Use of ejector for recirculating flow organization in hybrid membrane-sorption system

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Abstract. In this paper the possibility of ejector using for recycle organization in the hybrid membrane adsorption system is considered. An algorithm of system solution that connects its dimensions and output parameters of the flow was described. The dependence of output pressure on the ejection coefficient under the selected geometry of the ejector was obtained.

1. Introduction
Oxygen plays an important role in human life. Besides the fact that it is necessary for respiration, oxygen is used in many spheres of human activity: energetics, metallurgy and chemical industry. Therefore obtaining of oxygen is an important and necessary objective.

Currently, an obtaining of oxygen is performed advantageously from air. One of the most efficient systems, according to the average air enrichment with oxygen, is a hybrid membrane-sorption system. This system allows to obtain air enriched with oxygen up to 50-60%. Such air may be used in the medical field and also, in order to create an artificial environment.

Hybrid membrane sorption system includes two separation steps - sorption and membrane. The most perspective scheme of the hybrid system is a recycling system without compression [1], wherein the recycle flow is mixed into the feed flow, which exits from compressor, using the ejector mixer.

Principal scheme of the system is shown in Fig. 1.
Figure 1. Schematic diagram of the recirculation of Single hybrid membrane-sorption installation. 1 – air compressor. 2 – ejector. 3,4 – absorbers. 5 – membrane module. 6 - 12 – adjustable valves.

In this system ejector mixing of flows is used. Ejector design is shown in Fig. 2.

Figure 2. Schematic diagram of the ejector.

Gas ejector consists of inlet nozzle of high-pressure flow, low-pressure flow nozzle, flow part or mixing chamber and outlet diffuser. One of the main advantages of this device is the lack of moving parts.

As applied to the installation shown in Fig. 2, high-pressure jet is the flow, that will be fed to the compressor. Low-pressure jet is retentate flow from the membrane module. Obviously, the output flow has a pressure value which lies between the values of the high-pressure and low-pressure flows, and its value depends on the flow values and the geometric parameters of the ejector. Therefore, under known values of the high-pressure and low-pressure flow the main task is to calculate the geometric parameters of the ejector: high-pressure nozzle cross-sectional area, cross-sectional area of low-pressure nozzle and the area of the mixing chamber section.

Under calculations we will use a cylindrical mixing chamber profile as cylindrical mixing chamber provides a greater degree of pressure recovery compared with a chamber of other profile. [2] Furthermore cylindrical chamber is easy in manufacturing.

For a description of the output parameters of the flow using determined input parameters is sufficient to use the laws of energy, mass and momentum conservation [3].

\[ G_3 = G_1 + G_2, \]
where $G$ – is the mass flow:

$$G_3 c_p T_3^* \equiv G_1 c_p T_1^* + G_2 c_p T_2^* + Q,$$

where $c$ – specific heat capacity, $T^*$ - temperature, $Q$ – the total amount of heat, which is supplied to the gas in 1 second into the mixing chamber by the way of the heat conductance through the walls of the chamber or allotting in consequence of chemical reactions in the flow;

$$G_3 w_3 + p_3 F_3 \equiv G_1 w_1 + p_1 F_1 + G_2 w_2 + p_2 F_2,$$

where $w$ – enthalpy, $p$ – static pressure, $F$ – flow area.

While providing calculations of the ejector, only the laws of energy, mass and momentum conservation were used, we can not take into account the processes occurring in the flow part of the ejector. From the system of equations all the necessary parameters using determined input parameters according to [3] can be calculated:

$$\frac{T_3^*}{T_1^*} = \frac{1 + n\theta + \frac{\phi}{n+1}}{1 + \frac{1}{\alpha}}$$

where $n = \frac{G_2}{G_1}$ – ejection coefficient, $\theta = \frac{T_2^*}{T_1^*}$, $\phi = \frac{Q}{c_p T_1^* G_1}$ – per-second supplied amount of heat to heat content of per-second ejecting gas discharge ratio;

$$\sqrt{(n+1)(1+n\theta + \phi)} z(\lambda_3) = z(\lambda_1) + n\sqrt{\phi} z(\lambda_2),$$

where $\lambda$ – ratio of the real flow velocity in a section under consideration to the value of the critical velocity, therein: $z(\lambda) = \lambda + \frac{1}{\lambda^2}$;

$$\frac{p_3^*}{p_1^*} = \frac{\sqrt{(n+1)(1+n\theta + \phi)}}{1 + \frac{1}{\alpha}} \frac{q(\lambda_1)}{q(\lambda_3)},$$

where $q$ – gas current density; $\alpha = \frac{p_1^*}{p_2^*}$;

$$n = \frac{1}{\Pi_0 \sqrt{\phi}} \frac{q(\lambda_2)}{q(\lambda_1)},$$

where $\Pi_0 = \frac{p_1^*}{p_2^*}$.

Thus, obtained system consists of the ejecting flow, a mass flowrate $G_1$ and the static pressure $P_1$, stream ejected with mass flow $G_2$ and static pressure $P_2$. The temperature in the whole the system is assumed to be constant. Adiabatic constant is equal to 1,4.

Values $G_1, G_2, T, P_1, P_2$ are considered to be predefined. Quantities $\alpha, \lambda_1, \lambda_2$ remain unknown.

According to [2] for any preselected geometric parameters of the ejector, it is possible to realize a work mode in which ejection coefficient was the highest under given values of the pressure at the outlet of the ejector. This mode is called critical. It occurs when the ejected flow is moving in the narrowing channel bounded by the walls of the mixing chamber and expanding cause of the ejecting flow and accelerates to the acoustical velocity, that this flow can not exceed. This fact determines the maximum of the ejection coefficient.

Critical mode has great practical interest. This ejector operation mode in majority cases, is the most advantageous. In this mode, an ejector under given ejection coefficient value provides the greatest total pressure of the gas mixture and has the greatest ejection coefficient under predetermined value of the total pressure. Also, ejector, designed to work at a critical mode, has the lowest relative size of the mixing chamber under given value $n$.

Calculation of the critical operation modes of the ejector is conducted as follows, using the continuity condition and the fact that ejected gas, driving on the narrowing channel, doesn’t mix with the ejecting flow, an expression [1] can be obtained:
\[ q(\lambda_2) = q(\lambda_2') \left( 1 - \alpha \left[ \frac{q(\lambda_1)}{q(\lambda_1')} - 1 \right] \right) \] (5)

In critical mode \( \lambda_2' = 1 \) and \( q(\lambda_2') = 1 \).

Equation (3) shows that at a constant geometry the increase of reduced velocity \( \lambda_1' > 1 \) leads to decrease of the speed of ejected flow at the inlet of mixing chamber. if \( \lambda_1' \) increases on, that

\[ q(\lambda_1') = \frac{\alpha}{\alpha + 1} q(\lambda_1) = \frac{F_1}{F_3} q(\lambda_1), \]

than \( q(\lambda_2) = 0 \) and \( \lambda_2 = 0 \). Consequently, there is no longer ejection process.

In this case \( F_1 = F_3 \). This phenomenon is called locking the ejector.

Expression (3) can be rewritten as:

\[ q(\lambda_2) = q(\lambda_2') \left( 1 - \frac{1}{\Pi_0 n \sqrt{\Theta}} \frac{q(\lambda_1)}{q(\lambda_1')} \left[ \frac{q(\lambda_1)}{q(\lambda_1')} - 1 \right] \right) \]

or

\[ n \sqrt{\Theta} = \frac{1}{\Pi_0 \left( \frac{1}{q(\lambda_1)} - \frac{1}{q(\lambda_2)} \right)} \]

under calculations values \( \lambda_1 = 1 \), and \( \lambda_2' \leq 1 \) limit the range of possible values \( \lambda_2 \) and \( n \).

As the interaction with the walls surface does not give forces directed along the flow direction, than, gas motion is determined by the gas pressure difference at the boundaries of the motion area.

The equation of kinetic momentum can be written as:

\[ G_1 (w_1 - w_1') + G_2 (w_2 - w_2') = p_1' F_1' + p_2' F_2' - p_1 F_1 - p_2 F_2 \]

Using equation \( Gw + pF = \frac{k+1}{2k} G a_{xp} z(\lambda) \), next expression is obtained

\[ G_1 a_{xp1} [z(\lambda_1') - z(\lambda_1)] = G_2 a_{xp2} [z(\lambda_2) - z(\lambda_2')] \]

or

\[ n \sqrt{\Theta} = \frac{z(\lambda_1') - z(\lambda_1)}{z(\lambda_2) - z(\lambda_2')} \] (3)

Fig. 3 shows the calculated dependence of the output pressure of the ejector according to the ejection coefficient on different values of high-head gas inlet pressure. According to Fig. 3 the pressure at the outlet of the ejector for preselected ejection coefficient \( n \) can be determined, on condition that a critical mode is reached in the ejector.
Figure 3. The dependence of outlet pressure $P_3$ on ejection coefficient $n$, operating in the critical mode, at different values of the supplied flow pressure $P_1$.

On the Fig. 3 is shown, that, as expected, then the ejection coefficient $n$ tends to zero; i.e., in the absence of the recycle flow entering from a membrane module, the pressure at the outlet of the ejector tends tends to pressure $P_1$ of the feed flow. When the ejecting coefficient $n$ increases, the pressure at the outlet of the ejector will decrease. It can be seen that the outlet pressure is reduced slightly, which proves the appliance possibility of ejector in recirculating hybrid membrane-sorption gas separation system.

**Conclusions**

In this paper one of the most perspective systems of air enrichment with oxygen was considered. It is a hybrid membrane system with recycle. Recycle flow is returned to the system via an ejection mixer. This method of flow returning improves the characteristics of the system without requiring additional energy.

In this work system of equations for calculating the parameters of an ejection mixer operating in a critical mode was described. It was shown that pressure in a such mixer decreases slightly versus input pressure. That fact proves the appliance possibility of ejector in recirculating in the hybrid membrane-sorption gas separation system.

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