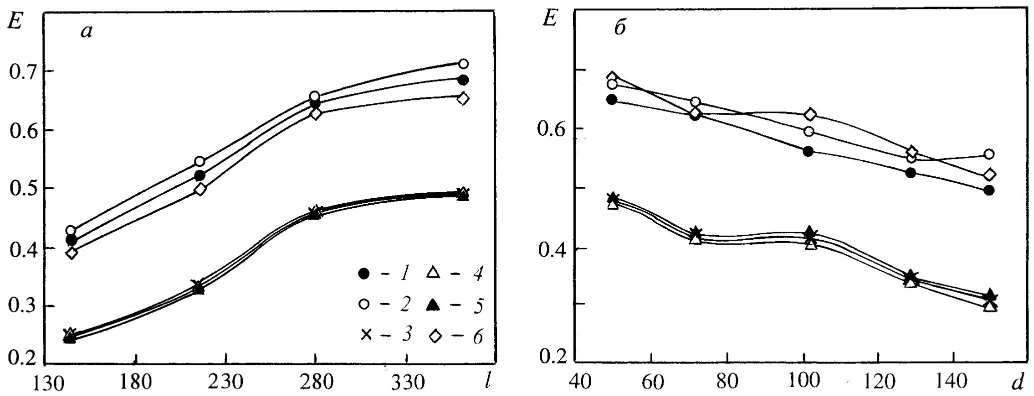

Fig. 2. Efficiency of the contact element vs. length of the branch pipe (a) and its diameter (b) at a vapor velocity of $W = 21$ m/sec: 1–6) designations are the same as in Fig. 1.

In investigating the efficiency of the contact elements with a less than 150 mm diameter, a false shell 400 mm in height with its diameter exceeding the branch pipe diameter by 30% was installed to retain the same hydrodynamic situation on each plate. The efficiency of mass exchange was determined by the middle contact element.

An investigation was also made of three plates with seven contact elements, each having a diameter of $d = 102.5$ mm, a length of $l = 3d$, and an angle of inclination of the vanes of $\alpha = 37.5^{\circ}$, on a pilot column 500 mm in diameter [7]. Unlike the one-element stage, the liquid was fed from plate to plate through common overflow pipes 25 mm in diameter; the liquid level on each plate was 50 mm. The column worked also with complete return of reflux, which provided multiplicity of liquid circulation through the elements from four at a vapor velocity of 4.5 m/sec to two at a velocity of 10 m/sec.

By interpolation, proceeding from the equilibrium data [9] and a comparatively narrow range of change in the concentration of acetic acid (2.1–2.9 mol.%), the coefficient of phase equilibrium was assumed to be $m = 1.0833$.

Results of the investigations are given in Figs. 1–3. At a vapor velocity higher than 30 m/sec in the branch pipe with a diameter of $d = 72$ mm and a length of $l = 216$ mm the efficiency of the contact element is observed to decrease (Fig. 1), which is explained by the decrease in the time of contact of the phases and removal of the liquid from the stage. It should be noted that with increasing angle of inclination of the swirler vanes the efficiency of the contacting stage decreases more substantially when the vapor velocity increases.

The influence of the length of the branch pipe with a diameter of $d = 72$ mm was investigated at an angle of inclination of the vanes of $\alpha = 37.5^{\circ}$. The basic mass exchange in the long branch pipes proceeds in the lower part of the contact element and an increase in its length up to more than four diameters at a vapor velocity of 20 m/sec causes a slight increase in the efficiency (Fig. 2a).

With increasing length of the branch pipe at its length $3d$ and a vapor velocity of 20 m/sec the efficiency decreases (Fig. 2b), which is explained by the increase in the amount of splashes carried away and penetration of some amount of vapor over the center of the contact element. As a consequence, we can consider the investigated diameter range of the branch pipe to be the optimum one.

At other vapor velocities, the dependences of the efficiency on the length and diameter of the contact element (not given) are the same as in Fig. 2.

At small vapor velocities in the branch pipes of a multielement plate (Fig. 3), the efficiency is small and is attributed to the pulsation regime. Moreover, on passing to a steady regime the efficiency increases and remains virtually unchanged within a wide range of vapor loading. The efficiency of the multielement plate is slightly smaller than for one branch pipe.

From Figs. 1–3 it is seen that the efficiency in the complex model virtually coincides with those in the Murphree model and is approximately 1.5 times smaller than the corresponding quantities in the Hausen model. Some differences in the efficiencies in the Hausen model obtained from calculations and graph-analytic dependences are attributed apparently to the inaccuracy in constructing the graphs. All the models have the same typical responses to a change in the concentrations.

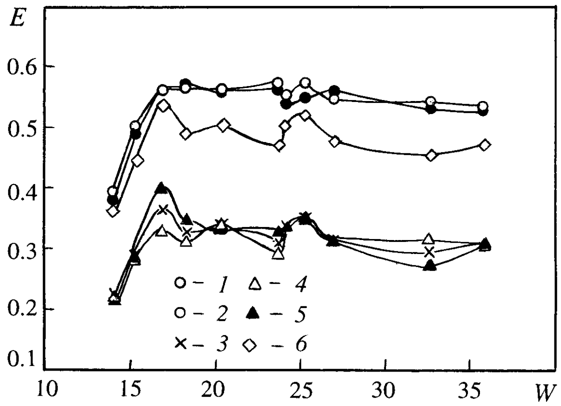

Fig. 3. Efficiency of the plate with seven contact elements vs. vapor velocity: 1–6) notation is the same as in Fig. 1.

For the sake of comparison of the models under consideration, we have also performed calculations of the efficiencies on release of furfurol and ethanol in industrial columns which were carried out in a certain sequence. As the initial data we adopted:

(a) the ratio of molar flow rates L/V;

(b) the concentration of a highly volatile component in the bottom product x_{bot} and on the feeding plate x_{top};

(c) the zeroth concentration of the highly volatile component in the vapor arriving from a still since the columns were heated by live steam;

(d) an arbitrary value of the efficiency.

The coefficients of phase equilibrium were determined for furfurol by the formula [10]

$$m = 2\,\frac{12 - x}{3 + x}\,, \tag{7}$$

and for ethanol by the formula

$$m = 0.277\,\frac{250 - x}{5.3 + x} + 0.006x\,, \tag{8}$$

which differs from the experimental data [11] no more than by, on the average, ±0.9% within the entire ethanol concentration from zero to the azeotropic point and has a maximum discrepancy of up to 5% only within the interval up to 1.6 mol.%. In expressions (7) and (8), the content of the highly volatile component is given in molar percentage.

Initially, the phase-equilibrium coefficients m were calculated from the initial data. Next, compositions of the liquid arriving from below on the first plate and of the vapor leaving it were calculated by the formulas obtained in [1, 3], which were refined for the complex model with account for (2). With use of the new values of x the values of m were refined for the second, from below, plate and the corresponding concentrations for it were determined. Similar calculations were carried out for all plates, including the feeding one. If a calculated concentration of the highly volatile component in the liquid entering the feeding plate disagreed with its experimental value, we prescribed a new value of the efficiency and repeated calculations until the concentrations coincided.

An analysis has been carried out for cross motion of the vapor and liquid without mixing the latter on a plate and with complete mixing of the liquid when the calculated relations coincided with the formulas of concurrent motion of the flows.

As the objects of investigations, we chose 23 basic furfurol columns of enterprises of the hydrolysis type. The data are borrowed from the process regulations for furfurol production in 1978–1982, i.e., the period of relatively stable operation of the enterprises and comparatively uniform loading of the rectification columns. The diameter of the columns with bubble-cap plates amounted to 1.8 m for the Bendery biochemical works, the Leningrad and Lobvinsk hydrolysis enterprises, to 2.2 m for the Bel'sk, Georgievsk biochemical works and for the Khorsk hydrolysis enterprise, to 4 m for the Volzhskii hydrolysis-yeast enterprise and for the Kirovsk biochemical works, and to 2 m for the re-

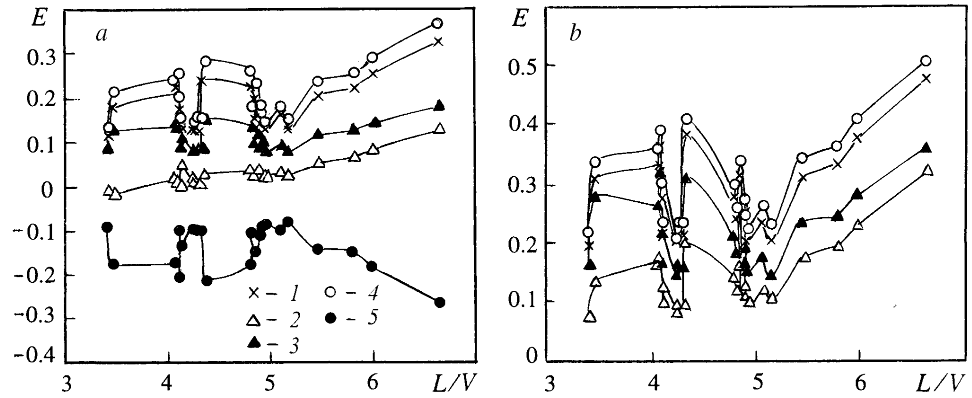

Fig. 4. Efficiency in the basic furfurol columns vs. ratio *L/V* [a) cross motion; b) concurrent motion]: 1), complex model; 2), 3), Murphree model in analysis of the efficiency in the vapor phase and liquid, respectively; 4) the Hausen model; 5) the hypothetical model.

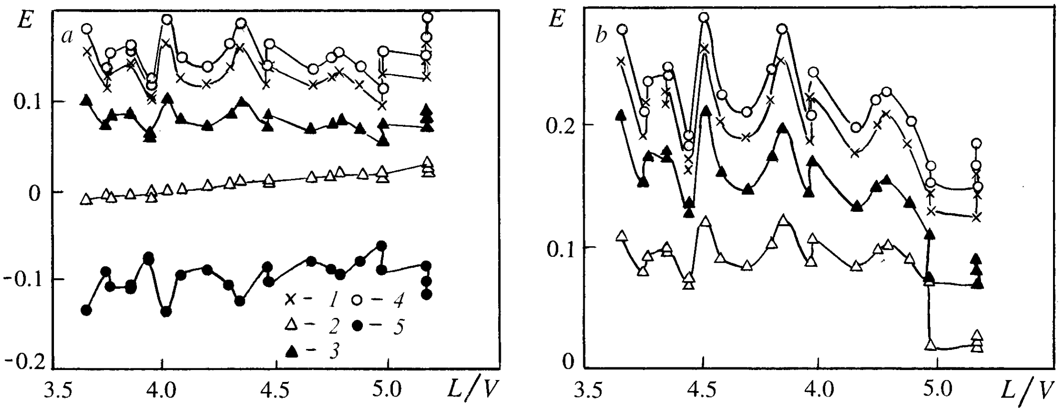

Fig. 5. Efficiencies of basic main furfurol column at the Bendery biochemical work vs. ratio *L/V* [a) cross motion; b) concurrent motion]: 1–5) notation is same as in Fig. 4.

maining enterprises. The number of plates in the depleting part of a column varied from 13 for the Volzhskii hydrolysis-yeast enterprise to 28 for the Krasnodarsk group of chemical enterprises.

Heating of the columns was accomplished by live steam; therefore the content of furfurol in the vapor entering the first, from below, plate was assumed to be equal to zero. The furfurol concentration in the feeding liquid changed from 0.2 wt.% for the Khorsk hydrolysis enterprise to 3.472 wt.% for the Krasnodarsk group of chemical enterprises, in the bottom product (lutter) from 0.017 wt.% for the Manturovsk biochemical works to 0.05 wt.% for the Krasnodarsk group of chemical enterprises. The flow rates of the vapor and liquid in the columns under consideration differed as well.

In analysis of the basic furfurol column of the Bendery biochemical works, 1.8 m in diameter with 25 bubble-cap plates in the depleting part, the flow rate of vapor changed within 4.0–5.7 tons/h, of the bottom product, from 17.88 to 23.433 tons/h. The concentration of furfurol in the feeding liquid amounted to 0.37–0.87 wt.%, and in the bottom product, to 0.021–0.087 wt.%. The flow rates of flows and concentrations were measured once a shift.

Results of the calculations are given in Figs. 4 and 5. Here, a ratio of efficiencies different from that in Figs. 1–3 is observed since on rectification of the low-concentration solutions of furfurol the coefficients of phase equilibrium increase up to 6–8. The complex model in this case is intermediate between the Hausen and Murphree models in analysis of the efficiency in the liquid phase in the Murphree model but closer to the Hausen model in the case of countercurrent and cross motion. It is pertinent to note that in the last form of organizing the flows at small *L/V* ratios the Murphree model can give even negative values in analysis of the efficiency in the vapor phase. The hypotheti-

TABLE 1. Parameters of Some Columns at the Bobruisk Hydrolysis Enterprise

Column	L/V	x_{top}, wt.%	x_{bot}, wt.%	n	m	Flow characterization	E_k, E_{con}	E_1	E_2	E_3
Beer column, depleting part	6.5	0.8457	0.01736	20	12.3–13.05	cross flow	0.2410	0.0257	0.1503	0.2625
						concurrent flow	0.3752	0.1787	0.3007	0.3929
Alcohol column, depleting part	2.5586	20.0	0.01527	15	4.75–13.05	cross flow	0.2950	–0.1405	0.2480	0.3291
						concurrent flow	0.5247	0.1939	0.4960	0.5502
Alcohol column, enriching part	0.8123	92.42	20.0	51	1.0–4.75	cross flow	0.0971	–0.0132	0.1132	0.2213
						concurrent flow	0.2122	0.1519	0.2263	0.3207

cal model always has negative efficiencies, but with respect to the absolute value they approach, through being slightly smaller, the corresponding values in the complex model.

In all the models the efficiencies in concurrent motion are 1.5–2 times larger as compared to cross motion of the vapor and liquid.

The characteristics of the rectification columns in ethanol production of the Bobruisk hydrolysis enterprise borrowed from the process regulations for ethanol production are given in Table 1. These columns were also heated by live steam. In design of depleting parts of the columns, the content of ethanol in the vapor entering the lower plate was assumed to be zero, and in the enriching part of the alcohol column, 0.2277 mol.%, which is obtained from the design of the depleting part.

The data in Table 1 show that at the greater values of the coefficient m the efficiency in the complex model is also intermediate between the efficiencies in the Murphree model (the second variant of mass exchange) and in the Hausen model. As m increases, the complex model approaches the Hausen model. At the smaller values of $m = 1 - 4.75$, the efficiency in the complex model is intermediate between the efficiencies in the Murphree model of both variants as in Figs. 1–3. It should be emphasized that the mentioned features are characteristic of concurrent and cross motion of the interacting phases.

It also follows from the table that in concurrent motion the efficiencies in all the models considered, with the exception of the Murphree model (the first variant), are 1.5–2 times higher than the efficiencies in cross motion. In the Murphree model, in analysis of the efficiency in the liquid (the second variant) this ratio is equal to two for all columns and their parts. The negative efficiencies in cross motion in the Murphree model, dropping out of the indicated regularity, are attributed to the small ratios L/V (the alcohol column), which deteriorates this variant.

The analysis carried out confirms the assumption that the Hausen model is the limiting case of the complex model to which it tends as m increases [7].

Thus, the Hausen model makes it possible to obtain acceptable efficiencies at $m >> 1$, the Murphree model, at $m \to 1$, and the complex model in all cases. Use of the hypothetical model in the form given in [1, 3] is inexpedient because of the negative efficiencies obtained but useful if the coefficient of phase equilibrium is within the limits $1 > m > 0$.

NOTATION

α, angle of inclination of the vanes of a contact element toward the horizon, deg; d, diameter of the branch pipe, mm; E, efficiency of the plate; h and h_1, dimensionless distance from the site of input of the vapor and liquid, respectively, to the surface of equality of the phase concentrations in ideal and real plates; L, molar flow of the liquid; l, length of the contact element, mm; m, coefficient of phase equilibrium; V, molar flow of the vapor; W, axial velocity of the vapor in the branch pipe, m/sec; x and y, concentration of the highly volatile component in the liquid and in the vapor, respectively. Subscripts: top, feeding from top of a column part; k, cross motion of the phases; bot, removal from the bottom of a column part; n, number of the plate under consideration; $n - 1$, number of the preceding plate as vapor moves; con, concurrent motion of the phases; 1–4, variants of mass exchange corresponding to the conditions of interrelation of the ideal and real plates in the Murphree models in analysis of the efficiency in the vapor phase and liquid, in the Hausen model, and in the hypothetical model.

REFERENCES

1. V. N. Pavlechko, *Inzh.-Fiz. Zh.*, **74**, No. 1, 50–56 (2001).
2. V. N. Pavlechko, *Inzh.-Fiz. Zh.*, **74**, No. 1, 57–61 (2001).
3. V. N. Pavlechko, *Inzh.-Fiz. Zh.*, **74**, No. 2, 38–42 (2001).
4. E. V. Murphree, *Ind. Eng. Chem.*, No. 7, 747–750 (1925).
5. H. Hausen, *Chem. Ing. Tech.*, **25**, No. 10, 595–597 (1953).
6. V. N. Pavlechko, *Inzh.-Fiz. Zh.*, **75**, No. 1, 112–116 (2002).
7. É. I. Levdanskii, *Development, Investigation, and Practical Application of Contact Plates with Forward-Flow Centrifugal Elements*, Dissertation for the title of Candidate of Engineering Sciences, Minsk (1974), pp. 210–219.
8. É. I. Levdanskii, I. M. Plekhov, A. I. Ershov, A. S. Korneev, P. E. Sergeichuk, and V. A. Ivanov, *Mass Exchanger*, USSR Inventor’s Certificate No. 498009, B 01 D 3/26, B 01 D 3/30; Byull. Izobret., No. 1, 10 (1976).
9. P. G. Romankov, V. F. Frolov, O. M. Flisyuk, and M. I. Kurochkina, in: *Methods of Calculation of Processes and Apparatus of Chemical Technology* (*examples and problems*) [in Russian], St. Petersburg (1993), p. 457.
10. V. N. Pavlechko, *Gidroliz. Lesokhim. Prom.*, No. 8, 2–3, (1987).
11. V. N. Stabnikov, in: *Distillation and Rectification of Ethyl Alcohol* [in Russian], Moscow (1969), pp. 44–46.