COMPARISON OF STATIONARY AND CYCLIC MODES OF INJECTOR-TYPE EXTRACTING COLUMN*

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Mathematical models were developed for two operational modes of the injector-type extraction column upon separation of the initial mixture. On the basis of a numerical experiment comparison of the cyclic operational mode with the stationary operational mode was carried out with respect to the extraction degree and the energy demand. It was confirmed that, as compared to the stationary operational mode, the cyclic operational mode provides a greater degree of extraction. The ratio of the extraction degrees in these operational modes of the extractor depending on the mass transfer criterion is of an extremal type. The maximum value of this ratio falls within the range from 1 to 4 and is equal to 1.5. It was also shown that the stationary operational mode of the extractor is more energy consuming than the cyclic one. The ratio of the energy demand for the stationary operational mode of the extractor to the energy demand in the cyclic operational mode depends on the extraction degree. This ratio grows from 1 to 5within the interval of the extraction degree from 0.1 to 0.47.

Keywords: *liquid-liquid extraction, column injector, cyclic mode, stationary mode, mass transfer, extraction degree, driving force, mathematical model.*

Introduction

Spray-type extracting columns are elementary devices in their design. They have high capacity, are suitable for separating not only liquid mixtures, but also suspensions – liquids with suspended solid particles, can be used as contact heat exchangers, for example, when desalting water, and also for studying the general regularities of mass transfer between liquids.

However, such columns have an essential shortcoming: low efficiency. This fact limits the application sphere of the considered columns in the industry, particularly, as mass-transfer devices. The low efficiency of spray-type columns is a consequence of short-term contact of phases and of the considerable axial diffusion coefficient of both phases.

These shortcomings can be partially overcome when using the cyclic operating mode of such devices. The essence of this method is alternation of the flows of the interacting phases after certain periods of time divided by short pauses. The cyclic method successfully combines advantages of periodic and continuous processes in one device. Such a method of carrying out mass-transfer processes was successfully used for the first time for increasing the productivity of an orifice extraction column [1–3]. The published results of laboratory studies of such a column in the cyclic and stationary modes not only confirmed the possibility of increasing its productivity, but also showed an increase of its mass-transfer ability [4–7]. Most theoretical and experimental studies

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on the cyclic mode in extraction, rectification and crystallization columns carried out subsequently by various authors show the advantage of the cyclic mode as compared with the stationary mode [8 – 12].

We chose the injector-type extraction column as an object of study on the mass-transfer ability of the spray-type extraction columns operating both in the stationary and in the cyclic modes [5]. A numerical experiment made on the basis of mathematical modeling of the injector extraction column operating in the stationary and cyclic modes allowed comparing these modes with respect to their main indicators: degree of extraction, driving force of the process and energy consumption.

Mathematical model of an injector column (extractor) in case of the stationary mode of its operation

Let us make the mathematical model of an extractor operating in the stationary mode, the structure of flows in which corresponds to one cell of ideal mixing of each phase [13].

Figure 1 shows a scheme of a counterflow injector extractor according to the chosen structure of flows of the raffinate and extract.

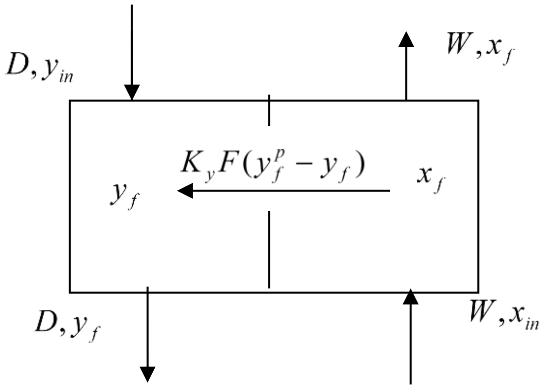

Figure 1. Scheme of a counterflow injector extractor (stationary mode).

Let us write down the equations of material balance for the extracted substance for each of the phases (Figure 1).

For the raffinate phase:

$$Wx_{in} = Wx_f + K_y F(y_f^p - y_f).$$

For the extract phase:

$$Dy_{in} + K_y F(y_f^p - y_f) = Dy_f.$$

Dividing each of the equations, respectively, by *W* and by *D* and considering that $y_f^p = Rx_f$ we have

$$x_f = x_{in} - \frac{K_y F}{W}(Rx_f - y_f), \qquad (1)$$

$$y_f = y_{in} + \frac{K_y F}{D}(Rx_f - y_f). \tag{2}$$

Here $\frac{K_y F}{D} = a$ is the ratio of working capacities of the surface stage and the flow stage of mass transfer for the extract phase (provided the partition coefficient is constant), or the number of transfer units in the extract phase, and $\frac{RK_y F}{W} = b$ is the ratio of working capacities of the surface stage and the flow stage for the raffinate phase, or the number of transfer units in the raffinate phase [13]. All the above considered, the system of equations (1)–(2) is transformed to

$$x_f = x_{in} - \frac{b}{R}(Rx_f - y_f),$$

$$y_f = y_{in} + a(Rx_f - y_f).$$

After ordering we have

$$(b+1)x_f - \frac{b}{R} y_f = x_{in},$$

$$-aRx_f + (a+1)y_f = y_{in}.$$

Considering that $b+1=c$, and $a+1=d$ we finally have

$$cx_f - \frac{b}{R} y_f = x_{in} \tag{3}$$

$$-aRx_f + dy_f = y_{in} \tag{4}$$

The system of equations (3)–(4) is a mathematical model of mass transfer in the injector extraction column at the stationary mode of its operation.

The general solution of the system of equations (3)–(4) is

$$x_f = -\frac{d \cdot x_{in}}{a \cdot b - c \cdot d} - \frac{b \cdot y_{in}}{R(a \cdot b - c \cdot d)}, \tag{5}$$

$$y_f = -\frac{c \cdot y_{in}}{a \cdot b - c \cdot d} - \frac{R \cdot a \cdot x_{in}}{a \cdot b - c \cdot d}. \tag{6}$$

Mathematical model of an extractor in case of the cyclic mode of its operation

Let us assume that each cycle of the extractor operation consists of 4 periods: two periods of interchange of the raffinate and extract phases and two periods of mass transfer. Besides, let us assume that the structure of flows during the periods of mass transfer corresponds to one cell of ideal mixing for each phase. During the periods of change of the phases displacement of the phases occurs completely and instantly in the mode of ideal displacement.

Let us describe in more detail each of the cycle periods assuming that the duration of the cycle is equal to the sum of durations of the first and second mass transfer periods: $\tau_1 + \tau_2 = \tau_c$. The current time of the first and second mass transfer periods changes respectively within the limits $\tau_1 \ge \tau \ge 0$ and $\tau_2 \ge \bar{\tau} \ge 0$.

When the raffinate phase in the working area of the extractor is completely interchanged during the first period of the cycle, its composition at the end of this period or at the initial moment of the first period of mass transfer is equal to the composition of the initial solution $x_{10} = x_{in}(\tau = 0)$ (see Figure 2). Besides, the structure of the interchanged phase of the raffinate is equal to the composition of this phase at the end of the fourth period of the cycle or the second period of mass transfer $x_{2\tau 2}$.

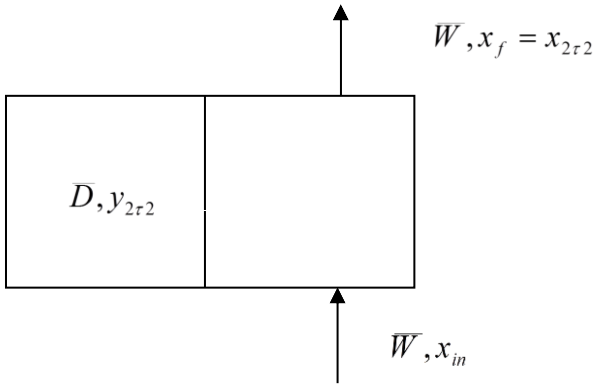

Figure 2. Scheme of the injection extractor in the period of interchange of the raffinate phase.

The second period of the cycle, or, what is the same, the first period of mass transfer, is characterized by variable values of the compositions of the raffinate phase x_1 and the extract phase y_1 (Figure 3) from x_{10} to $x_{1\tau 1}$ and from y_{10} to $y_{1\tau 1}$, respectively.

When the extract phase is completely replaced during the third period of the cycle, its composition in the working area of the extractor at the end of this period or at the initial moment of the second period of mass transfer is equal to the composition of the extractant at the apparatus inlet y_{in}. The composition of the replaced extract phase at the outlet of the extractor working area is equal in value to the composition of the extract phase at the end of the first period of mass transfer $y_{1\tau 1}$ (Figure 4).

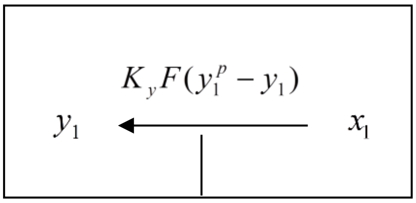

Figure 3. Scheme of the injector-type extractor at the first period of mass transfer.

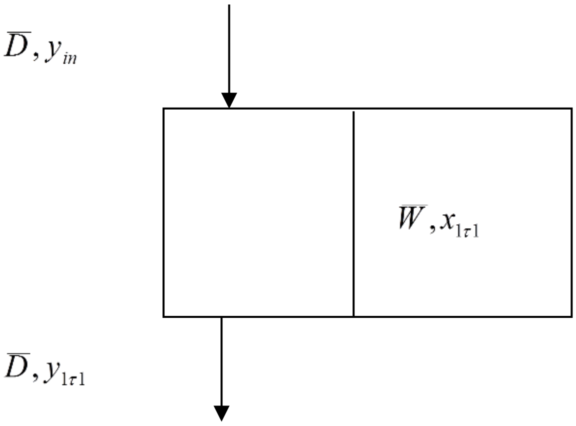

Figure 4. Scheme of the injector-type extractor at the period of the extract phase replacement.

The fourth period of the cycle, or the second period of mass transfer, is characterized by variable compositions of the raffinate phase x_2 and the extract phase y_2 in the device from x_{20} to $x_{2\tau 2}$ and from y_{20} to $y_{2\tau 2}$, respectively (Figure 5).

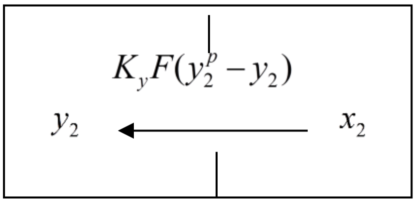

Figure 5. Scheme of the injector-type extractor at the second period of mass transfer.

Let us write the equation of material balance for the raffinate phase for the first period of mass transfer during an elementary period of time for the transferred component (TC) (Figure 3):

$$\overline{W}\frac{dx_1}{d\tau}d\tau = -K_y F(y_1^e - y_1)d\tau\,, \tag{7}$$

where $\overline{W}$ is the mass of the raffinate phase in the cell during any period of the cycle; y_1^e is the equilibrium value of TC concentration in the raffinate phase equal to the product of partition coefficient *R* by the current value of TC concentration in the extract phase; K_y is the coefficient of mass-transfer from the raffinate phase to the extract phase; *F* is the contact area of the extractor phases.

Let us make some transformations, namely: let us multiply the left and right sides of equation (7) by the same magnitude – the cycle duration τ_c. Let us divide both parts of the equation by the raffinate mass. This gives

$$\frac{dx_1}{d\theta} = -\frac{K_y F}{\overline{W}}\tau_c(Rx_1 - y_1)\,, \tag{8}$$

where $\theta = \frac{\tau}{\tau_c}$ is the current relative time of the first period of mass transfer.

Let us assume that each period of mass transfer lasts the same relative time equal to 0.5 taking into account that the duration of each of the periods of the phases interchange is equal to zero according to the above assumption. For this reason the limits of relative time of the first period of mass transfer are: $0.5 \geq \theta \geq 0$.

The corresponding equation of material balance for the extract phase of the first period of mass transfer is given by

$$\frac{dy_1}{d\theta} = \frac{K_y F}{\overline{D}}\tau_c(Rx_1 - y_1)\,. \tag{9}$$

Let us set up analogous material-balance equations for both phases of the extractor of the second period of mass transfer (Figure 5):

$$\frac{dx_2}{d\overline{\theta}} = -\frac{K_y F}{\overline{W}}\tau_c(Rx_2 - y_2)\,, \tag{10}$$

$$\frac{dy_2}{d\overline{\theta}} = \frac{K_y F}{\overline{D}}\tau_c(Rx_2 - y_2)\,, \tag{11}$$

where $\overline{\theta} = \frac{\overline{\tau}}{\tau_c}$ is the current relative time of the second period or mass transfer, the limits of which are: $0.5 \geq \overline{\theta} \geq 0$.

Note that ratios $\frac{\overline{W}}{\tau_c} = W$ and $\frac{\overline{D}}{\tau_c} = D$ are average flow rates for the cycle of the raffinate and extract phases. On the other hand, $\frac{K_y F}{D} = a$ and $\frac{RK_y F}{W} = b$. In view of these remarks the differential material-balance equations for the first and second periods of mass transfer (8)–(11) take the form:

$$\frac{dx_1}{d\theta} = -bx_1 + \frac{b}{R} y_1 , \tag{12}$$

$$\frac{dy_1}{d\theta} = aRx_1 - ay_1 , \tag{13}$$

$$\frac{dx_2}{d\overline{\theta}} = -bx_2 + \frac{b}{R} y_2 , \tag{14}$$

$$\frac{dy_2}{d\overline{\theta}} = aRx_2 - ay_2 . \tag{15}$$

The system of equations (12)–(15) is the mathematical model of mass transfer in the injector extraction column for the cyclic mode of its operation.

The following expressions are the general solution of differential equations (12)–(15):

$$x_1(\theta) = C_1 + C_2 \exp(-(a+b)\theta) , \tag{16}$$

$$y_1(\theta) = RC_1 + RC_2 (-\frac{a}{b}) \exp(-(a+b)\theta) , \tag{17}$$

$$x_2(\overline{\theta}) = C_3 + C_4 \exp(-(a+b)\overline{\theta}) , \tag{18}$$

$$y_2(\overline{\theta}) = RC_3 + RC_4 (-\frac{a}{b}) \exp(-(a+b)\overline{\theta}) . \tag{19}$$

Graphical interpretation of partial solutions of the systems of algebraic and differential equations ((5)–(6) and (16)–(19)). Discussion of the obtained results.

The solutions were found for a ternary system with mutual insolubility of a diluting agent and extractant: kerosene – benzoic acid – water [5]. The following assumptions were made: $R = 0.47$; $a = [0.4; 0.8; 1; 2; 3; 4; 5: 1000]$; $W/D = 0.439$; $x_{in} = 7.5$ g/kg; $y_{in} = 0$.

Figure 6 presents phase trajectories and vectors of material balance of extraction in the injector column modelled by one cell of thorough mixing for both phases at the stationary and cyclic operating modes of the device. The ratio of capacities of the surface and flow stages of mass transfer (mass transfer criterion *a*) for the extract phase took the values 1 and 5.

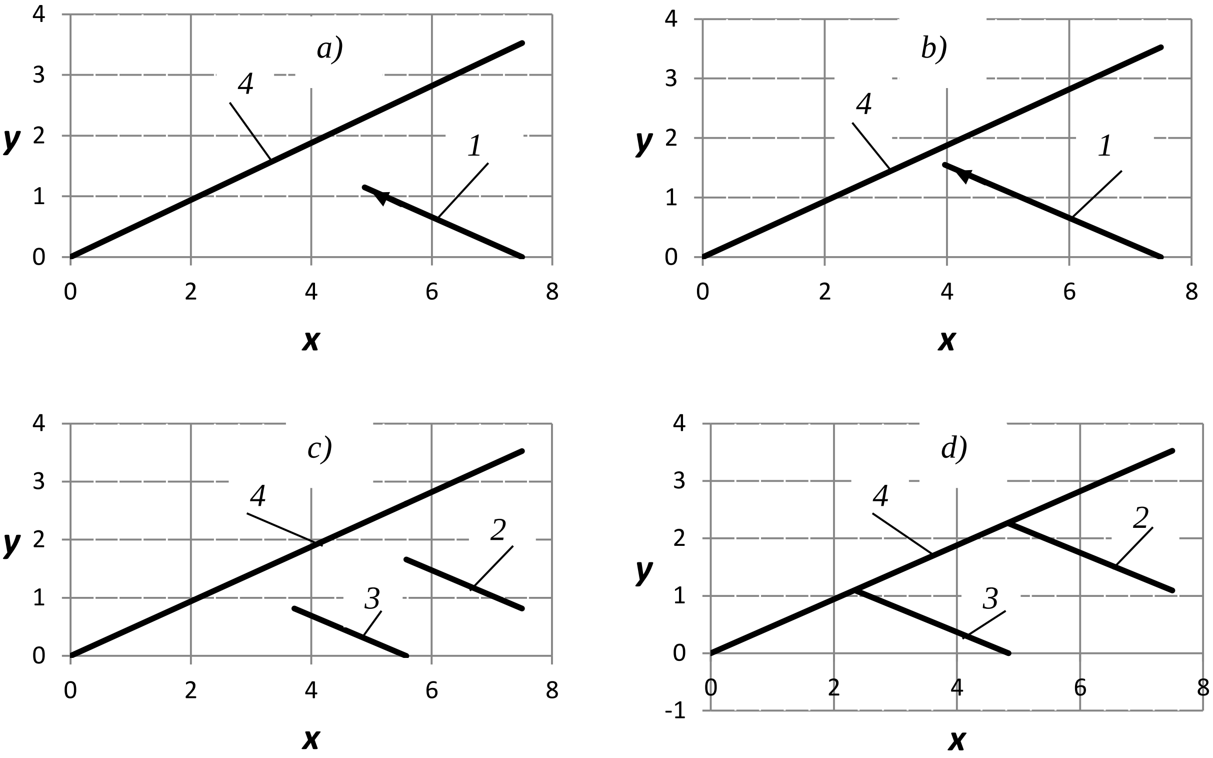

Figure 6. Results of extraction in the injector column: *a*) and *b*) – stationary mode of the extractor operation; *c*) and *d*) – cyclic mode of operation; mass transfer criterion: *a*) and *c*) $a = 1$; *b*) and *d*) $a = 5$; *1* – vector of material balance for the stationary mode; *2*, *3* – phase trajectories for the first and second periods of mass transfer; *4* – equilibrium line.

At the low value of the criterion ($a = 1$) neither the phase trajectories nor the vector of material balance reach the equilibrium concentration (Figure 6). At the higher value of the criterion ($a = 5$) the phase trajectories touch the equilibrium line, whereas the vector of material balance is still at some distance from the equilibrium line. This phenomenon is caused by a greater driving force of extraction when the operating mode of the extractor is cyclic, which is shown in Figure 7. Both in the first period (curve 2 in Figure 7) and in the second period (curve 3 in Figure 7) of mass transfer the driving force at the cyclic mode is significantly greater than the driving force at the stationary operating mode of the extractor (straight line 1 in Figure 7).

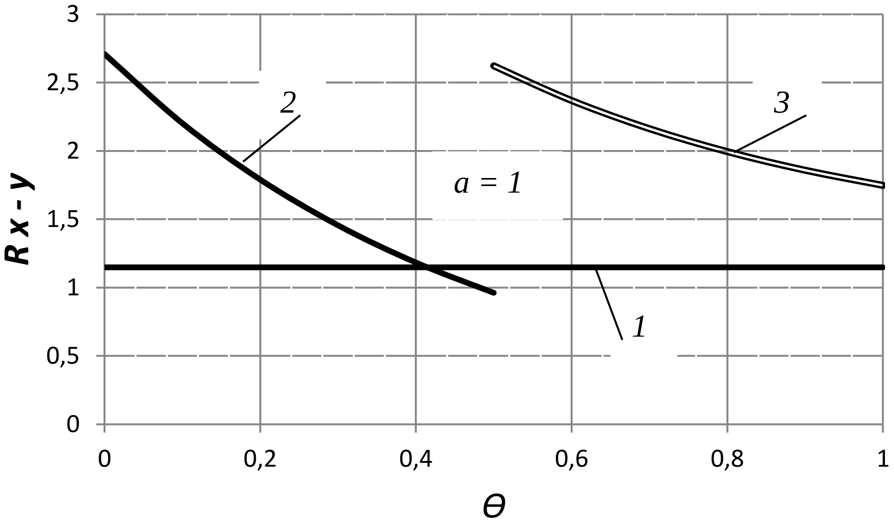

Figure 7. Dependence of the driving force of extraction on the current relative time of the cycle at different operation modes of the injector column: *1* – the stationary mode; *2* – the first period of mass transfer at the cyclic mode; *3* – the second period of mass transfer at the cyclic mode.

Comparison of the final concentration in the process of extraction at any identical value of mass transfer criterion *a* for various operating modes of the extractor shows an advantage of the cyclic mode (see Figure 6). For a quantitative evaluation of this advantage let us use the degree of extraction as a criterion of efficiency. The degree of extraction for any operating mode of the extractor can be calculated by the following formula:

$$\eta = 1 - \frac{x_f}{x_{in}}. \qquad (20)$$

Results of studying the dependence of the degree of extraction on the criterion of mass transfer for various operating modes of the injector extractor are presented in Figure 8.

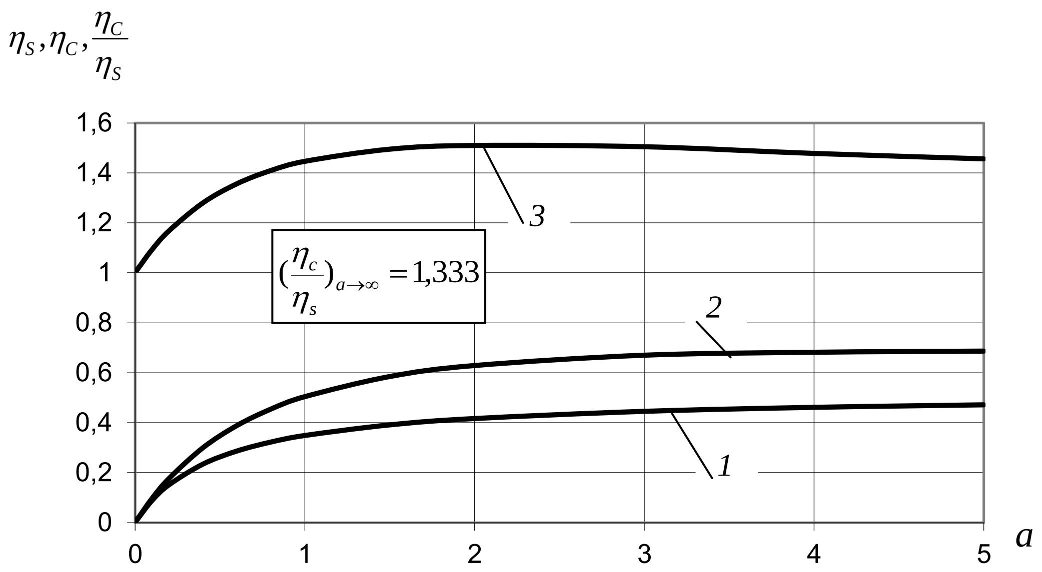

Figure 8. Dependence of the degree of extraction on the criterion of mass transfer for different modes of the extractor operation: *1* – the stationary mode; *2* – the cyclic mode; *3* – the ratio of the degrees of extraction for different modes.

It can be seen that the cyclic mode has an advantage in comparison with the stationary one (see curves 1 and 2 in Figure 8) in the whole variation range of the criterion of mass transfer. The dependence of the ratio of degrees of extraction for different modes on *a* has an extremum character (see curve 3 in Figure 8). As criterion *a* changes from 0 to 1000, the ratio of degrees of extraction changes from 1 to 1.333. The maximum value of this ratio is in the variation range from 1 to 4 and is equal to $\left.\frac{\eta_C}{\eta_S}\right|_{\max} = 1.5$.

Note that the variation of criterion *a* in the numerical experiment was made by changing the throughput capacity of the surface stage of the process $K_y F$, because the flow rate of the extract phase remained unchanged. On the other hand, $K_y F$ determines the intensity of extraction in the device. The higher is energy supply N from the outside into the extractor mass transfer zone, the higher is the process intensity, i.e., $K_y F = f(N)$. Thus, comparison of the cyclic and stationary operating modes of the extractor by the value of criterion *a* allows to judge the advantage of one or another mode in terms of energy consumption. Figure 9 presents comparison of the mentioned modes by the value of criterion *a* at identical values of the degree of extraction in the device.

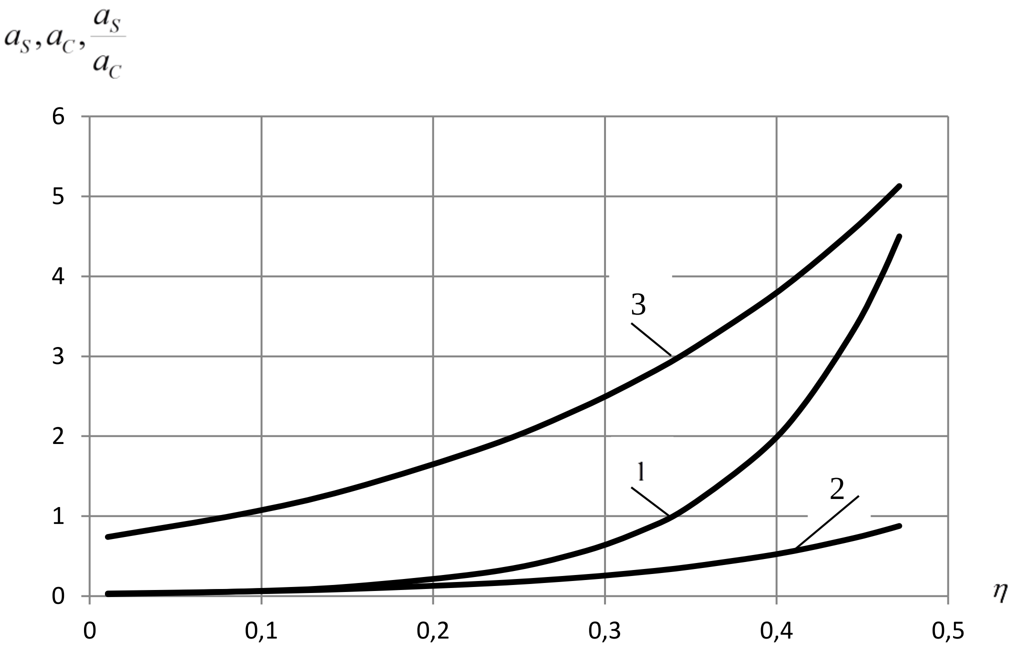

Figure 9. Dependence of required value of criterion of mass transfer *a* on the degree of extraction: 1 – the stationary mode of the extractor operation; 2 – the cyclic mode of the extractor operation; 3 – the ratio of energy consumption upon the extractor operation in different modes.

It can be seen that the ratio of the required values of the criterion of mass transfer $\frac{a_S}{a_C}$ increases with increasing degree of extraction. Therefore, the ratio of the values of the energy supplied into the extractor mass transfer zone at the stationary and cyclic modes of its operation also increases with increasing degree of extraction. An exception is the range of the degree of extraction from 0 to 0.1. Here a certain advantage of the stationary operating mode of the extractor is observed.

Conclusions

The results of the numerical experiment show an advantage of using the cyclic operating mode of the injector extraction column in comparison with the stationary mode with respect to the degree of extraction and energy consumption in the whole range of changing the criterion of mass transfer.

In actual practice the cyclic mode provides a decrease of the longitudinal mixing of both phases in comparison with the stationary mode [4]. This allows concluding that the obtained results are of practical importance.

DESIGNATIONS:

a is the criterion of mass transfer efficiency, the ratio of the throughput capacities of the surface stage and the flow stage of mass transfer for the extract phase; b is the ratio of the throughput capacities of the surface stage and the flow stage of mass transfer for the raffinate phase; F is the contact area of the phases; W is the mass flow rate of the raffinate phase; $\overline{W}$ is the mass of the raffinate phase in the cell in any period of the cycle; x is the concentration of the transferred component (TC) in the raffinate phase; y is the concentration of TC in the extract phase; R is the phase-equilibrium constant; D is the mass flow rate of the extract phase; $\overline{D}$ is the mass of the crystalline phase in the cell in any period of the cycle; η is the degree of extraction of TC; K_y is the mass transfer coefficient for the extract phase; τ is the current time of the cycle; θ is the current relative time of the first period of mass transfer; $\overline{\theta}$ is the current relative time of the second period of mass transfer.

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p is the equilibrium concentration; *in* is the concentration of TC in the raffinate or extract phases at the extractor inlet; f is the concentration of TC in the raffinate or extract phases at the extractor outlet; c is the cyclic operating mode of the extractor; s is the stationary operating mode of the injector column; *0* is the beginning of the first or second period of mass transfer; *1* is the first period of mass transfer; *2* is the second period of mass transfer; τ_1 is the end of the first period of mass transfer; τ_2 is the end of the second period of mass transfer.

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