Optimal Characteristics Calculation of the Air Chemical Regeneration System of Sealed Habitable Objects

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Abstract

Using the developed mathematical model of a flow-type chemisorption reactor and RPK-P regenerative product (nanocrystalline potassium superperoxide attached to the fibers and pore surfaces of the fibrous polymer matrix), a series of computational experiments was carried out to study the effect of the load (the number of people in the shelter, their breathing patterns) and design parameters of a chemisorption reactor for the duration of the protective action of the life support system of people. The problem of calculating the optimal design parameters of a chemical air regeneration system that provides the composition of the atmosphere for oxygen and carbon dioxide in an airtight inhabited facility at a level comfortable for human breathing for a guaranteed time in the presence of uncertain ("inaccurate") information about the respiratory load and heat generation of people located in a sealed facility is formulated. An algorithm for solving it has been developed.

Introduction

In recent decades, active scientific research has been carried out on the creation of promising air regeneration systems for pressurized habitable objects (**PHOs**), while chemical air regeneration systems based on potassium superoxide are most widely used in Russia and abroad [1–12].

Regenerative products are formed in one form or another (granules, tablets, plates, perforated blocks, etc.), depending on operating conditions and design features of the air regeneration system. Thus, the RPK-P regenerative product developed at Roskhimzashita Corporation OJSC [12] is a plate made of a fibrous polymer matrix 3–5 mm thick, on the fibers and pore surfaces of which potassium superoxide crystals are fixed. The plate-shaped product is characterized by a highly developed mass transfer surface and a high porosity of ~ 0.93, which compares favorably with block products with a porosity of ~ 0.5–0.6.

Most of the existing hardware options for chemical air regeneration systems use a combined scheme that provides simultaneous absorption of carbon dioxide

and oxygen evolution [1–11, 13–23]. The extraction of carbon dioxide from the gas-breathing mixture is carried out in a chemisorption reactor due to the chemical interaction (topochemical reaction) of potassium superoxide with CO_2 in the presence of water vapor, which occurs on the solid surface of the chemisorbent with the participation of solids (KO_2 crystals), gases (CO_2, O_2) and liquids (H_2O, KOH) [24].

When setting the task of calculating the optimal characteristics of a chemical air regeneration system, it is necessary to select a target function (optimality criterion), optimization parameters, restrictions on the quality and effectiveness of its functioning, determine the set of acceptable operating modes and develop an algorithm for calculating the optimality criterion and restriction functions using equations of a mathematical dynamics model functioning of the system.

The analysis of literary sources, theoretical and experimental studies showed that it is not possible to accurately determine (assign) a part of the initial data for designing a system of chemical air regeneration.

Thus, in [25–38], the values of a person's respiratory load are used as inaccurate parameters, the values $g_{\text{ind}}^{O_2}$, $g_{\text{ind}}^{CO_2}$ which can change at certain intervals during the functioning of the regeneration system. In [26, 30], inaccurate parameters also include the total heat loss Q_Σ; in [26, 28, 30–32] – air temperature; in [32] – air pressure and humidity. The presence of inaccurate parameters indirectly has a noticeable effect on the quality of the chemical air regeneration system, characterized by known technological and technical and economic indicators, for example, the time of the protective action of the system, the cost of air regeneration, etc. The values of a person's respiratory load for oxygen and carbon dioxide and the total heat released by people and devices of the chemical air regeneration system can unpredictably change depending on the breathing mode (normal, excitement or light load, stressful). The quantitative accounting of a number of these "inaccurate" / random factors is the essence of the optimal design of a system for chemical air regeneration under conditions of partial (incomplete) uncertainty.

The aim of this work is to formulate and study the problem of optimizing the design parameters of a chemisorption reactor, in which a favorable atmosphere is provided for the life of people in the PHO for a guaranteed time of protective action under conditions of uncertainty of "inaccuracy" in the values of the respiratory load (for oxygen and carbon dioxide) and the total heat release of people and equipment in a PHO; development of an algorithm for its solution.

The study of characteristics
of the chemical air regeneration system

The process of chemical regeneration of air is carried out in a flow-through reactor with a regenerative product in the form of plates, which are made of a highly porous glass fiber matrix with KO_2 nanocrystals deposited on its fibers and pore surface. The pressurized habitable object is divided into three zones: I: the zone of exit of the gas-breathing mixture from the reactor; II: the vital area of people hiding in the facility; III: the zone of entry of the gas-breathing mixture into the reactor.

The volume of the regenerative product placed on one side of the plate is determined by the width b, height l and layer thickness γ: $V_{\text{layer}} = b \times l \times \gamma$. The reactor operates in forced ventilation mode.

Let the dynamics of functioning of the designed life support system be described by a vector nonlinear operator [24]:

$$\mathbf{f}(x, d, y, y_t, y_x, a) = 0,$$

where $x = \{x_j, j = \overline{1, m}\} \in X$ is the vector of input coordinates (V_{ob} is the volume of the pressurized habitable object, m; n is the number of people sheltering, people; $c_{CO_2}^{\text{in}}, c_{O_2}^{\text{in}}, c_{H_2O}^{\text{in}}$ the concentration of carbon dioxide, oxygen and water at the inlet of the reactor, mol/m³; g_{O_2}, g_{CO_2} the respiratory load created by a person with oxygen and carbon dioxide, respectively, mol/s; T_g^{in} is temperature of the gas-air mixture at the reactor inlet, K; W_1, W_2 – chemical reaction rates of carbon dioxide absorption and oxygen evolution, mol/(m³·s); Q_Σ is total heat release in a pressurized habitable object, W; G^{in} is the volumetric flow rate of the gas-air mixture provided by the fan at the inlet to the reactor, m³/s); X is a bounded closed set from a number space E^m;

$y(x, t) = \{y_i(x, t), i = \overline{1, n}\} \in Y$ vector-function of the object's output coordinates $c_{CO_2}(z, t), c_{O_2}(z, t),$ $c_{H_2O}(z, t)$ concentration of carbon dioxide, oxygen and water in the gas phase, distributed over the height z of the reactor plates, mol/m³; $\bar{c}_{CO_2}, \bar{c}_{O_2}, \bar{c}_{H_2O}$ concentration of carbon dioxide, oxygen and water in the air of an airtight object, mol/m³; a_{KO_2}, a_{KOH} concentration of substances KO_2 and KOH in a regenerative product, distributed over the height z of the reactor plates, mol/m³; $\bar{T}_g$ is temperatures of the gas-air mixture and chemisorbent, distributed over the height z of the plates with the regenerative product, K; air temperature in a sealed inhabited object, K); y_t, y_x partial derivatives of the output coordinates $y(x, t)$;

$Y = \{y(x, t) : y^- \le y(x, t) \le y^+\}$;

$d = \{d_j, j = \overline{1, r}\} \in D$ vector of design parameters from a closed set $D \in E^r$ (b, l, γ width, height and depth of the layer of the regenerative product on one side of the plate, respectively, m; δ is the distance between the plates, m; N is the number of plates with the regenerative product, pcs.);

$a = \{a_\rho, \rho = \overline{1, r}\}$ is vector of physicochemical parameters from a limited closed set A (kinetic parameters of chemical reactions: k_{01}, k_{02}, m³/mol; E_1, E_2, J/mol); R – universal gas constant, J/mol·K;

$c_{p,\mathrm{g}}, c_{p,\mathrm{x}}$ specific heat of the gas phase and chemisorbent, respectively, J; ρ_g, ρ_x gas density phase and chemisorbent, respectively, kg/m^3; α is heat transfer coefficient, W/m^{2}K; h_1, h_2 thermal effects of chemical reactions, J/mol);

$\mathbf{f}(\cdot) = \{f_i(\cdot), i = \overline{1,n}\}$ nonlinear vector function twice continuously differentiable with respect to arguments x, y and parameters a and d.

Let us consider in more detail the arguments of the operator and their relationship. Part of the components of the x coordinate can be represented in the form where $\overline{x} + \Delta x$ the specified load on the life support system, $\overline{x}$ is an indefinite alternating component, such that $\| \Delta x \| < \| \overline{x} \|$ or even $\| \Delta x \| << \| \overline{x} \|$; the vector parameter a can also be represented in the form $\overline{a} + \Delta a$ where $\overline{a}$ is the "exact" or given component, but Δa depends on the random component Δx, changes in the environmental parameters of the pressurized habitable object (temperature, humidity, pressure, etc.) and sometimes on variations Δd in the design parameters of the reactor $d = \overline{d} + \Delta d$. We will simplistically consider both Δx and $\overline{x}$, and also Δa and $\overline{a}$, Δd and $\overline{d}$ linearly independent, and x and d are independent of each other (although Δd can affect Δa), but Δd exists only at the design stage, and Δx and Δa – throughout the life cycle of the life support system.

For the convenience of the presentation of the material, we combine the undefined parameters $\overline{x} + \Delta x$ and $\overline{a} + \Delta a$ into a vector from a limited numerical set $\Xi = \{\xi_\rho : \xi_\rho^- \leq \xi_\rho \leq \xi_\rho^+\}, \rho = \overline{1, n_\xi}$.

Earlier, we developed a mathematical model [24] that describes the dynamics of changes in the concentrations of O_2, CO_2, H_2O and the temperature of the gas-air mixture at the outlet of a chemisorption reactor and in a pressurized habitable object. Using the developed mathematical model, we carried out a numerical study of the dynamics of the chemisorption process and the effect of the load and structural parameters of the reactor on the time t_pr of the protective action of the air regeneration system in the PHO. The ranges of variation and nominal values of operating and structural parameters of a chemisorption reactor in a numerical study of the dynamics of the life support system are presented in Table 1.

The analysis of the dependence of the protective time t_pr on the number of plates with chemisorbent N (not shown in the figure) (dimensions of one plate: length $l = 0.87$, width $b = 0.58$, thickness of chemisorbent $\varphi = 0.002$ m) for different respiratory load $g_\mathrm{ind}^{CO_2}$ of a group of people (4 people) in a pressurized habitable object, shows that it is almost linear in nature. So, with an increase in the number of plates by 3 times, the time t_pr of the protective action of the air regeneration system in the PHO (with a respiratory load $g_\mathrm{ind}^{CO_2} = 16$ dm^3/s) increases on average by ~ 90 min, and with a constant number of plates $N = 4$ and an increase in respiratory load $g_\mathrm{ind}^{CO_2}$ of 2.4 times the protective action time t_pr decreases by ~ 70 min.

Figures 1a and 1b show graphs of the dependence of the protective action time t_pr on the number of people n in the pressurized habitable object for various values of the number of plates mounted in the reactor (Fig. 1a) and the respiratory load of people (Fig. 1b).

Table 1

Initial data for computational experiments

| Initial data		
Gas-breathing mixture consumption, dm^3/s		27
Volume V_ob PHO, m^3		24
The thickness φ of the regenerative product on one side of the plate, m		0.002
L/b ratio		1.5
The distance γ between the plates, m		0.02
Variables	Ratings	Range
The number of people in the shelter, n, people	4	$2 \leq n \leq 6$
The rate of carbon dioxide release by a person $g_\mathrm{ind}^{CO_2} \times 10^3$, dm^3/s	16	$16 \leq g_\mathrm{ind}^{CO_2} \leq 38$
The surface area of the mass exchange gas-respiratory mixture with chemisorbent, m^2	4.0	$1.65 \leq S \leq 7.70$
The number of plates N regenerative product, pcs	4	$2 \leq N \leq 6$
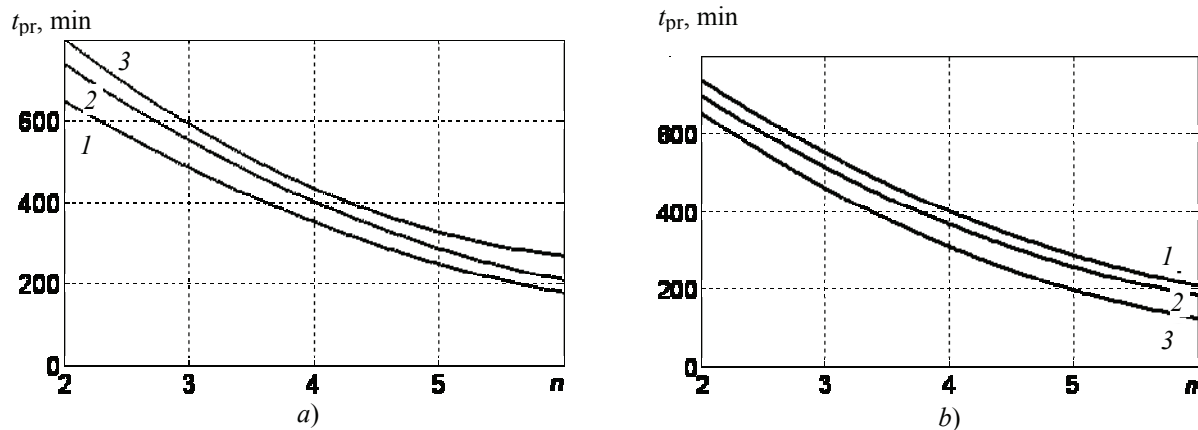
Fig. 1. Dependences of the protective action time t_{pr} at $N=4$ from n:
a: $1 - S = 1.65$; $2 - S = 4$; $3 - S = 7.70$, m^2; b: $1 - g_{ind}^{CO_2} = 16$; $2 - g_{ind}^{CO_2} = 27$; $3 - g_{ind}^{CO_2} = 38 \times 10^{-3}$ dm^3/s

The analysis of the graphs shows that the time of the protective action of the air regeneration system in the PHO non-linearly depends on the number of people in the pressurized object and on their respiratory load. So from the graphs in Fig. 1b, it follows that with an increase in the group of people from 2 to 6 people, the time of the protective action of the air regeneration system in the PHO decreases by ~ 3.35 times.

Comparison of different breathing patterns of people in the PHO (normal $g_{ind}^{CO_2} = 16$ m^3/s, with some excitement or light load $g_{ind}^{CO_2} = 27$ m^3/s, under stressful conditions $g_{ind}^{CO_2} = 38$ m^3/s) shows that the transition from normal breathing to breathing when stressful conditions (with a constant number of people (4 people)) leads to a twofold decrease in the time of the protective action of the air regeneration system of a PHO.

An analysis of the results obtained in the study of the functioning of the chemical air regeneration system made it possible to determine the areas of permissible modes of system functioning, as well as the maximum permissible values of the varied optimization parameters.

Statement of the problem of optimal characteristics calculating of a chemical air regeneration system

The task of calculating the optimal characteristics of a chemical air regeneration system contains the following components: objective function $I(u, \xi)$ (optimality criterion) – given time $t_{pr}(u, \xi)$ of the protective action of the life support system; control variables u is vector of design parameters of the chemisorption reactor (number of plates N with

chemisorbent, height l, width b, thickness φ of chemisorbent and distance γ between the plates); uncertain parameters ξ is the magnitude of a person's respiratory load $g_{ind}^{O_2}$, $g_{ind}^{CO_2}$ and heat Q_Σ (from people and devices), $\xi \in \Xi$, $\Xi = \{\xi_\psi : \xi_\psi^- \le \xi_\psi \le \xi_\psi^+\}$, $\psi = \overline{1, f}_\xi$; communications in the form of equations of the mathematical model [24], which allow calculating the concentrations $\overline{c}_{CO_2}^{(j)}, \overline{c}_{O_2}^{(j)}, \overline{c}_{H_2O}^{(j)}$, $j = 1,2,3$ and temperature $T_{ob}^{(j)}, j = 1, 2, 3$ in a pressurized habitable object, as well as the values of the objective function – the protective action time t_{pr} of the life support system; restrictions on the permissible content in the air of a sealed oxygen object O_2 ($\overline{c}_{O_2}^{(2)}(u, \xi) \ge 19.0\%$ vol.) and carbon dioxide CO_2 ($\overline{c}_{CO_2}^{(2)}(u, \xi) \le 1.0\%$ vol.); as well as, actually, the mathematical formulation of the problem.

In addition to the input and output coordinates, the mathematical model of the dynamics of the process of chemical air regeneration includes indefinite (inaccurately specified) values of a person's respiratory load for oxygen $g_{ind}^{O_2}$ and carbon dioxide $g_{ind}^{CO_2}$, depending on his breathing mode, as well as the total heat Q_Σ (from people and devices) in the PHO. Since it is not possible to determine the true values of these parameters at the design stage of the air regeneration system, in the best case they can be set by intervals of possible values, which also include the true values of these parameters.

In [24], as a criterion for solving the optimization problem, it was proposed to find the minimum protective action time t_{pr} (and, accordingly, the

minimum dimensions of a chemisorption reactor) at which the restrictions on the concentration of oxygen and carbon dioxide in an airtight inhabited object are met. However, in the terms of reference for the development of a chemisorption rector, as a rule, the required time for its protective action is indicated $t_{pr}^{t.t}$.

Therefore, as a criterion for optimizing the design parameters of the air regeneration system under conditions of uncertainty, it is more correct to use the mathematical expectation $M_\xi\{(t_{pr}(u,\xi)-t_{pr}^{t.t})^2\}$, since this indicator gives the average value of the deviation of the estimated time of the protective action $t_{pr}(u,\xi)$ from the given one $t_{pr}^{t.t}$.

We present a refined statement of the problem of calculating the optimal design parameters of a chemisorption reactor under conditions of uncertainty $\xi = \{g_{ind}^{O_2}, g_{ind}^{CO_2}, Q_\Sigma\}$: for given values of the load on the life support system, it is necessary to determine the number and size of the chemisorbent layer $u^* = \{N^*, l^*, b^*, \gamma^*\}$ using a fixed depth φ on one side of the plate, the protective action time t_{pr} of the life support system such that

$$I(u^*) = \min_u M_\xi\left\{(t_{pr}(u,\xi)-t_{pr}^{t.t})^2\right\}, \qquad (1)$$

where $M_\xi\{\}$ the operation of "taking the mathematical expectation"; with connections in the form of equations of a mathematical model of the dynamics of the process of chemisorption [24] and restrictions:

– on the content of oxygen O_2 and carbon dioxide CO_2 in the PHO air:

$$\max_{\xi \in \Xi}\left(g_1(y(u,\xi)) = 19.0 - \bar{c}_{O_2}^{(2)}(u,\xi)\right) \le 0; \qquad (2)$$

$$\max_{\xi \in \Xi}\left(g_2(y(u,\xi)) = \bar{c}_{CO_2}^{(2)}(u,\xi) - 1.0\right) \le 0; \qquad (3)$$

– by the number N and dimensions (height l, width b of the plate and the distance γ between the plates) of the chemisorbent plates

$$N \le N^+, \ l \le l^+, \ b \le b^+, \ \gamma \le \gamma^+. \qquad (4)$$

Where N^+ – the maximum allowable number of plates with chemisorbent; l^+, b^+, γ^+ – the maximum permissible values of the structural parameters of the regenerative cartridge of the chemisorption reactor.

The calculation of the multidimensional integral (1) was carried out according to an approximate formula

$$I(u) = M_\xi(t_{pr}(u,\xi) - t_{pr}^{t.t})^2 \approx \sum_{j \in J_1} \omega_j (t_{pr}(u,\xi^j) - t_{pr}^{t.t})^2,$$

where ω_j is weighting coefficients satisfying the conditions $\omega_j \ge 0, \sum_{j \in J_1} \omega_j = 1;$ $\xi^j (j \in J_1)$ is approximation points uniformly covering the region of uncertainty $\Xi = \{\xi_k^- \le \xi_k \le \xi_k^+\}$.

Calculation of optimal performance of chemical air recovery systems

We show the algorithm for solving problem (1) – (4) under conditions of uncertainty in the parameters of the respiratory load $g_{ind}^{O_2}$, $g_{ind}^{CO_2}$ a group of people, and heat Q_Σ (from people and devices), i.e. $\xi = \{g_{ind}^{O_2}, g_{ind}^{CO_2}, Q_\Sigma\}$.

We introduce a priori the sets of approximation points $P_1 = \{\xi^j : \xi^j \in \Xi, j \in J_1\}$ and "critical" points $P_2 = \{\xi^l : \xi^l \in \Xi, l \in J_2\}$ at which the constraints of problem (2) – (3) can be violated.

Since the constraint functions (2), (3) are convex $g_\lambda(y(u,\xi)), \lambda = 1, 2$, it is advisable to include the corner points $\xi_\psi^-, \xi_\psi^+, k = \overline{1, f}_\xi$ in the initial set of critical points $P_2^{(0)}$ of the uncertainty region $\Xi \subset E^{f_\xi}$. We formulate the auxiliary problem (A): determine the minimum value of the function $I(u)$ and the vectors of design parameters $\hat{u}$ such that

$$I(\hat{u}) = \min_u \sum_{j \in J_1} \omega_j \left(t_{pr}(u,\xi^j) - t_{pr}^{t.t}\right)^2 \qquad (A)$$

with connections in the form of equations of a mathematical model of the dynamics of the chemisorption process [24] and constraints (2) – (4):

– at approximate points

$$g_1(y(u,\xi^j)) = \left(19.0 - \bar{c}_{O_2}^{(2)}(y(u,\xi^j))\right) \le 0,$$

$$g_2(y(u,\xi^j)) = \left(\bar{c}_{CO_2}^{(2)}(y(u,\xi^j)) - 1.0\right) \le 0,$$

$$\xi^j \in P_1, \ j \in J_1;$$

– at critical points

$$g_1(y(u,\xi^l)) = \left(19.0 - \bar{c}_{O_2}^{(2)}(y(u,\xi^l))\right) \le 0,$$

$$g_2(y(u,\xi^l)) = \left(\bar{c}_{CO_2}^{(2)}(y(u,\xi^l)) - 1.0\right) \le 0,$$

$$\xi^l \in P_2, \ l \in J_2.$$

Table 2

Ranges of possible changes in the uncertain parameters

Uncertain parameters	Rated value ξ	Range of possible values of undefined parameters ξ
Respiratory load $g_{ind}^{O_2} \times 10^3$, person in PHO, dm³/s	141	$83 \le g_{ind}^{O_2} \le 200$
The rate of carbon dioxide release by a person $g_{ind}^{CO_2} \times 10^3$, dm³/s	27	$16 \le g_{ind}^{CO_2} \le 38$
Total heat dissipation Q_Σ of a group of people and devices located in the PHO, W	43	$35 \le Q_\Sigma \le 51$

The initial data for solving problem (1) – (4) are given in Table 1.

The ranges of possible changes in the uncertain parameters ξ are presented in Table 2.

Since it is not known with what probability the uncertain parameters can take one or another value from the presented ranges in the Table 2 in a real process of chemical regeneration of air, we assume that the values of the uncertain parameters are equally probable. In this case, the coefficients ω_j will be the same for all approximation points, i.e. $\xi^j \, (j \in J_1)$, $\omega_j = 1/K_{J_1}$, $j = \overline{1, K_{J_1}}, j \in J_1$.

Next, we show an algorithm for solving problem (1) – (4) using the example of calculating the optimal characteristics of a chemical air-regeneration system for GOO. The block diagram of the algorithm is shown in Fig. 2.

Algorithm

Step 1. We set the initial iteration numbers $k = 1$, $v = 1$ and the initial value of the number of plates $N^{(k=1)} = 2$ with a chemisorbent thickness $\varphi = 0.001$ m.

Step 2. We set the set of approximation points $\xi^j, j \in J_1, \xi^j \in P_1$, the initial set of critical points $P_2^{(v-1)} = \{\xi^l : \xi^l \in \Xi, l \in J_2^{(v-1)}\}$, and the initial approximations of the design parameters $u^{(k)}: l^{(k)} = 0.8$, $b^{(k)} = 0.8, \gamma^{(k)} = 0.04$.

Each interval for changing the uncertain parameters ξ (Table 2) consists of five approximation points $\xi^j : j = \overline{1,5}$ $g_{ind}^{O_2} = \{83, 112.25, 141.5, 170.75, 200\}$, $g_{ind}^{CO_2} = \{16, 21.5, 27, 32.5, 38\}$, $Q_\Sigma = \{35, 39, 43, 47, 51\}$. As the initial set of critical points $P_2^{(k)}$ at which the restrictions can be violated, we choose the corner points of the region (interval boundaries) $\Xi: = \{83, 200\}; g_{ind}^{CO_2} = \{16, 38\}, Q_\Sigma = \{35, 51\}$.

Step 3. We find the solution of auxiliary problem (A) by the method of sequential quadratic programming [39, 40].

Next, we check the fulfillment of the conditions:

1) if $I(\hat{u}) > 10^{-3}$ hours and $N^{(k)} < N^+$ then increase the number of plates $N^{(k+1)} = N^{(k)} + 1$ and, assuming $k = k + 1$, $v = 1$, go to step 2;

2) if $I(\hat{u}) > 10^{-3}$ hours and $N^{(k)} = N^+$, then the algorithm finishes its work and the solution of problem (1) – (4) under these restrictions cannot be obtained;

3) if $I(\hat{u}) \le 10^{-3}$ hours and $N^{(k)} \le N^+$ then go to the next step.

Next, we present the results of solving auxiliary problem (A) for iterations $k = 1, 2, 3, 4$:

$$I(\hat{u})^{(k=1)} = 0.493,$$

$$\hat{u}^{(k=1)} = \{N^{(k=1)} = 2, l^{(k=1)} = 0.8, b^{(k=1)} = 0.8, \gamma^{(k=1)} = 0.04\},$$

$$I(\hat{u})^{(k=1)} > 10^{-3};$$

$$I(\hat{u})^{(k=2)} > 10^{-3} = 0.084,$$

$$\hat{u}^{(k=2)} = \{N^{(k=2)} = 3, l^{(k=2)} = 0.8, b^{(k=2)} = 0.8, \gamma^{(k=2)} = 0.04\},$$

$$I(\hat{u})^{(k=2)} > 10^{-3};$$

$$I(\hat{u})^{(k=3)} = 0.012,$$

$$\hat{u}^{(k=3)} = \{N^{(k=3)} = 4, l^{(k=3)} = 0.8, b^{(k=3)} = 0.8, \gamma^{(k=3)} = 0.04\},$$

$$I(\hat{u})^{(k=3)} > 10^{-3};$$

$$I(\hat{u})^{(k=4)} = 9 \cdot 10^{-4},$$

$$\hat{u}^{(k=4)} = \{N^{(k=4)} = 5, l^{(k=4)} = 0.8, b^{(k=4)} = 0.32, \gamma^{(k=4)} = 0.03\},$$
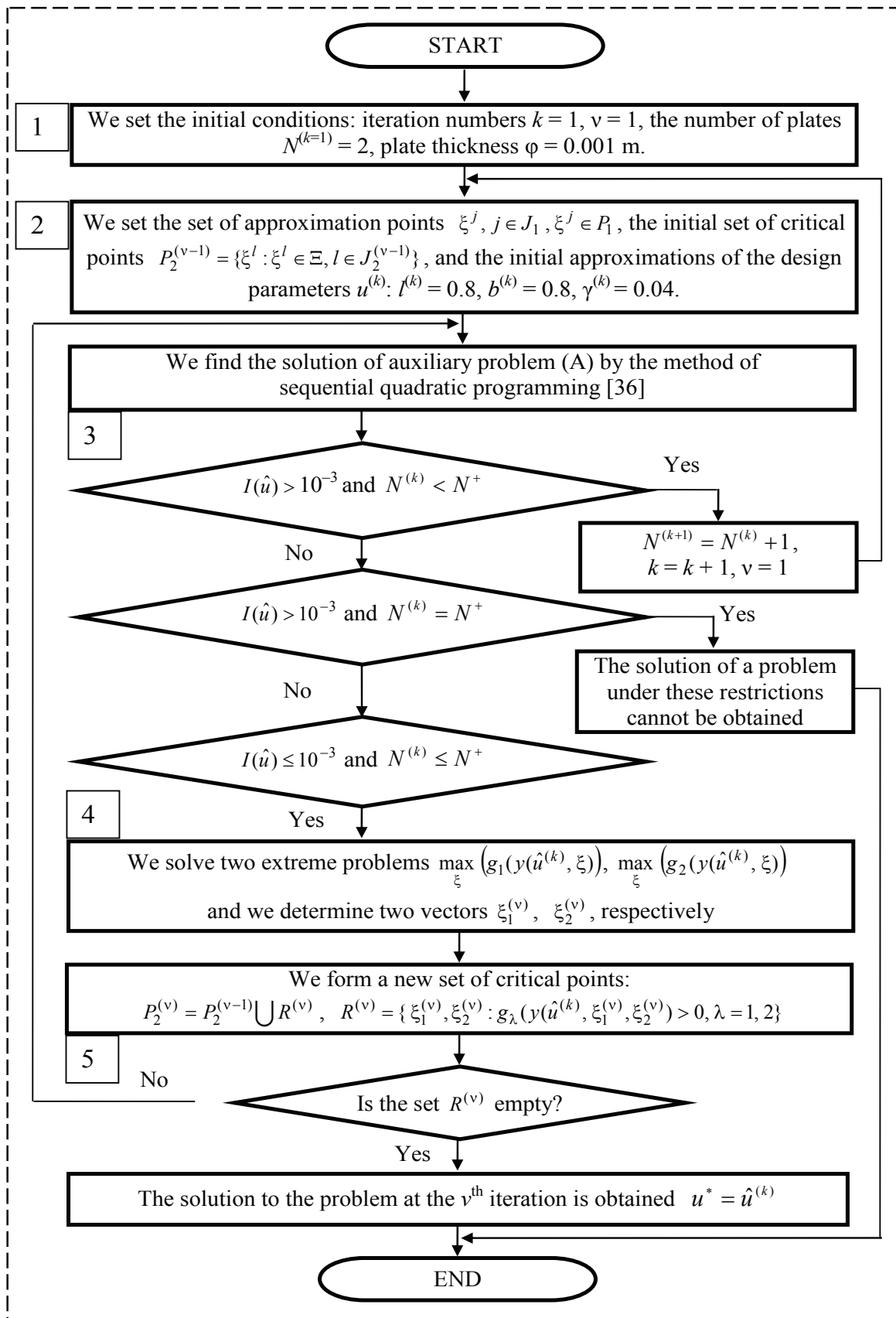
$$I(\hat{u})^{(k=4)} < 10^{-3}.$$

**Fig. 2. The flowchart of the algorithm for calculating the optimal characteristics
of a chemical air regeneration system under uncertainty**

Step 4. To determine new critical points, we solve two extremal problems $\max_{\xi}\left(g_1(y(\hat{u}^{(k)}, \xi)\right)$, $\max_{\xi}\left(g_2(y(\hat{u}^{(k)}, \xi)\right)$ and we determine two vectors $\xi_1^{(v)}$, $\xi_2^{(v)}$, delivering a maximum to the functions $g_1(y(\hat{u}^{(k)}, \xi) = \left(19.0 - \bar{c}_{O_2}^{(2)}(\hat{u}^{(k)}, \xi)\right)$ and $g_2(y(\hat{u}^{(k)}, \xi) = = \left(\bar{c}_{CO_2}^{(2)}(\hat{u}^{(k)}, \xi) - 1.0\right)$, respectively.

We present the results of solving extremal problems for the case $k = 4, v = 1$:

to limit g_1:

$$\xi_1^{(v=1)} = \left\{g_{ind}^{O_2(v=1)} = 200, \ g_{ind}^{CO2(v=1)} = 38, \ Q_{\Sigma}^{(v=1)} = 51\right\};$$

to limit g_2:

$$\xi_2^{(v=1)} = \left\{g_{ind}^{O_2(v=1)} = 200, \ g_{ind}^{CO2(v=1)} = 32, \ Q_{\Sigma}^{(v=1)} = 51\right\}.$$

Step 5. Verify that the constraints of the main problem (1) – (4) are fulfilled at the vth iteration $g_{\lambda}(y(\hat{u}^{(k)}, \xi_1^{(v)}, \xi_2^{(v)}) \le 0, \lambda = 1, 2$ and form a new set of critical points:

$$P_2^{(v)} = P_2^{(v-1)} \bigcup R^{(v)},$$

$$R^{(v)} = \{\ \xi_1^{(v)}, \xi_2^{(v)} : g_{\lambda}(y(\hat{u}^{(k)}, \xi_1^{(v)}, \xi_2^{(v)}) > 0, \lambda = 1, 2\}.$$

If the set $R^{(v)}$ is empty, then the solution to the problem at the vth iteration is obtained $u^* = \hat{u}^{(k)}$ and the algorithm finishes its work; otherwise, accept $v = v + 1$ and go to step 3.

We present the results of checking the fulfillment of the constraints of problem (1) – (4) at the iteration $k = 4, v = 1$:

$$\left(19.0 - \bar{c}_{O_2}^{(2)}(\hat{u}^{(k=4)}, \ \xi_1^{(v=1)})\right) = 19.0 - 20.3 = -1.3;$$

$$\left(\bar{c}_{CO_2}^{(2)}(\hat{u}^{(k=4)}, \xi_1^{(v=1)}) - 1.0\right) = 0.85 - 1.0 = -0.15;$$

$$\left(19.0 - \bar{c}_{O_2}^{(2)}(\hat{u}^{(k=4)}, \xi_2^{(v=1)})\right) = 19.0 - 20.3 = -1.3;$$

$$\left(\bar{c}_{CO_2}^{(2)}(\hat{u}^{(k=4)}, \xi_2^{(v=1)}) - 1.0\right) = 1.0 - 1.0 = 0.$$

Since $g_1(\hat{u}^{(k=4)}, \xi_1^{(v=1)}) \le 0$, $g_1(\hat{u}^{(k=4)}, \xi_2^{(v=1)}) \le 0$, $g_2(\hat{u}^{(k=4)}, \xi_1^{(v=1)}) \le 0$, $g_2(\hat{u}^{(k=4)}, \xi_2^{(v=1)}) \le 0$, then the set $R^{(v=1)}$ is empty and in our case the algorithm finishes its work, the solution to problem (1) – (4) is obtained: $u^* = \hat{u}^{(k=4)}$: number of plates – $N^* = 5$ pcs; plate dimensions – length $l^* = 0.8$ m, width $b^* = 0.32$ m and the distance between the plates $\gamma^* = 0.03$ m.

At the same time, a guaranteed time $t_{pr}^{t.t} = 5$ hours of protective action of the PHO chemical air regeneration system is achieved regardless of the possible change in the uncertain parameters within the specified limits (Table 2).

Conclusions

One of the significant results of this article is the development of a new approach in conditions of uncertainty of the respiratory load of people and the total heat release in an airtight habitable object to the calculation of the optimal characteristics of a chemical air regeneration system that provide the composition of the atmosphere (in terms of oxygen and carbon dioxide) in an airtight habitable object that is comfortable for breathing human level for a given time.

The developed algorithm can be used for the optimal design of new life support systems for people with guaranteed protective action time in the conditions of uncertainty of the initial data for design.

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