

Number of Adsorbers for a Gas Separation System

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Abstract—An algorithm for the total number of adsorbers and the number of active adsorbers (i.e., the ones in the adsorption mode at the moment in question) has been designed in terms of the ergodic hypothesis. This algorithm is intended for the design of gas separation systems.

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In the design of adsorption systems for gas separation, of importance are the total number of similar adsorbers n and their division into active adsorbers, which are in the adsorption mode at a certain moment of the cycle (their number is n_a), and passive ones, which are in the regeneration mode (discharge, purging, and pressure rise) at the same moment (their number is $n_p = n - n_a$). Let us denote the fraction of active adsorbers in the separation system as α_a :

$$\alpha_a = n_a/n. \quad (1)$$

Most commercial air separation systems use two adsorbers (one in the adsorption mode and the other in the regeneration mode; $\alpha_a = 0.5$) or three adsorbers (two in the adsorption mode and the third in the regeneration mode; $\alpha_a = 0.66$). The system for hydrogen separation from the products of methane conversion developed by the UCC company employs nine adsorbers [1].

The number of adsorbers n in the separation system is usually chosen proceeding from economic considerations. One should keep in mind that addition of one adsorber to the separation system decreases the load per adsorber and, thus, decreases the pressure drop upon gas filtration through the bed, but dramatically complicates control over the whole separation system. In addition, the smaller the number of adsorbers n_p at each moment of the cycle, the better the cycle efficiency.

The provision for the value and continuity of the product flow Q , mol/s, is one of the major requirements for the design of an adsorptive separation system. Let us denote the product flow from one active adsorber as q , mol/s. Then, the number of active adsorbers equals

$$n_a = Q/q. \quad (2)$$

For the specific product flow $j = q/S_0$, where S_0 is the cross-sectional area of an individual adsorber (m^2), there are natural upper limits imposed by the following two factors: the pressure drop along the bed and the convective instability of the adsorption front. The pressure drop due to gas filtration through the adsorbent bed

of a given cross-sectional area depends on the weight gas flow and the bed structure; this dependence is expressed through many semiempirical relationships proposed for the hydraulic drag of the bed [2]. The convective instability of the adsorption front is determined by the Archimedes adsorption number [3, 4].

The results of experiments carried out on a laboratory adsorber or testbed can be represented as the ratio of the duration of the adsorption mode to the overall duration of the cycle τ_0 (s):

$$\alpha_\tau = \frac{\tau_a}{\tau_c} = \frac{\tau_a}{\tau_a + \tau_d + \tau_0}. \quad (3)$$

The duration of the adsorption mode τ_a (s) equals the travel time of the adsorption front at the linear velocity w_f (m/s) through the bed with the length L (m): $\tau_a = L/w_f$. The duration of the discharge stage, τ_d (s), can by analogy be identified with the travel time of the desorption front at the linear velocity w_d (m/s) through the bed with the length L : $\tau_d = L/w_d$. Let us denote the duration of auxiliary stages of the regeneration mode (purging and filing) as τ_0 (s). Then, Eq. (3) becomes

$$\alpha_\tau = \frac{1}{\varphi(L)}, \quad (4)$$

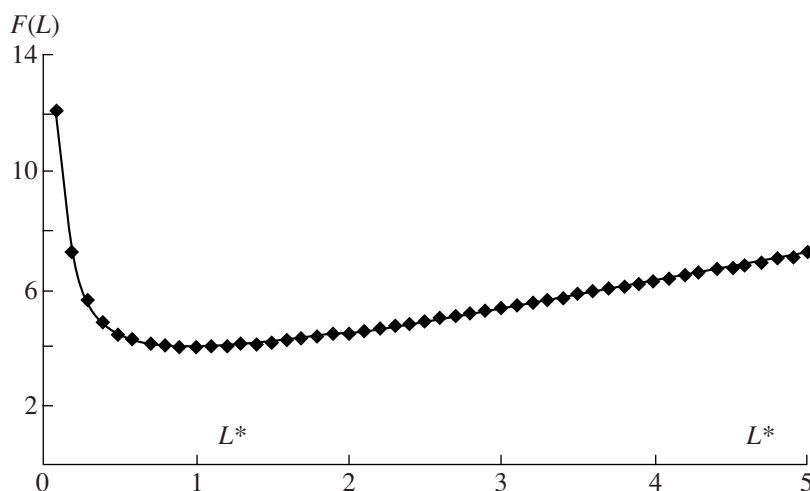
where

$$\varphi(L) = 1 + \frac{w_f}{w_d} + \frac{w_f \tau_0}{L}. \quad (5)$$

Let us consider a system of an infinite number of adsorbers,

$$\left(n \rightarrow \infty, \quad n_a \rightarrow \infty, \quad \frac{n_a}{n} \rightarrow \alpha_{a,\infty} \right),$$

as a set of random objects. From the fundamental ergodic hypothesis for such a system, the fraction of time during which one randomly chosen adsorber is in



Schematic plot of the $F(L)$ target function (11). To the minimum $F(L)$ function, L^* calculated from Eq. (12) corresponds.

the active mode, α_τ , equals the fraction of active adsorbers among the set of all adsorbers, $\alpha_{a,\infty}$:

$$\alpha_{a,\infty} = \alpha_\tau. \quad (6)$$

In a real system, which is some finite sample, the fraction of active adsorbers α_a (1) is the ratio of two integers, whereas the experimentally determined parameter α_τ (3) is an arbitrary number. Therefore, the ergodic constraint (6) for a real system with a finite number of adsorbers should be considered only as an approximate equality:

$$\alpha_a \approx \alpha_\tau. \quad (7)$$

In order for the exact ergodic constraint (6) to match the approximate equality (7), the parameter β should be introduced so that

$$\frac{1}{\beta} \alpha_a = \alpha_\tau. \quad (8)$$

We note that the choice of the parameter β is much affected by the intuition and skill of the researcher. For a sufficiently large number of adsorbers n in the system, this parameter should be on the order of unity. From Eqs. (1), (2), (4), (5), and (8),

$$n = \frac{Q}{\beta q} \left(1 + \frac{w_f}{w_d} + \frac{w_f \tau_0}{L} \right). \quad (9)$$

Equation (9) can help to derive certain conclusions about the optimum gas-separation system. For example, in many significant cases, the optimization of an adsorption system consists in the minimization of its weight and size. Let us consider the target function,

which is proportional to the volume (weight) of the separation system composed of n adsorbents:

$$F = Lns_0 + nV_0, \quad (10)$$

Here, V_0 is the volume of the auxiliary elements of the system per adsorber. The first term in Eq. (10) equals the adsorber volume; the second one equals the volume of the process equipment (including valves, throttles, and intrasystem pipelines). For simplicity, let the volume of auxiliary elements per adsorber be independent of the adsorber length.

Substituting relation (9) into Eq. (10), we express the target function through the adsorber length $F(L)$:

$$F(L) = \frac{Qs_0}{q\beta} \left(L + \frac{V_0}{s_0} \right) \left(1 + \frac{w_f}{w_d} + \frac{w_f \tau_0}{L} \right). \quad (11)$$

Solving the algebraic equation $\partial F/\partial L = 0$, we arrive at

$$L^* = \sqrt{\frac{V_0 w_f \tau_0}{s_0 \left(1 + \frac{w_f}{w_d} \right)}}. \quad (12)$$

To L^* (12), the minimum $F(L)$ target function (11) corresponds (figure).

The calculated L^* (12) value can be used to estimate, from Eq. (9), the total number of adsorbers in the separation system for the given output Q and load per adsorber q .

In concluding, we should note that, distributing adsorbers over adsorption stages, one should try to best satisfy relationship (8), which is a consequence of fundamental equality (6). The simplest route is to increase n , the total number of adsorbers in the system. For example, let laboratory or bed tests result in $\alpha_\tau = 0.7$. Guided by the constraints imposed on the pressure drop upon the filtration of the given gas flow to be separated, the process engineer has to use a system of four active

adsorbers. At least two adsorbers operating in the regeneration mode are required to provide the steady-state operation of this system. In this case, $\alpha_a = 0.66$ and $\beta = 1.06$. If further experiments show that the load per active adsorber q is still unduly high, a system of seven adsorbers, including five active adsorbers ($\alpha_a = 0.71$), can be considered. In this case, $\beta = 1.014$.

CONCLUSIONS

An algorithm for the number of adsorbers in gas separation systems has been designed. The target func-

tion has been designed for the optimization of the number of adsorbents.

REFERENCES

1. Sircar, S., Golden, T.C., and Rao, M.B., *Carbon*, 1996, vol. 34, p. 1.
2. White, D.H. and Barkley, P.G., *Chem. Eng. Prog.*, 1989, vol. 85, p. 25.
3. Zelenko, V.L., Makeev, E.A., and Kheifets, L.I., *Izv. Akad. Nauk, Ser. Mekh. Zhidk. Gaza*, 2006, no. 3, p. 77.
4. Makeev, E.A., Zelenko, V.L., and Kheifets, L.I., *Vestn. Mosk. Univ, Ser. 2: Khim.*, 2006, vol. 47, p. 318.