Investigation of hybrid membrane-sorption technologies for air fractionating

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Abstract. Main aim of the work is to develop and to research single-circuit hybrid membrane-sorption system for enriching air with oxygen. The developed system allows to produce air, enriched with air up to 50%, purified from dust of any size, including nanoscale dust received in consequence of sorbent abrasion. In the course of the work the research of existing systems for air enrichment with oxygen, and the possibility of combining two methods of gas separation: membrane, and sorption, was conducted. The developed system differs from its analogues in that it has improved energy efficiency compared to methods of the membrane and sorption separation. Also work presents method of cyclogram determining of the hybrid system. In this methodic an algorithm for calculating of the cycles number, and determining of the stages duration in order to obtain the desired performance was presented.

1. Introduction

The single-circuit membrane sorption hybrid system was investigated in this paper. Numerical studies of separation features and energy efficiency of the system for enriching air with oxygen at different parameters of dividing cells were conducted. System with an increased pressure of permeate flow, designed for feeding of apparats of artificial lung ventilation, was considered.

Air enriched with oxygen is necessary to create mobile air separation systems that can be used in order to develop an artificial breathing atmosphere. Due to the use of single-circuit membrane-sorption scheme the energy efficiency of such a system can be improved.

The artificial breathing atmosphere has a wide range of applications: medicine, atmosphere generators, etc.

Hybrid membrane-sorption system (Fig. 1) consists of a compressor, two alternately working adsorbers with the sorbent, the valve system and the membrane module. The air after passing through the ejector fills one receiver and is enriched with oxygen, while the other receiver takes place desorption of the sorbent [2,3], and then, the air, enriched with oxygen, enters into the membrane unit.
In works [1,4,5] different variations of hybrid system schemes was investigated. The dependence of the selection on the pressure of the product flow was analyzed and it was shown that it is better to use a circuit with a feed of a power flow through the ejector shown in Figure 1 in order to obtain a flow of enriched air at high pressure. As it is shown by the diagram, first feed flow passes through the ejector, then it is enriched with the oxygen in sorption unit, then goes to a membrane module, wherein the part of the flow is enriched with the oxygen and goes in the product flow, afterwards a retentate flow of the membrane unit is returned into the ejector where it is mixed with the feed flow. Since the retentate flow is already enriched with oxygen, then as a consequence, the output of the ejector concentration of the oxygen becomes higher than the natural, which increases energy efficiency of the system.

A system of equations describing the two-component gas mixture separation is used for the calculation of the membrane module under the assumption of ideal displacement in the cavity of high pressure by perpendicular outflow in the cavity of the low pressure [1]. This model describes well the process of gas separation in hollow fiber membrane modules. Calculations of the sorption stage were carried out in assumptions about ideal model of linear sorption [1,6,7].

In the paper [6] an algorithm for calculating the hybrid membrane adsorption system and a numerical research of the energy efficiency depending on the selectivity of separating elements is presented. It is shown that the primary separation operation does sorption part, while membrane portion serves as a divider of the product flow, part of which is directed to the filling of adsorber for the increase of the concentration of oxygen in the feed flow and allows to provide a product flow completely purified from nanometer-sized particles. These particles get into the flow due to the abrasion sorbent.

2. Methods of determining the sequence diagram of the hybrid membrane-sorption system

2.1. The assumptions in the construction of the model.

The problem of determining sequence diagram of the hybrid membrane-sorption system is the multiparameter. In constructing the cyclogram, consider the following:
• Sorbent parameters, namely sorbent porosity $\varepsilon$, sorption constant $\sigma$, the capacity of the sorbent, the sorbent form (granules, cuttings), geometrical parameters of the sorbent;
• Membrane parameters: gas permeability and selectivity of the membrane $\alpha$;
• Accommodation of displacement stage and filling stage to ensure proper operation of the system;

To determine the cyclogram of the system (Figure 2), problem of coordination of unsteady stages of the system should be solved: it is necessary that by the end of displacement stage in one adsorber, in the other the filling stage had already finished and the stage of displacement began. This is necessary to ensure continuous product flow after the PSA stage to membrane module working in a steady regime at constant parameters operating mode. To meet this requirement, it is necessary to displacement stage time equal to the amount of filling phase time and the desorption stage time.

The duration of the filling stage is determined by the following factors:
1) Adsorption pressure $P_{ads}$;
2) The geometric characteristics of the adsorber;
3) Characteristics of the compressor used: productivity and the volume of the receiver.

Figure 2. Cyclogram of the hybrid membrane-sorption systems. 0-$\tau_1$ - first stage of filling the canister, $\tau_1$-$\tau_3$ - displacement stage, $\tau_3$-$\tau_4$ - desorption stage from the first adsorber.

As the displacement stage is carried out at a small differential pressure $\Delta P$, the duration of the displacement stage determines by the maximum of pressure drop. The pressure differential is selected so that the adsorption rate satisfies the following criteria:
• minimum gas velocity is determined by the Peclet number cause if the speed is too low, the adsorption front will be blurred;
• maximum velocity of the gas is determined by the Reynolds number, cause if the speed is too high, then there will be a turbulence and mixture isn’t enriched to the desired concentration;

The duration of the adsorption stage is determined by desorption pressure $P_{des}$ and geometric characteristics of adsorber. The duration of filling stage is determined by the geometrical characteristics of the adsorber, the flow from the compressor, the pressure of the feed flow.

As can be seen from the graph, minimum duration of the displacement stage is determined by the sum of the durations of the stages of filling and desorption.

2.2. Algorithm for calculating the number of cycles and their duration
Calculation algorithm of the system was proposed in order to construct a cyclogram. Firstly, the product flow parameters are set: productivity $P$, the pressure of the product flow and the oxygen concentration in this flow. From these data volume adsorber is selected and such membrane and a
sorbent that can provide the necessary enrichment is selected. After that, the calculation of useful product flows and concentrations according to the formulas described in work [6].

Under calculating flows and concentrations of useful product in flows, the number of cycles of the system can be determined. If the necessary performance \( P \) is known, the number of cycles \( N \) is determined by dividing the value of the resulting product flow to a predetermined system performance. After determining the number of cycles, it is possible to determine the duration of each cycle by dividing the time, which should be achieved for a given performance, to the calculated number of cycles.

Then the duration of the filling stage and desorption stage is determined experimentally. The sum of these durations determines the minimum duration of the displacement stage. If calculated cycle time by the above described algorithm is not equal to the sum of the durations of the filling stage and the desorption stage, it is due to the fact that the selected volume adsorber \( V \) is not optimal for a preselected performance. If the calculated duration is more than experimentally determined duration, it is necessary to reduce the volume of adsorber, if less, it is necessary to increase the volume of adsorber.

2.3. Evaluation of filling time of adsorber by the gas

Adsorber filling with the gas cannot be described by a simple analytical dependence. But it is possible to describe the dynamics of the gas filling the adsorber empirically.

In the literature [8], the case of filling the tank with gas is described. If sorption is fast enough, then the adsorber filling with the sorbent volume \( V_0 \) can be viewed as the filling of the empty adsorber with volume \( V = \varepsilon V_0 \), \( \varepsilon \) - porosity of the sorbent. This process is described by the following equation:

\[
\gamma R T_0 dW_0 = Vdp + \gamma p dV,
\]

where \( \gamma \) - adiabatic index, \( W_0 \) - the mass of the gas, which is pumped into the volume \( V \), \( T_0 \) - temperature of the gas.

To determine the filling time of the volume \( V \), it is necessary to substitute in the equation (1) \( dW = Gdt \), where \( G \) - the mass flow rate. The mass flow depends on the pressure ratio, which is defined in the following ways:

In subcritical mode (when \( \sigma_i < \sigma^* \), \( \sigma_i = \frac{p_i}{p_0} \), \( \sigma^* = \left( \frac{2}{\gamma+1} \right) \gamma \gamma - 1 ):

\[
G = K \mu f \frac{p_0}{\sqrt{R T_0}} \left[ \sqrt{\frac{2}{\gamma}} - \sigma^* \frac{\gamma+1}{\gamma} \right]
\]

where

\[
K = \frac{2 \gamma}{\gamma-1}
\]

in the supercritical mode (when \( \sigma_i > \sigma^* \)):

\[
G^* = K^* \mu f \frac{p_0}{\sqrt{R T_0}}
\]

where

\[
K^* = K \left( \frac{2}{\gamma} \right) \gamma - 1 \frac{\gamma+1}{\gamma}.
\]

After integration of the equation (1) with corresponding definitions of the \( G \) mass flow rate, according to the equations (2) and (3), the following equation for the estimated fill time [Hz] is obtained:

- for the subcritical mode

\[
\text{Hz} = \frac{1}{G}
\]
\[ t = \frac{2V}{(y-1)\mu f K \sqrt{RT_0}} \left( \sqrt{1 - \frac{y-1}{\sigma_1^y}} - \sqrt{1 - \frac{y-1}{\sigma_2^y}} \right) \tag{4} \]

and for the supercritical mode

\[ t = \frac{V}{\gamma \mu f K \sqrt{RT_0}} (\sigma_2 - \sigma_1) \tag{5} \]

2.4. Evaluation of gas expiration time from the adsorber

Using the ideal gas equation, next equation can be obtained:

\[ dp = \frac{RT}{\mu V} dm, \quad dm = -\rho Sw dt, \]

where \( \mu \) - molar mass, \( dm \) - mass of the gas flowing in time \( dt \) through the opening area \( S \).

The formula for the instantaneous rate of gas outflow from the reservoir [9]:

\[ w = \sqrt{2 \frac{\gamma}{\gamma - 1} pv \left[ 1 - \left( \frac{p_{out}}{p} \right)^{(\gamma-1)/\gamma} \right]}, \]

where \( \gamma \) - adiabatic index, \( p \) - gas pressure in the tank, \( v \) - specific volume of gas in the tank, \( p_{out} \) - external pressure. The dimension \( w \) - m/s. The specific volume of gas is calculated using the formula:

\[ v = \frac{1}{\rho}, \]

where \( \rho \) - density of gas.

Using a linear relationship between pressure and density:

\[ \rho = \rho_0 \frac{p}{p_0} \]

where indicators index 0 correspond to the initial:

\[ dp = \alpha p \sqrt{1 - \left( \frac{p_{out}}{p} \right)^{(\gamma-1)/\gamma}} dt, \tag{6} \]

where

\[ \alpha = \frac{SRT}{\mu V} \sqrt{\frac{2}{\gamma - 1}} \frac{\rho_0}{p_0} \]

Equation (6) shows that it was possible to establish a connection between the change in pressure in the adsorber and time. According to the solution of this equation, conclusion about the dynamics of the adsorber desorption can be done, as well as the duration of the desorption process can be determined.

Conclusion

The method of cyclogram determining of the hybrid membrane-sorption system was presented. Then, an algorithm was proposed for calculating the number of system cycles and duration of each cycle required to obtain the desired performance of the system. The methods for evaluating of the duration of the filling stage and the duration of the desorption stage of the gas from the adsorber were proposed.

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