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Membrane system for regulating oxygen and carbon gas concentration indoors

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Abstract. In the present work, a conditioning system was simulated based on membrane gas separation technology. The considered system is suitable for the simultaneous monitoring of the following indoor air parameters: oxygen concentration, carbon dioxide concentration. The membrane air conditioning system consists of two membrane modules, one to remove carbon dioxide from the room and the second to maintain the required oxygen level in the room. The effectiveness of using the membrane method for the removal of carbon dioxide formed in the process of human life is shown. It is shown that the use of membrane technologies as part of air conditioning systems helps to reduce the gas consumption necessary for normal human life.

1. Introduction

In the modern world, the quality of atmospheric air significantly affects the quality of human life and health, and the environmental situation in modern cities is unfavorable. It is significantly affected by the development of industry and the increase in the number of personal vehicles, leading to an increase in the concentration of harmful substances in the air, which in most cities exceeds the permissible norms [1, 2]. To improve the quality of inhaled air, people buy expensive equipment in the form of air conditioners, air purifiers, humidifiers, etc. Such equipment is most often able to regulate 1-2 air parameters [3].

The main task of air conditioning systems is to maintain a comfortable microclimate in residential and work areas [4]. Creating a comfortable microclimate implies the possibility of maintaining its parameters (temperature, humidity, mobility, gas composition of the air and its pollution) within the required values [5]. Depending on the specific requirements for the room atmosphere and technical conditions, some parameters may be fully controlled, or have limited control range, or not controlled at all.

Indoor air temperature is one of the most important parameters affecting comfort. Air conditioners are used to regulate the air temperature. At the moment, there are a huge number of different air conditioners, but they all work on the General principle of a heat pump [6]. An equally important parameter of indoor air is the concentration of CO₂ in it. At the moment, there is only one household device on the market designed for active removal of CO₂ from a room [7], "UNIQFRESH" by the



Finnish company Alfaintek. The device is an absorption device that absorbs excess carbon dioxide. However, in reality, most often the concentration of carbon dioxide is regulated by airing or ventilation, which leads to significant heat losses [8].

There is climate equipment in the form of air conditioners with built-in membranes to increase the oxygen concentration in the premises [9]. For example, the Panasonic Super Deluxe and Deluxe Slim models are able to saturate the air with oxygen up to 21% or higher. The air supplied from the street is enriched with oxygen. This effect is achieved due to the fact that the permeability of oxygen molecules through the membrane is 2.5 times higher than the permeability of nitrogen molecules. The manufacturer claims that such air conditioners can increase the oxygen concentration 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 an increase in oxygen concentration [10].

A significant factor affecting the human body is the humidity of the air. For a comfortable stay, it is recommended to maintain relative humidity in the range from 40 to 60 %. In contrast to such components as oxygen and carbon dioxide, humidity control, as well as temperature, is not difficult [11, 12]. At the moment, there are a large number of devices that can both dehumidify and humidify the air.

Thus, at present, the development of a system that can simultaneously regulate the concentration of carbon dioxide and oxygen in a room with people is a very urgent task. One of the promising solutions to this problem may be the development of a device using a membrane gas separation module [13]. This article is devoted to the development and modeling of the membrane apparatus for air conditioning and ventilation of premises.

2. Statement of the problem

Membrane technology in the tasks of separation of gas mixtures has found wide application in industry. Due to the simplicity of the design of devices based on it and low operating costs, the membrane technology can also find its application in everyday life, in particular in air conditioning.

Atmospheric air mainly consists of the following mixture of gases: nitrogen, oxygen, argon, carbon dioxide, water vapor. The main components of air that need to be regulated are oxygen and carbon dioxide.

To model the separation process, we assume the following assumptions:

- Gas flow through the membrane is stationary;
- Each of the components of the gas mixture is transferred through the membrane independently of the other, i.e. the permeability coefficient of the mixture component 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 the temperature.

We believe that the gas permeability is high enough and mixing of gas fractions occurs only at the exit from the porous substrate. This means that the module operates in the ideal displacement mode in the HPC (high-pressure cavity) with a perpendicular outflow in the LPC (low-pressure cavity). This type of calculation is performed when the flow rates, the ratio of the length and width of the HPC, the membrane separation factor and the flow division coefficient are high. Transport to HPC and LPC is mainly carried out by convection. Such an organization of flows in which the ideal displacement mode is realized in HPC, and ideal mixing in LPC is possible in flat-frame devices with permeate removal from the center of a plane-parallel double membrane element [14]. This mode is also performed in half-fiber membrane modules, where the input stream is fed into the fiber. Hollow fiber membrane modules are widely used at the present time.

A mathematical model that allows us to determine the partial flows of a shared k-component mixture in a stage with boundary conditions has the form [15]:

$$F = P + R \quad (1)$$

$$FC_F^i = PC_P^i + RC_R^i \quad (2)$$

$$\frac{dz^i}{ds} = -\pi_i p_h (C_q^i - \gamma^* C_l^i) \quad (3)$$

$$C_q^i = \frac{z^i}{q_h}, \quad i = 1 \dots N \quad (4)$$

$$q_h = \sum_{j=1}^N Z_j \quad (5)$$

$$C_l^i = \frac{\pi_i (C_q^i - \gamma^* C_l^i)}{\sum_j \pi_j (C_q^j - \gamma^* C_l^j)} \quad (6)$$

Boundary condition:

$$Z^i(s = 0) = FC_F^i \quad (7)$$

$$Z^i(s = S) = RC_R^i, \quad (8)$$

where F is the feed flow; P is the product flow; R is the retentate flow; C_F^i is concentration of the i component in the feed flow; C_P^i is concentration of the i component in the product flow; C_R^i is concentration of the i component in the retentate flow; π_i - coefficient of permeability of the i component through the membrane, $L/(\text{m}^2 \cdot \text{h} \cdot \text{atm.})$; p_h is the pressure in the cavity high pressure, atm; p_l is the pressure in the cavity of the low pressure, atm; Z^i - partial flow of the gas mixture, L/h ; C_q^i concentration of the i component in flow cavity high pressure; C_l^i - concentration of the i component in the cavity of the low pressure; $\gamma^* = \frac{p_h}{p_l}$; N - number of components of the separated gas mixture.

When calculating the membrane module, you need to know the following values: flow rate, composition, pressure and temperature of the input stream, permeability of the gas mixture components.

In this paper, mathematical modeling of systems for creating an artificial atmosphere is carried out. The essence of this model is that all values that characterize the state of the atmosphere in a closed room are assumed to be average over the entire volume. Thus, the generally distributed atmospheric parameters are concentrated at a single point (point model). This model allows us to effectively solve non-stationary problems of forming an artificial atmosphere of a room.

To study changes in the concentration of gas mixture components in a room, a component-by-component material balance equation is used (9).

$$\frac{dC_i}{d\tau} = \frac{M_i}{V} + \frac{L_1 C_i^{\text{in}}}{V} - \frac{L_2 C_i^{\text{out}}}{V}, \quad (9)$$

where M_i is consumption of the i component of gas coming into the room from domestic sources, L/h ; $L_{1,2}$ is flow rate of air supplied and discharged from the premises, L/h ; C_i is the concentration of the i component air gas mixture to the space, vol. fr.; C_i^{in} is the concentration of the i component in supply air duct, vol. fr.; C_i^{out} is the concentration of the i component in the flow of exhaust from the premises, vol. fr.; V is the amount of air in the room, L . Equation (9) is written for the case when the temperatures of the supply and displaced air are equal.

3. Results and discussion

The mathematical model of the system for creating an artificial atmosphere using membrane modules consists of the equation of the material balance in the room (9) and the system of equations for calculating the membrane module (1 – 8).

Thus, when a room is ventilated by a flow from the external environment that has passed through the membrane, the concentrations of carbon dioxide (figure 1a) and oxygen (figure 1b) in the room increase. The results show that ventilation with an oxygen-rich flow does not solve the problem of maintaining a given composition, but even aggravates it. As the concentration of carbon dioxide increases.

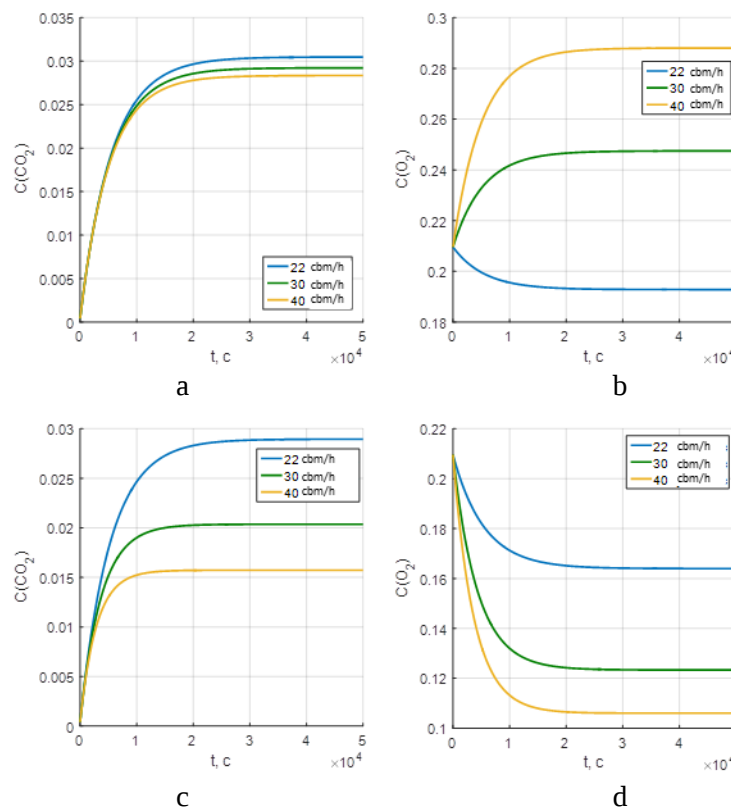


Figure 1. Changes in the concentrations of carbon dioxide (a) and oxygen (b) from the time of supply and changes in the concentrations of carbon dioxide (c) and oxygen (d) from the time when pumping air into the room through the membrane ($20 m^2$) and the presence of 30 people in the room.

To solve the problem of carbon dioxide accumulation, it is advisable to use a second membrane module. The input stream of the second membrane module must come from the room itself. The permeate stream enriched with carbon dioxide must be released into the external environment. For the same reasons as with the first membrane module, the permeate stream will be enriched not only with carbon dioxide, but also with oxygen. As a result of continuous operation of such a membrane module, a decrease in the concentration of both carbon dioxide (figure 1c) and oxygen (figure 1d) will be observed in the room. It can be seen that the concentration of carbon dioxide decreased by an order of magnitude compared to the concentration obtained from the operation of the first membrane module. The oxygen concentration is also reduced, and it falls to a dangerous value for health.

It is obvious that the amount of carbon dioxide passed through the membrane of a given area, according to equation (9), will depend on the input flow of this membrane module and the composition

of the gas mixture. Figure 2 shows a surface showing the amount of carbon dioxide that has passed through the membrane, depending on the input flow of the membrane module and the concentration of carbon dioxide in it. Thus, the essence of the method for regulating the composition of the atmosphere using membrane modules is that when the concentration of carbon dioxide in the room increases, the membrane module of the same area will feed into the room and pump out different amounts of carbon dioxide. The same applies to oxygen. Since its concentration in the room is lower than in the external environment, the oxygen supply through the membrane will be more than pumped out.

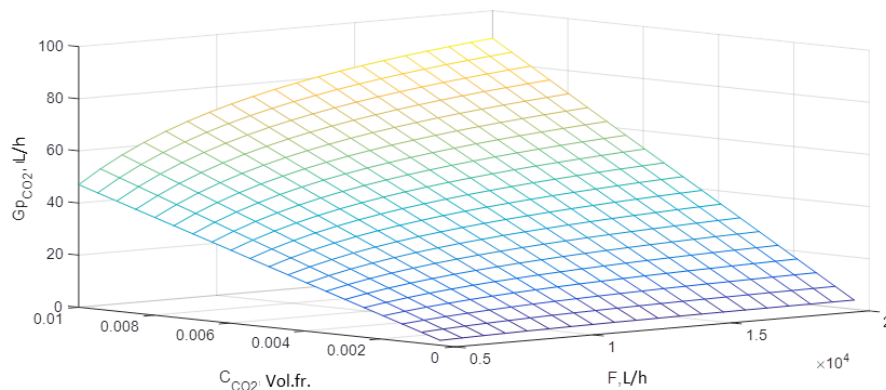


Figure 2. Dependence of the flow of carbon dioxide in the permeate on the inlet flow and the concentration of carbon dioxide in the inlet flow.

Consider as an example a room where air exchange occurs with the external environment through a membrane air conditioning system. Let's assume that there are 30 people in a room with an area of 15 m². 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 L in one hour, which is 8% of the total volume of oxygen in the room at normal oxygen concentration. The average release of carbon dioxide by one person is 20 L/h. Consequently, 30 people will emit 600 L of carbon dioxide per hour, while in such a room with a normal concentration of carbon dioxide, it is only 18 L. Thus, the following concentrations will be established in one hour: carbon dioxide-1.4%, oxygen-19.4%, nitrogen-79.2%.

To determine the input flow of the membrane module, we find the concentration of carbon dioxide, at which the difference between the flows 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. To maintain the indoor concentration at 0.05% using a 20 m² membrane, a flow of 260 m³/h is required. In the case of a flow of 260 m³/h, which maintains the concentration of carbon dioxide at 0.05%, an internal atmosphere with an oxygen concentration of 20.35% will be created. While to maintain the concentration of carbon dioxide at 0.1% requires 1000 m³/h of fresh air.

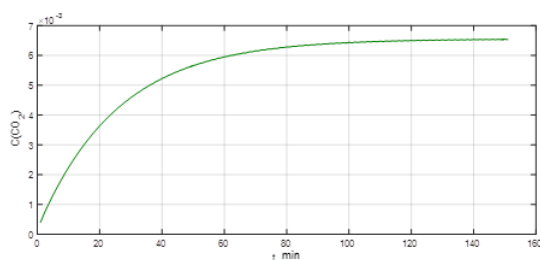


Figure 3. Dependence of the concentration of carbon dioxide in the room on the operating time of the system.

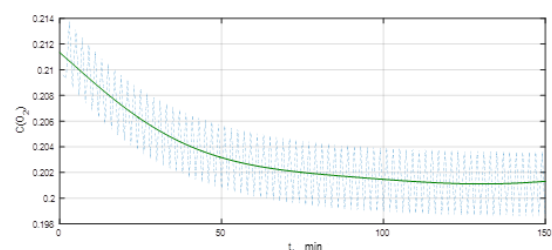


Figure 4. Dependence of the oxygen concentration in the room on the operating time of the system.

Figure 3 shows a graph of changes in the concentration of carbon dioxide over time. The change in oxygen concentration is shown in figure 4. The oxygen concentration decreases slightly, but still remains within acceptable values. Thus, the use of a membrane gas separation system with two membrane modules for ventilation of the room allows you to reduce the flow of supply air by almost 4 times, and, consequently, reduce the cost of heating and regulating the humidity of the room.

In the future, hybrid membrane-sorption technologies can be additionally used to increase the efficiency of carbon dioxide removal and oxygen saturation in the air [16, 17]. On their basis, a device for regulating the atmosphere in the room works [18], in which a three-adsorber sorption unit is used instead of a membrane at the first stage of separation [19].

4. Conclusions

The use of membrane technologies in the system of creating an artificial atmosphere helps to reduce the consumption of gases supplied and pumped out of the room. This reduces the cost of maintaining the temperature and humidity conditions. A single-compressor single-stage membrane system can solve the problem of creating an artificial atmosphere, but the ability to control concentrations lies in a very narrow range. Since it is not possible to increase or decrease the area of the membrane modules during operation, the system can only work effectively for certain parameters specified during design.

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