Air conditioning system based on membrane gas separation technology

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Abstract. Air quality has a significant impact on both health and human performance and productivity. In the urban environment, where there are such polluting factors as road transport, industrial enterprises and dense buildings, air quality issues are most acute. One of the most promising methods of air purification, currently, is the method of membrane gas separation. Installations based on membrane technology have the following advantages: compact and light weight, relatively low operating costs, the ability to work in a wide range of gas pressure, ease of installation and maintenance, quick start and stop, as well as a long service life. In this paper, we consider an air conditioning system based on membrane technology that can control the following parameters of indoor air: oxygen and carbon dioxide concentrations. The system operation was modeled and the efficiency of using the membrane method for removing carbon dioxide generated during human activity from the premises was shown.

1. Introduction

In modern cities, the quality of atmospheric air is getting worse year after year [1], while for productive work and recreation the atmosphere in the room should be favorable. To ensure a microclimate in the residential and working premises, high-quality operation of ventilation systems must be ensured [2]. Thanks to which the air is exchanged with the external atmosphere, carbon dioxide and other harmful substances are removed, oxygen is supplied, humidity and air temperature are regulated. If the ventilation system is not configured correctly, the room may be too humid in summer, and the air in the room may become excessively dry in winter. In addition, the process of direct ventilation or airing leads to significant heat losses, which can reach up to 30% [3]. In closed rooms, the atmosphere may become unsuitable for human activity in a short period of time due to the accumulation of carbon dioxide in it and a decrease in oxygen concentration, which will have an extremely negative impact on human well-being [4]. During respiration, the amount of carbon dioxide increases by 4-5%, and the amount of oxygen decreases by 4-5%, respectively [5]. At the same time, the safety limit for oxygen is considered to be 18% of oxygen, upon reaching which, there are negative consequences of oxygen starvation, up to loss of consciousness and death [6], for carbon dioxide, the concentration limit is considered to be 0.5% [7].

To maintain the microclimate, some manufacturers of climate equipment began to produce air conditioners with built-in membranes to increase the concentration of oxygen in the room [8]. For
example, Panasonic models are able to saturate the air with oxygen to a level of 21% or higher. The air supplied from the street is enriched. This effect is achieved due to the fact that oxygen molecules are able to pass through the membrane 2.5 times faster than nitrogen molecules. The manufacturer stated that such air conditioners can increase the concentration of oxygen to a level of 30%.

Air conditioners with the function of increasing the concentration of oxygen in addition to their obvious advantages have one significant drawback. Such systems not only enrich the air with oxygen, but also with carbon dioxide. The accumulation of carbon dioxide can minimize the effect associated with increased oxygen concentration.

It is possible to solve this problem using membrane technologies [9]. Membranes are widely used for separation of liquid and gas media [10]. Currently, in the field of gas separation, and especially in air separation, membrane technologies are one of the most economically sound and reliable technologies [11, 12]. Energy costs for membrane gas separation consist mainly of energy costs for compressing the gas to the operating pressure in the compressor. And since the membrane modules do not contain moving parts, if the stated technological requirements are met, the service life of these products can be very long [13].

2. Statement of the problem
The use of membrane technologies in air conditioning is designed to reduce the flow rate of ventilation, which will reduce the cost of maintaining the temperature and humidity regime.

Consider a membrane gas separation stage consisting of a single membrane module with one input and two outputs [14]. The gas supplied to the input of the membrane module enters the high-pressure cavity (HPC), passes through the membrane into the low-pressure cavity (LPC) and is discharged through the output of the membrane module, the gas that has not passed through the membrane is output through the second output of the module. To model this stage we will make the following assumptions:

- The process of transfer through the membrane is steady-state and consists of several stages: adsorption of gas mixture components on the membrane surface, activated gas diffusion through the membrane material, desorption to the low-pressure zone;
- Each of the components of the gas mixture is transferred through the membrane independently of the other, i.e. the permeability coefficient of the component of the mixture does not differ from its value for pure gas;
- The permeability coefficients do not depend on the partial pressure of the components, but are determined only by the nature of the gas-membrane system and temperature.

A mathematical model that allows us to determine the partial flows of a shared k-component mixture in a step with boundary conditions is described in [15].

When calculating the membrane module, the following values must be set: flow rate, composition, pressure and temperature of the feed stream; permeability of the gas mixture components.

The system of equations [15] is solved by the fourth-order Runge-Kutta method. At each step, the integration is solved using simple iterations. After integrating the equations [15] over the entire area of the membrane, the retentate flow is calculated using the formula and the permeate flow using the formula. The concentrations of gas mixture components in the retentate flow and permeate flow are calculated. Thus, this model allows you to calculate the fluxes and concentrations of gas mixture components.

For example, figure 1 shows graphs of the dependence of the concentration in the permeate flow on the membrane area. Initial concentration values: $C_{F}^{CO2} = 0.04\%$, $C_{F}^{O2} = 20.96\%$, $C_{F}^{N2} = 0.79\%$, PVTMS membrane.
Figure 1. The dependence of the concentration of air mixture components in the permeate and retentate flow of the membrane module on the membrane area.

From figure 1, it can be seen that carbon dioxide already at 60 m² almost all penetrates into the HPC and exits with the permeate flow. This is due to its high permeability. Oxygen also almost completely penetrates at this area. This fact imposes restrictions on the use of membranes in air conditioning, since the main task when maintaining the gas composition in the room is the separation of carbon dioxide and oxygen. Figure 2 shows that the rate of extraction of carbon dioxide from the stream is higher than oxygen.

Figure 2. Dependence of the extraction degree on the membrane area.

Different rates of penetration of carbon dioxide and oxygen through the membrane are the basis for more efficient removal of carbon dioxide from the room. So unlike a simple exhaust, the membrane allows you to save some of the oxygen in the room, returning the flow of retentate back to the room.

The PVTMS membrane allows for oxygen enrichment of up to 40%. Figure 3 shows the dependence of concentrations of gas mixture components in permeate and retentate flows.
Thus, using the membrane, you can achieve a significant reduction in the flow supplied to the room. However, the permeate stream is enriched not only with oxygen, but also with carbon dioxide. Therefore, with a simultaneous increase in the concentration of oxygen in the room, the concentration of carbon dioxide will also increase.

3. Results and discussion
To solve the problem of carbon dioxide accumulation in the room when using a membrane module for ventilation, you can organize an air supply and pumping system using two membrane modules, shown in figure 1 [16]. The main gas separation elements of this system are two membrane modules 9, 10. The membrane module 9 is designed to enrich the respiratory atmosphere with oxygen. To do this, an oxygen-rich stream that has penetrated through the membrane is fed into the room. The non-penetrated stream is output to the external environment.

The membrane module 10 is used for removing carbon dioxide. To do this, the flow enriched with carbon dioxide is removed to the external environment. Since for most membrane materials, the permeability of carbon dioxide is higher than that of oxygen and nitrogen, the flow enriched in carbon dioxide is the permeate flow of the membrane module.

This system can work under adverse external conditions, when the atmosphere contains undesirable and harmful impurities, the system can work in sequential operation of the membrane modules. In this mode, membranes 9 and 10 work in turn. First, the membrane 9 enriches the internal atmosphere with oxygen, and then the membrane 10 removes carbon dioxide from it. At the same time, a gas stream drawn from the outer atmosphere is fed to the membrane 9, and a gas stream drawn from the inner atmosphere is fed to the membrane 10. Thus, it is possible to prevent the ingress of harmful components that cannot penetrate the non-porous membrane.

Consider the model of a membrane air conditioning system shown in figure 4 [16]. Let's assume that there are 30 people in a room with an area of 15 m$^2$. We also believe that the room is absolutely airtight.
With an average oxygen uptake of 25 l/h per person, 30 people will absorb 750 liters in one hour, which is 8% of the total volume of oxygen in the room at normal oxygen concentration. The average carbon dioxide emission by one person 20 l/h. Thus, 30 people will emit 600 liters of carbon dioxide per hour while in this room with a normal concentration of carbon dioxide its just 18 liters. Thus, for one hour, is established the following concentrations: carbon dioxide – 1.4%, oxygen – 19.4%, nitrogen – 79.2%. In order to reduce the concentration of carbon dioxide to 0.1%, ordinary ventilation will require 1000 m³/h of air.

To determine the feed flow of the membrane module, we find the concentration of carbon dioxide, at which the difference between the flow of carbon dioxide supplied through the first membrane and the output through the second membrane is equal to the amount of carbon dioxide released by people.

For a 100 m² membrane, we obtain the following dependence (figure 5).

To maintain the indoor concentration at 0.05%, a flow of 260 m³/h with normal component concentrations is required. Thus, by choosing the feed stream of the membrane module, we choose the equilibrium concentration of carbon dioxide.

![Figure 4. Membrane air conditioning system [16].](image)

**Figure 4.** Membrane air conditioning system [16].

![Figure 5. The value of the equilibrium concentration of carbon dioxide in the room from the feed flow of the membrane module.](image)

**Figure 5.** The value of the equilibrium concentration of carbon dioxide in the room from the feed flow of the membrane module.

![Figure 6. The value of the equilibrium oxygen concentration in the room from the feed flow of the membrane module.](image)

**Figure 6.** The value of the equilibrium oxygen concentration in the room from the feed flow of the membrane module.
The same is true for oxygen. Figure 6 shows a graph of the dependence of the equilibrium oxygen concentration in the room on the value of the feed flow of the membrane module.

In the case of a flow equal to 260 m$^3$/h, which maintains the concentration of carbon dioxide at the level of 0.05%, it will create an internal atmosphere with an oxygen concentration of 20.35%. Thus, the air flow required to maintain an acceptable indoor atmosphere will decrease by almost 4 times from 1000 m$^3$/h to 260 m$^3$/h.

The development of membrane air conditioning technology in the future will make it possible to create on its basis hybrid membrane-sorption [17, 18] technologies for air conditioning and air preparation, suitable, including for use in production, medical [19] and electronic industries [20].

4. Conclusions
In this paper, a simulation of a room air conditioning system based on membrane gas separation technologies is carried out. The main elements of such an air conditioning system are two membrane modules, one of which serves to remove carbon dioxide from the room, and the second to maintain an acceptable oxygen concentration inside the room. It is shown that the use of membrane technologies in the air conditioning system helps to reduce the consumption of gases supplied and pumped out of the room. In the example considered in this paper, the flow required for ventilation of the room was reduced by four times.

5. Acknowledgements
The work was financially supported by FASIE 13707GU/2018.

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