OPTIMIZATION OF THE TECHNICOECONOMIC INDICATORS OF THERMODIFFUSION INSTALLATIONS FOR ISOTOPE ENRICHMENT IN THE LIQUID PHASE

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The article analyzes the operating conditions of thermodiffusion installations ensuring the lowest specific expenditures in isotope separation in the liquid phase with specified output.

Of the existing methods of isotope enrichment that are used in practice, not one, except the electromagnetic method, is universal, and the question, which method should be used to solve some actual problem of separation, is answered on the basis of the technicoeconomic indicators of the method. In this sense it is expedient to examine the thermodiffusion method of isotope enrichment so as to determine its place among the other separation processes. In the literature there are no data making it possible to determine the conditions under which the thermodiffusion process has the best technicoeconomic indicators for carrying out the process in the liquid phase, and the object of the present work is to fill this gap on the basis of using the generalized physical characteristics of separated mixtures. Although such a generalization is not distinguished by great accuracy of the results because the physical characteristics of the liquids somewhat differ from each other, it nevertheless permits some useful evaluations.

The principle on which the thermodiffusion column operates is shown in Fig. 1. The vertical slotted channel 1 contains the mixture to be separated. The channel walls 2, 3 are maintained at different temperatures. The density gradient over the cross section of the channel thus produced gives rise to two oppositely directed convective streams 4. At the same time, the temperature gradient causes transverse thermodiffusion transfer 5. Under the effect of these two factors (convection and thermal diffusion), the lighter components of the mixture concentrate in the upper part of the column, and the heavier components concentrate in the lower part, where they can be extracted at the certain rate.

It follows that the process of thermal diffusion requires the continuous supply and removal of heat, and that it is irreversible.

In view of the great sensitivity of the hydrodynamic processes occurring in the thermodiffusion column to temperature inhomogeneities arising because of irregular supply and removal of heat on each of the surfaces 2, 3 (Fig. 1), heating has to be effected with saturate steam [1], and cooling with water circulating at a speed that ensures heat-transfer coefficients commensurable with those of the steam.

The thermodiffusion installation consists of a number of columns with mutual parallel-series connection so that the profile of the obtained cascade is as close as possible to the ideal cascade characterized by minimum heat expenditure and time required for attaining the specified concentration of the target isotope at that end of the apparatus where the enriched product is supposed to be extracted. Calculation shows that three or four stages suffice to ensure an efficiency better than 95% of an ideal cascade [2]. It must be demonstrated that the index of time is very important because the duration of the transient process may be commensurable with or even exceed the time during which the target product is processed; this may occur when the output is small.

To judge the technicoeconomic indicators of the thermodiffusion method, the following have to be specified: initial c_0 and final k_E concentrations; amount of isotope to be processe G, kg; salaries of the operating personnel k_s, rubles/sec; price of the heat energy k_w, rubles/J; price of the cooling water k_w, rubles/kg; amortization per 1 m^2 of heat-transfer surface k_a, rubles/m$^2\cdot$sec. As regards the price of the initial raw material and other auxillary materials, it is so low compared with other expenditures that it is disregarded.

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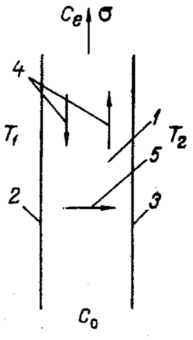

Fig. 1

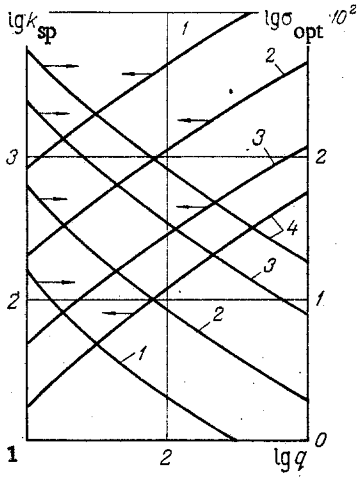

Fig. 2

Fig. 1. Diagram of the thermodiffusion column.

Fig. 2. Dependence of the logarithm of minimum specific expenditure log k_{sp}, rubles/g, and of the logarithm of optimum productivity log $\sigma_{opt}\cdot 10^2$, g/day, of the thermodiffusion apparatus on the logarithm of the degree of separation log q for different α_T: 1) 0.01; 2) 0.02; 3) 0.04; 4) 0.06.

Thus, specific expenditures per unit of enriched product are

$$k_{sp} = \frac{1}{G}(k_E Q + k_W W + k_a F + k_s)(t_p + t_t). \tag{1}$$

The values of k_E, k_W, k_a, k_s can be found on the basis of the following considerations. According to the present rates, steam is supplied by a thermal power station at the price $k_E = 1.1$ rubles/GJ $= 1.1\cdot 10^{-9}$ ruble/J. In cooling by circulating water, specific expenditure of electric power for the pump is $9.8\cdot 10^{-4}$ P/η, J/kg, where P is the pressure, and η is the efficiency of the pump. Proceeding from the price of electric power, $1.1\cdot 10^{-9}$ rubles/J and assuming that $\eta = 0.5$, $P = 5\cdot 10^6$ N/m^2, we obtain $k_W \approx 1.1\cdot 10^{-5}$ rubles/kg. The value k_a is associated with the theoretical service life of the installation which for thermodiffusion apparatus may be taken as 8 years. On the basis of available experience in building such apparatus it was established that the price of the entire equipment per unit working area of the columns is 5000 rubles/m^2, i.e., $k_a = 2\cdot 10^{-5}$ rubles/m$^2\cdot$sec. Since a high degree of automation of thermodiffusion installation can be ensured, making it possible to limit the number of operating staff to the attendants for taking samples, we arrive at the value $k_s \approx 2.5\cdot 10^{-4}$ rubles/sec.

For the subsequent calculations, we need the formulas ensuing from the theory of thermodiffusion separation apparatus [1, 3] given below:

$$Q = \frac{40}{7}\,\frac{\lambda}{\alpha_T^2 \rho D}\cdot\frac{\overline{T}^2}{\Delta T}\,\sigma V(c_e,\ c_0), \tag{2}$$

$$F = \frac{40}{7}\,\frac{\delta \overline{T}^2}{\alpha_T^2 \rho D(\Delta T)^2}\,\sigma V(c_e,\ c_0), \tag{3}$$

$$t_t = \frac{40}{7}\,\frac{\delta^2}{\alpha_T^2 D}\left(\frac{\overline{T}}{\Delta T}\right)^2\left[\frac{q+1}{2(q-1)}\ln q - 1\right]. \tag{4}$$

The flow rate of cooling water is determined by the degree of its heating during its passage through the thermodiffusion column. To avoid that the difference between temperatures of the heating steam and the cooling water changes greatly along the installation, the temperature increase of the water may be taken as equal to 10°C, and hence

$$W = \frac{Q}{10c_p} = 2.39 \cdot 10^{-5} Q. \tag{5}$$

The individual liquids that may be used for isotope separation have physical characteristics that differ relatively little from each other, and for the evaluations that interest us, we may accept the following: $\rho \approx 10^3$ kg/cm^3, $D = 2.5 \cdot 10^{-9}$ m^2/sec, $\beta = 10^{-3}$ deg^{-1}, and $\lambda = 0.13$ W/m•deg.

The size of the working gap in the thermodiffusion columns for liquids is $\delta = 2.5 \cdot 10^{-4}$ m. With regard to the temperature regimes, in view of the possibility of the installation operating under excess pressure in the working gap, we take $\Delta T = 100$°C and $\bar{T} = 360$°K. In addition, we assume that the processing time for isotope enrichment is correlated with the productivity of the installation by the relationship

$$t_p = G/\sigma. \tag{6}$$

With a view to the above formulas, the numerical values of the coefficients k, and the physical magnitudes, Eq. (1) assumes the form

$$k_{sp} = \left[0.674 \frac{\sigma V(c_e, c_0)}{\alpha_T^2} + 2.5 \cdot 10^{-4}\right] \left\{\frac{4.65 \cdot 10^3}{G\alpha_T^2} \left[\frac{q+1}{2(q-1)} \ln q - 1\right] + \frac{1}{\sigma}\right\}. \tag{7}$$

It can be seen from Eq. (7) that the specific expenditures for unit weight of enriched product depend on the amount of product that has to be processed, the productivity of the installation, the magnitude of the thermodiffusion constant, and also on the initial and final concentrations determining the price function

$$V(c_e, c_0) = \frac{(c_e - c_0)(1 - 2c_0)}{c_0(1 - c_0)} - (1 - 2c_e) \ln q, \tag{8}$$

and the degree of separation

$$q = \frac{c_e(1 - c_0)}{c_0(1 - c_e)}. \tag{9}$$

Of all the above factors, only the productivity of installation can be changed arbitrarily, whereas all the others are specified magnitudes. With some value of productivity, the specific expenditures determined from Eq. (7)

$$\sigma_{opt} = 2.8 \cdot 10^{-4} \alpha_T^2 \left\{\frac{G}{V(c_e, c_0)\left[\frac{q+1}{2(q-1)} \ln q - 1\right]}\right\}^{1/2} \text{kg/sec} \tag{10}$$

will be minimal and are expressed by the formula

$$k_{sp,\,min} = \frac{1}{\alpha_T^2} \left\{0.82 \sqrt{V(c_e, c_0)} + 1{,}08 \sqrt{\frac{1}{G}\left[\frac{q+1}{2(q-1)} \ln q - 1\right]}\right\}^2 \text{rubles/kg} \tag{11}$$

It can be seen from (10) and (11) that σ_{opt} and $k_{sp,min}$ depend largely on the thermodiffusion constant and to a lesser extent on the production program and the degree of separation.

As an example, we examine the case of a production program G = 10 g, with $c \ll 1$,* which changes Eq. (8) to the form

$$V(c_e, c_0) = q - \ln q - 1. \tag{12}$$

The results of calculation by (10)-(12) are presented in Fig. 2; after examination of the figure, the following conclusions are arrived at.

1. When $\alpha_T > 0.02$, liquid thermal diffusion ensures that isotopes are obtained with lower specific expenditure than by the electromagnetic method, even when the degree of enrichment is high.

2. It is most expedient to use thermal diffusion as the concluding stage of obtaining highly enriched isotopes, with preliminary enrichment carried out by another method (e.g.,

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*With $c \ll 1$, specific expenditure is largest.

by isotope exchange). It can be seen from Fig. 2 that with a degree of separation q = 10 (log q = 1) and $\alpha_T = 0.04$, specific expenditure is no more than 50 rubles/g with a productivity of 2.2 g/day and a duration of 5 days for processing 10 g. If the process is not optimized and we take, e.g., $\sigma = 1.1$ g/day, then, in accordance with (7), $k_{sp} = 248$ rubles/g, i.e., specific expenditure thus obtained is five times higher.

The applicability of formulas (10) and (11) for approximate calculations can be illustrated on the basis of the data obtained by Rutherford [4] on enriching the isotope sulfur 34 in carbon bisulfide up to 90% (q = 200); here the author estimated that the price of 1 g enriched product is 100-200 dollars. Since for sulfur isotope in carbon bisulfide $\alpha_T = 0.06$ [5], we find from curve 4 in Fig. 2 that $\log k_{sp} \approx 2.3$ or $k_{sp} \approx 200$ rubles/g, i.e., a value close to the value given by Rutherford [4].

NOTATION

G, amount of product to be processed; σ, productivity of the thermodiffusion apparatus; Q, heat flow rate; W, water flow rate; F, heat-transfer area; T_1, T_2, temperatures of less and more heated surfaces of the column, respectively; $\Delta T = T_2 - T_1$; $\bar{T} = {}^1/_2(T_1 + T_2)$; t_p, time of processing the final product; t_t, time of transient process; λ, D, thermal conductivity and diffusion coefficients, respectively, of the separated mixture; ρ, density; α_T, thermal diffusion ratio; δ, working gap of the column; q, degree separation, see (9); c_0, c_e, initial and final mass concentrations, respectively; $V(c_e, c_0)$, see (8).

LITERATURE CITED

1. G. D. Rabinovich, R. Ya. Gurevich, and G. I. Bobrova, Thermodiffusion Separation of Liquid Mixtures [in Russian], Nauka i Tekhnika, Minsk (1971).
2. N. I. Laguntsov, E. V. Levin, and G. A. Sulaberidze, Inzh.-Fiz. Zh., 31, No. 3 (1976).
3. K. Aleksander, Usp. Fiz., Nauk. 76. No. 4 (1962).
4. W. M. Rutherford and W. J. Roos, in: Proceedings of Symposium on Isotope Ratios as Pollutant Sourc nd Behavior Indicator (1975), p. 295.
5. W. M. Rutherf . Chem. Phys., 59, No. 11 (1973).