

experimental data on performance of such facilities. Unlike the biological methods of wastewater treatment which are sufficiently well studied and widely used in the municipal economy, the methods of biological purification of gaseous emissions are just at a starting stage of their development.

The lack of a general procedure for calculating the biological gas purification facilities as well as insufficient knowledge of the impact of design and operation mode parameters on efficiency of biochemical oxidation determine the urgency and necessity of further studies.

2. Literature review and problem statement

At present, biological methods are actively developed and increasingly used in purification and deodorizing off-gases from food, biochemical and processing industries due to their high efficiency and economic feasibility [1]. Biofilters, biological gas scrubbers and bioreactors with a washed layer are used for biological purification [2]. Most often, the biological method of detoxication of gaseous emissions is used to deodorize and detoxify air in livestock farms [3] and at industrial facilities to purify mixtures of organic substances of relatively low concentration [4, 5].

Microorganisms in biological purification facilities can also efficiently utilize mixtures of organic and inorganic compounds such as ammonia, hydrogen sulfide, butyric acid, and ethyl mercaptan [6]. It was shown that when gases were contacting in the bioreactor for 22–34 seconds, concentration of above pollutants was reduced to 3.5–6.5 g·m⁻³·h⁻¹, respectively.

The regularities governing decomposition of hydrogen sulfide and methyl mercaptan described in the literature show that decomposition of these substances depends on the parameters of operation of bioreactors, for example, thickness of the biofilm, concentration of substances in a liquid phase and the maximum level of biological decomposition [7].

Studies of carbon disulfide decomposition in two irrigated biofilters of various designs have shown that the degree of degradation of impurities is also affected by the biofilter design and creation of conditions of their mixing with a liquid [8]. For example, the maximum degree of purification in biofilters for descending and variable flows was 11.6 and 16.6 g·m⁻³·h⁻¹, respectively.

An experience of biological elimination of dimethylsulfide from emissions (with an efficiency up to 73 %) and methyl mercaptan (with an efficiency up to 87 %) depending on the spatial distribution in the column of the irrigated biofilter was also described in [9].

The use of surfactant-containing biofilters to improve efficiency of purification of gaseous emissions from styrene is recommended in [10].

It was shown in [11] that membrane bioreactors can purify emissions from persistent organic pollutants at a rate of 200 g·m⁻³·h⁻¹.

Application of biological methods for purification of gaseous emissions is particularly effective at low pollutant concentrations and relatively small flows typical, among other things, for methane in sewerage networks. Regularities of soil biofiltering of stinking impurities were described and the optimizing factors of the process such as temperature, medium pH, concentrations of contaminants and substrate are considered in [12].

Several current studies address determining the kinetic parameters and mathematical description of the process of biochemical purification. For example, kinetic characteristics of the destruction process in biofilms of the gas purification facility are considered in [13]. Based on the results of industrial data, kinetic characteristics of hydrogen sulfide elimination are determined in [14]. Mathematical description of the processes occurring in an irrigated biofilter is given in [16, 17] based on the statistical method of estimating experimental data [15] and the concept of mass transfer.

Each known study contains information on parameters of specific devices in certain modes of their operation. No studies on identification of regularities of the process based on analysis of a large number of versions have been found. At the same time, efficient realization of the processes of biological purification requires knowledge of an integral picture of potentials of facilities of various types in wide ranges of variation of design and operation mode parameters. A scientifically substantiated assessment of performance of the systems of biological purification as objects of design and control is necessary. Such an analysis, in view of the multivariance and width of the ranges of parameter variation, can be performed based on numerical experiments.

The previously conducted experimental studies have made it possible to reveal regularities of the biological gas purification process and formulate ideas on the model of microkinetic process [18]. Mathematical models of the processes of biochemical destruction of gaseous soluble [19], insoluble [20] and dissolved in water [21] harmful substances were proposed and a universal model of kinetics of a stationary process of biological purification with a substrate inhibition was presented in [22]. Methods for calculating the design and operation parameters of the systems of biological purification of a corresponding type can be developed based on these models. Besides, it is necessary to develop a procedure for assessing efficiency of facilities of various types.

3. The aim and objectives of the study

The study objective was to identify regularities of the effect of design and operation mode parameters of the biological purification facilities on efficiency of effluent purification from dissolved, soluble and insoluble in water gaseous contaminants.

To achieve this objective, it was necessary to solve the following tasks:

- to develop a procedure for assessing efficiency of the systems of biological elimination of gaseous and dissolved in water harmful substances;
- to conduct numerical experiments based on the proposed procedure;
- to analyze regularities of the effect of design and operation mode parameters on efficiency of bioreactors in destruction of gaseous methane and hydrogen sulfide and a facility of biological elimination of formaldehyde dissolved in water.

4. The procedure for calculating and evaluating efficiency of the biological purification systems

The procedure of efficiency evaluation is based on the previously developed, and realized in mathematical VBA models, non-stationary processes of bio-oxidation of gas-

ous harmful substances soluble [19], insoluble [20] and dissolved in water [21] contaminants. In contrast to mathematical models of processes, the mathematical models of the biological purification systems should consider not only operation mode parameters but also design parameters to be determined. The connection between the design and the operation mode parameters is determined based on obvious geometric and physical relationships. To analyze efficiency of bio destruction, it is important to divide the facility design and operation mode parameters into preset and calculated parameters. In general, the preset parameters form a design solution requiring an assessment of its quality based on of a set of calculated indicators. The calculated indicators can be both design and operation mode indicators.

The following design parameters were adopted for the systems of biological elimination of a gaseous insoluble in water substance:

- g_0 : the rate of inflow of the contaminant into the collector in terms of weight;
- ρ_1 : the concentration of the contaminant at the exit from the bioreactor;
- N : the efficiency of the bioreactor in terms of volume of the gas-air mixture;
- μ_0 : the initial concentration of biomass;
- K_M : the ratio of biomass weight to the weight of the lavesan filament bed;
- K_T : the ratio of the average thickness of the water layer resting on the bed filaments to the filament diameter.

Efficiency of the design solution is evaluated based on analysis and comparison of calculated design parameters.

Let us consider a case of a constant rate g_0 of the pollutant inflow into the collector. The pollutant concentration, ρ_0 , in the collector, that is, at the entry to the bioreactor as an indicator of beginning of the bio oxidation process is calculated by the formula:

$$\rho_0 = \frac{g_0}{N}. \quad (1)$$

The calculated parameters of beginning of the process include also the rate of the pollutant inflow into the collector in terms of volume:

$$Q = \frac{g_0}{d_g}, \quad (2)$$

where d_g is the density of gaseous harmful substance (for example, 715 g/m³ for methane).

The preset concentration value at the exit from the bioreactor makes it possible to determine the rate of release of the harmful substance at the end of the bio oxidation process which is important in assessing efficiency of the facility in general.

The absolute and relative efficiencies of biological purification in the facility is estimated by the rate of elimination of the contaminant from the gas-air mixture, δ_g , and the purification degree, η , respectively. The average specific (that is, per unit of the bioreactor capacity) bio oxidation power, W , and the average specific rate of bio oxidation, V , were taken as the calculated design parameters for estimating the rate of bio oxidation in the facility.

In the case of cyclic variation of the rate of the pollutant inflow into the collector, its smaller and larger values, g'_0 and g_0 , are preset. Besides, additional preset parameters appear:

the collector capacity, K ; durations of the periods of lower and higher pollutant inflow rates, T' and T . The stable concentrations of harmful substance in the collector for respective periods (ρ'_{0y} and ρ_{0y}) are determined by the procedure described in [19].

The design values W and V are calculated from the average in a cycle rate of the pollutant inflow into the collector, g_{0c} , and the rate of its release, g_{1c} , at the completion of the biological purification process. The maximum and minimum in a cycle rates of the pollutant release at the bioreactor exit are:

$$g'_1 = \rho'_1 N, \quad (3)$$

$$g_1 = \rho_1 N. \quad (4)$$

The maximum and minimum in cycle concentrations, ρ_1 and ρ'_1 , at the completion of the biological purification process are determined by the process model [20] for the initial values equated to ρ_{0y} and ρ'_{0y} . Variation of ρ'_{1t} and ρ_{1t} concentrations of the harmful substance in time was also taken linear.

If zero concentration is not achieved, $\delta T' = \delta T = 0$ is taken and then $g'_c = g_c = g_{1c}$. When zero concentration is achieved, $g_1 = 0$, and $\delta T'$ and δT are calculated from this condition using correlations of the collector-bioreactor system model [20].

What concerns water-soluble contaminants, the process is non-stationary: bio oxidation and continuous additional inflow of the harmful substance take place simultaneously in the water moving on the filter bed. This character of the process predetermines the possibility of achieving the state of dynamic equilibrium with a constant equilibrium concentration, ρ_p , before the exit of water from the bioreactor [20]. The non-zero concentration of the contaminant in the discharged water is the principal characteristic of this biological purification process.

For the system of biological elimination of gaseous water-dissolved substances, the following design parameters were taken:

- g_0 : the rate of the contaminant inflow in the collector in terms of weight;
- R : the volume of the bioreactor space;
- r : the rate of irrigation of the filter bed with water;
- N : the efficiency of the bioreactor in terms of the gas-air mixture volume;
- μ_0 : the initial biomass concentration;
- K_M : the ratio of biomass to the mass of the lavesan filament bed;
- K_T : the ratio of the average thickness of the water layer held on the filter bed filaments to the filaments diameter.

Let us consider the case of a constant rate of the pollutant inflow to the collector, g_0 . Then the pollutant concentration in the collector, that is, in the air at the bioreactor entry is:

$$\rho_0^* = \frac{g_0}{N}. \quad (5)$$

The calculated parameters describing the conditions at the bioreactor entry include also the rate of the contaminant inflow of to the collector in terms of volume, Q , calculated by formula (2).

In calculations for hydrogen sulfide, sulfur dioxide and ammonia, their densities, d_g , were assumed to be equal to 1,539, 2,927 and 771.4 g/m³, respectively.

The contaminant concentration in water at the exit from the bioreactor, ρ_1 , is the main calculated design parameter characterizing the biological purification process proper. The procedure of its calculation is described in more detail in [19]. Knowledge of the final concentration makes it possible to determine the rate of release of the harmful substance at the final stage of the bio oxidation process:

$$g_1 = \rho_1 r. \tag{6}$$

This calculated parameter is also important when evaluating efficiency of the facility in general.

The absolute and relative efficiencies of biological purification in the facility is estimated according to the pollutant elimination rate, δg , and the degree of purification, η . The average specific bio oxidation power of the bioreactor, W , and the average specific rate of biological oxidation, V , were taken as the calculated design parameters of bio oxidation rate in the facility.

An indicative estimate of the level of absorption required for the process is determined by the parameter:

$$K_p = \frac{Q}{r}, \tag{7}$$

where K_p is the required solubility of the gaseous harmful substance in water, $\frac{m^3_{\text{gas}}}{m^3_{\text{water}}}$.

In the calculations of numerical experiments, a cylindrical form of the bioreactor was taken.

The process of bio destruction of formaldehyde dissolved in water is nonstationary: simultaneous bio oxidation, continuous additional inflow of a harmful substance and a growth of the volume in which biochemical reaction occur. This character of the process predetermines the possibility of achieving the state of dynamic equilibrium with a constant equilibrium concentration, ρ_p , and velocity, V_{pp} , determined from formula:

$$V_{pp} = a \rho_p^b e^{-c \rho_p}. \tag{8}$$

Equilibrium concentration is achieved in the case when the rate of contaminant inflow is equal to the sum of the bio destruction rate and the rate necessary to compensate for the increase in the solution volume in the vessel at a constant ρ_p concentration.

Let us call the weight of the harmful substance entering the solution per unit time and per unit of biomass a specific rate of the pollutant inflow to the vessel, V_g :

$$V_g = \frac{\rho_g r}{m_b}. \tag{9}$$

Then the value of equilibrium concentration is determined by the solution of the nonlinear equation:

$$V_{pp} = V_g \left(1 - \frac{\rho_p}{\rho_g} \right). \tag{10}$$

A diagram of equilibrium states of the process of anaerobic biological elimination of formaldehyde from water in which it is dissolved calculated from the correlation (10) is shown in Fig. 1.

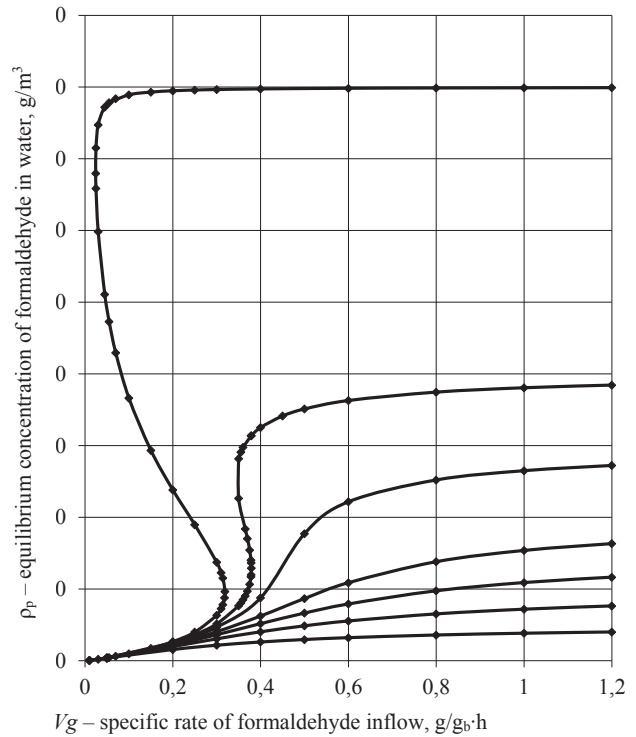


Fig. 1. The diagram of equilibrium states in a nonstationary process characterized by simultaneous destruction of formaldehyde and filling of the vessel with its solution in water: concentration of formaldehyde in the incoming solution for the curves from top to bottom, respectively, $\rho_g=8,000; 4,000; 3,000; 2,000; 1,500; 1,000; 500 \text{ g/m}^3$

Analysis of the data in Fig. 1 indicates presence of a zone of realization of an active non-stationary process of biological purification. This zone is characterized by achievement of equilibrium concentrations in the vessel, ρ_p , which are substantially lower than the concentration of the incoming solution, ρ_g . The active nonstationary process occurs in the region of simultaneous fulfillment of the correlations: $\rho_g < 3588.7 \text{ g/m}^3$ and $V_g < 0.4044 \text{ g/g}_b \text{ h}$. Transition to the passive mode characterized by an approximate equality of ρ_g and ρ_p is possible as a result of a sharp increase in the rate of the solution inflow, r , at a constant concentration of formaldehyde in it. A sharp increase in concentration of the aqueous solution, ρ_g , at a constant specific rate of pollutant inflow, V_g will result in a transition to a mode with a larger equilibrium concentration, ρ_p . The found regularities should be taken into account when choosing the design parameters of the purification facility.

The active mode is preferred when a significant effect of biological purification is already observed at the vessel filling stage.

The following design parameters were adopted for the facility of biochemical elimination of harmful substances dissolved in water:

- g : the rate of the contaminant inflow to the vessel in terms of weight;
- r : the rate of inflow of an aqueous solution of a harmful substance to the vessel in terms of volume;
- m_b : the amount of biomass;
- R_0 : the initial volume of the vessel filling;
- ρ_0 : the initial concentration of the contaminant in the vessel;

– t_j : the duration of the nonstationary stage of the vessel filling;

– ρ_k : the concentration of the harmful substance in the vessel at the time of completion of the stationary stage of the biological purification process.

Here and in what follows, the index shows the number of the process stage and refers to its completion. The equality $j=k$ corresponds to completion of the process in general.

The main calculated design parameter related to the biological purification process proper is the average in term of volume contaminant concentration in the vessel, ρ_j , at a completion of each non-stationary stage of the process. The procedure of its calculation is described in more detail in [21]. The value of the contaminant concentration at a completion of the j -th stage is the initial condition necessary for calculating either the subsequent nonstationary stage with other parameters or the final stationary process. Completion of each stage of the process is characterized by its volume of the vessel filling

$$R_j = R_0 + \sum r_j t_j \quad (11)$$

and concentration of biomass

$$\mu_i = \frac{m_b}{R_j}. \quad (12)$$

During the period of the vessel filling the at each stage, weight of the harmful substance entering it is

$$\delta G_{r,j} = g_j t_j. \quad (13)$$

The total weight of the harmful substance that has entered the vessel during the whole process of biological purification is

$$G_r = \rho_0 \cdot R_0 + \sum \delta G_{r,j}. \quad (14)$$

Important calculated parameters that jointly determine feasibility of an active or passive nonstationary process include the specific rate of the pollutant inflow

$$V_{gj} = \frac{g_j}{m_b} \quad (15)$$

and its concentration in the incoming solution

$$\rho_{gj} = \frac{g_j}{r_j}. \quad (16)$$

The vessel capacity, R , necessary for realization of the designed biological purification process belongs to the parameters of the purification facility and is determined by formula (11) at $j=k-1$. At the same time, weight of the harmful substance in the vessel at the moment of completion of the entire biological purification process is:

$$G = \rho_k \cdot R. \quad (17)$$

The absolute and relative efficiencies of biological purification in the facility are assessed by the eliminated contaminant weight, δG_V , and the degree of purification, η , respectively. It is obvious that the total duration of the process is:

$$t_d = \sum t_i. \quad (18)$$

The following was taken as the calculated design parameters of bio oxidation rate in the purification facility: efficiency in terms of volume of the processed aqueous solution, N , the average specific bio oxidative power of the facility in terms of the vessel capacity, W , and the average specific bio oxidation rate, V .

5. Results obtained in the calculation of efficiency of the design solutions for the biological purification systems

5.1. Effect of the design and operation mode parameters of the reactor on efficiency of the methane bio oxidation process

The effect of the design and operation mode parameters on efficiency of the biological purification systems was assessed by varying them with respect to some basic design solution. Two values of the studied parameter were preset greater and smaller than its base value.

The calculation for methane was performed for the following basic values: $g_0=100$ g/h; $R_g=3$ m³; $N=50$ m³/h; $\mu_0=750$ g_b/m³; $K_M=0.06$; $K_T=0.1$. The value of K_M was preset equal to that realized in the experiment and K_T as a potential real value. As it follows from the calculation results (Table 1), the total bioreactor capacity, R , increases by less than two percent at the indicated values of K_M and K_T . The latter indicates a low bed density and, consequently, low pressure losses of the injected gas-air mixture.

An increase in the rate of methane inflow to the collector (versions 1 and 2 in Table 1) results in simultaneous increase in its concentration both at the entry to the bioreactor, ρ_0 , and at its exit, ρ_1 .

This results in a decrease in the purification rate, η , and a growth of the average specific bio oxidative power, W . A fourfold growth of the rate of the pollutant inflow results in a reduction of the degree of purification from 94 % to 65 %.

The increase in efficiency of the facility in terms of volume of the gas-air mixture, N , (versions 3 and 4 in Table 1) results in a decrease in methane concentration at the entry to the bioreactor, ρ_0 , and an increase at its exit, ρ_1 . The latter circumstance is associated with a shorter duration of the biological purification process, t_n . In this case, both the purification degree, η , and the average specific bio oxidative power, W , decrease. The change in the degree of purification is approximately the same as in variation of the methane inflow rate (from 96 % to 62 %).

Naturally, an increase in the initial concentration of biomass μ_0 (versions 5 and 6 in Table 1) does not affect methane concentration in the collector, ρ_0 , but sharply decreases its concentration at the exit from the bioreactor, ρ_1 . In this case, there is a growth of the degree of purification, η , and the average specific bio oxidative power, W . A twofold increase in concentration of biomass results in a decrease in methane concentration from 0.1 to 0.02 %.

It is obvious that an increase in the volume of the bioreactor space occupied by the gas-air mixture, R_g , will, with other things being equal, lead to an increase in duration of the biological purification process, t_n , a decrease in methane concentration at the exit, ρ_1 , and an increase in purification degree, η .

Table 2 presents the results of calculation of the daily cycle of variation of the rate of methane inflow into collectors of various capacities. As it follows from data of Table 2, a change in the collector capacity up to 1,000 m³ significantly effects on the purification rate, η , and the average specific bio oxidative power, W . The further increase in the collector capacity does not lead to a noticeable change in the purification facility parameters.

The version 6 of Table 1 for a constant rate of methane inflow to the collector is the basic version for the calculations given in Table 2. Comparison of the results of calculations of the purification degree η and the average specific bio oxidative power, W , (version 6 in Table 1, and version 3 in Table 2,) shows their practical coincidence.

Thus, the characteristic regularity of the biological purification process proper consists in leveling of the difference between the maximum, ρ_1 , and the minimum, ρ'_1 , concen-

trations of methane at the bioreactor exit during growth of the collector capacity. Based on the foregoing, it can be asserted that growth of the collector capacity results in a higher inertia of the entire “collector-bioreactor” system. Sharp changes in the rate of pollutant inflow to the collector under conditions of their cyclic repeatability do not lead to significant changes in the facility design parameters and the biological purification process proper at a rather large collector capacity.

The effect of cyclic variations of input parameters on the parameters at the exit from the “collector-bioreactor” system is significant at relatively small collector capacities. The necessity of taking into account variation of the rate of a harmful substance inflow to the collector or the acceptance of the condition of its constancy is determined based on the analysis of concrete design conditions and is an element of the design solution.

Table 1

Versions of the process of methane bio oxidation at a constant rate of its inflow to the collector

Indicator meaning	Calculation version					
	1	2	3	4	5	6
Design parameters of the facility						
D : the bioreactor diameter, m	1	1	1	1	1	1
H : the bioreactor height, m	3.869	3.87	3.87	3.87	3.853	3.887
R : the bioreactor capacity, m ³	3.039	3.039	3.039	3.039	3.026	3.053
R_b : the bed volume, m ³	0.02713	0.02714	0.02714	0.02714	0.01801	0.03634
m_b : the bed weight, g	37,500	37,502	37,502	37,504	25,002	50,004
m_b : the biomass amount, g	2,250	2,250.1	2,250.1	2,250.3	1,500.1	3,000.2
δg : methane elimination rate, g/h	46.95	129.5	95.69	62.49	61.03	92.85
η : the purification degree, %	93.89	64.76	95.69	62.49	61.03	9.85
N : efficiency in terms of the gas-air mixture, m ³ /h	50	50	25	100	50	50
W : average specific power of bio oxidation, g/m ³ ·h	15.45	42.61	31.48	20.56	20.17	30.42
V : average specific rate of oxidation, g/g _b ·h	0.02086	0.05756	0.04252	0.02777	0.04068	0.03095
Design parameters of the process of biological purification						
Q : the rate of methane inflow to the collector in terms of volume, m ³ /h	0.07	0.2798	0.1399	0.1399	0.1399	0.1399
g_o : the rate of methane inflow to the collector in terms of weight, g/h	50	200	100	100	100	100
ρ_o : methane concentration at the bioreactor entry, g/m ³	1	4	4	1	2	2
ρ_1 : methane concentration at the bioreactor exit, g/m ³	0.0611	1.4097	0.1726	0.3751	0.7795	0.143
g_1 : the rate of methane release at the bioreactor exit, g/h	3.055	70.49	4.315	37.51	38.98	7.15
t_d : duration of the process of biological purification, h	0.06	0.06	0.12	0.03	0.06	0.06
μ_o : initial biomass concentration, g _b /m ³	750	750	750	750	500	1,000

Versions of the process of bio oxidation of methane at the cyclic rate of its inflow to the collector

Indicator meaning	Calculation version		
	1	2	3
Design parameters of the facility			
K : the collector capacity, m^3	100	1,000	10,000
D : the bioreactor diameter, m	1	1	1
H : the bioreactor height, m	3.887	3.886	3.886
R : the bioreactor capacity, m^3	3.053	3.052	3.052
R_b : the bed volume, m^3	0.03634	0.03634	0.03634
m_b : the bed weight, g	50,878.1	50,878.1	50,878.1
m_b : the biomass amount, g	3,052.7	3,052.4	3,052.4
δg_o : the average rate of methane elimination, g/h	79.28	91.95	92.84
η : the purification degree, %	79.28	91.95	92.84
N : efficiency in terms of the gas-air mixture volume, m^3/h	50	50	50
W : average bio oxidative power, $g/m^3 \cdot h$	25.97	30.12	30.42
V : average specific rate of oxidation, $g/g_b \cdot h$	0.02597	0.03012	0.03042
Design parameters of the process of biological purification			
The period of lower methane inflow rate			
Q : the rate of methane inflow to the collector in terms of volume, m^3/h	0.06996	0.06996	0.06996
g'_0 : the rate of methane inflow to the collector in terms of weight, g/h	50	50	50
ρ'_{1y} : stable concentration of methane at the bioreactor entry, g/m^3	1.001	1.636	1.96
T : the period duration, h	16	16	16
ρ'_1 : concentration of methane at the exit from bioreactor (minimum in the cycle), g/m^3	0.00097	0.06696	0.1336
g'_1 : rate of methane release at the bioreactor exit (average in a period), g/h	20.72	8.049	7.16
Period of the higher rate of methane inflow			
Q : the rate of methane inflow to the collector, m^3/h	0.2798	0.2798	0.2798
g_o : the rate of methane inflow to the collector in terms of weight, g/h	200	200	200
ρ_{0y} : stable methane concentration at the bioreactor entry, g/m^3	3.945	2.415	2.04
T : the period duration, h	8	8	8
ρ_1 : methane concentration at the bioreactor exit (maximum in a cycle), g/m^3	0.8278	0.255	0.1528
g_1 : average in a period rate of methane release at the bioreactor exit, g/h	20.72	8.049	7.16
T_c : the cycle duration, h	24	24	24
g_{1c} : average in a cycle rate of methane release at the bioreactor exit, g/h	20.72	8.049	7.16
t_d : duration of the process of biological purification, h	0.06	0.06	0.06
μ_o : initial concentration of biomass, g_b/m^3	1,000	1,000	1,000

5. 2. The influence of design and operation mode parameters of biological purification systems on efficiency of the process of hydrogen sulfide elimination

Tables 3, 4 show the results of calculations for hydrogen sulphide at the following basic values: $g_0=5$ g/h; $R=1$ m³; $r=0.1$ m³/h; $N=50$ m³/h; $\mu_0=1000$ g_b/m³; $K_M=0.1$; $R_T=0.1$. The value of R_T was preset as a potential real value and K_M is as close to the value used in the experiment.

An increase in the rate of hydrogen sulfide inflow to the collector, g_0 , (versions 1 and 2 in Table 3) simultaneously resulted in an increase in its concentration in air at the entry to the bioreactor, ρ_0^* , and in water at the exit from it, ρ_1 . In this case, there was a slight decrease in the degree of purification, η , and an increase in the specific bio oxidative power, W . A fourfold increase in the rate of pollutant entrance has resulted in a reduction of the degree of purification from 98 % to 95 %.

The increase in the facility efficiency in terms of the air-gas mixture volume, N , (versions 3 and 4 in Table 3) caused a decrease in concentration of hydrogen sulphide in the collector, ρ_0^* . The rest of parameters have remained unchanged.

An increase in the initial concentration of biomass, μ_0 , (versions 5 and 6 in Table 3) did not affect concentration of hydrogen sulphide in the collector but significantly reduced its concentration in water at the exit from the bioreactor, ρ_1 . As a result, some increase in both the purification degree, η , and the specific bio-oxidative power, W , was observed. An increase in initial concentration of biomass by a factor of 1.7 caused a decrease in concentration of hydrogen sulfide in water from 2.5 to 1.1 g/m³.

Growth of K_M coefficient (versions 1 and 2 in Table 4) increased weight of the bed, m_3 , and the time of water movement on it, t_p . The parameters characterizing the efficiency and rate of the biological purification process did not change.

Table 3

Versions of realization of the process of bio oxidation of hydrogen sulphide at a constant rate of its inflow to the collector

Indicator meaning	Calculation version					
	1	2	3	4	5	6
Design parameters of the purification unit						
D : the bioreactor diameter, m	1	1	1	1	1	1
H : the bioreactor height, m	1.273	1.273	1.273	1.273	1.273	1.273
R : the bioreactor capacity, m ³	1	1	1	1	1	1
R_b : the bed volume, m ³	0.007143	0.007143	0.007143	0.007143	0.005357	0.008929
m_b : the bed weight, g	10,000	10,000	10,000	10,000	7,500	12,500
m_b : the biomass amount, g	1,000	1,000	1,000	1,000	750	1,250
δg : the rate of hydrogen sulfate elimination, g/h	2.447	9.532	4.843	4.843	4.754	4.889
η : the degree of purification, %	97.86	95.32	96.87	96.87	95.08	97.79
N : the efficiency in terms of the air-gas mixture, m ³ /h	50	50	25	100	50	50
W : the average specific bio oxidative power, g/m ³ h	2.447	9.532	4.843	4.843	4.754	4.889
V : average specific oxidation rate g/g _b h	0.002447	0.009532	0.004843	0.004843	0.006339	0.003911
Design parameters of the biological purification process						
Q : the rate of inflow of hydrogen sulfate to the collector in terms of volume, m ³ /h	0.001624	0.006498	0.003249	0.003249	0.003249	0.003249
g_0 : the rate of inflow of hydrogen sulfate to the collector in terms of weight, g/h	2.5	10	5	5	5	5
ρ_0^* : hydrogen sulfate concentration at the bioreactor entry, g/m ³	0.05	0.2	0.2	0.05	0.1	0.1
ρ_1 : hydrogen sulfate concentration at the bioreactor exit, g/m ³	0.535	4.682	1.567	1.567	2.459	1.107
g_1 : the rate of hydrogen sulfate release at the bioreactor exit, g/h	0.0535	0.4682	0.1567	0.1567	0.2459	0.1107
t_d : duration of the biological purification process, h	0.03143	0.03143	0.03143	0.03143	0.02357	0.03929
μ_0 : initial concentration of biomass, g _b /m ³	1,000	1,000	1,000	1,000	750	1,250
R_b : calculated volume of water on the bed, m ³	0.003143	0.003143	0.003143	0.003143	0.002357	0.003929
r : the rate of the bed irrigation with water, m ³ /h	0.1	0.1	0.1	0.1	0.1	0.1
K_s : the required solubility of gas in water, m ³ _{gas} /m ³ _{water}	0.01624	0.06498	0.03249	0.03249	0.03249	0.03249

Versions of the process of bio oxidation of hydrogen sulphide at a constant rate of its inflow to the collector

Indicator meaning	Calculation version					
	1	2	3	4	5	6
Design parameters of the purification facility						
D : the bioreactor diameter, m	1	1	1	1	1	1
H : the bioreactor height, m	1.273	1.273	1.273	1.273	0.637	2.546
R : the bioreactor capacity, m ³	1	1	1	1	0.5	2
R_b : the bed volume, m ³	0.01429	0.00357	0.00714	0.00714	0.00357	0.01429
m_b : the bed weight, g	20,000	5,000	10,000	10,000	5,000	20,000
m_b : biomass amount, g	1,000	1,000	1,000	1000	500	2,000
δg : the rate hydrogen sulfate elimination, g/h	4.843	4.843	4.922	4.687	4.532	4.947
η : the degree of purification, %	96.87	96.87	98.43	93.73	90.64	98.93
N : efficiency in terms of the air-gas mixture volume, m ³ /h	50	50	50	50	50	50
W : the average specific bio oxidative power, g/m ³ h	4.843	4.843	4.922	4.687	9.064	2.473
V : the average specific rate of oxidation, g/g _b h	0.004843	0.004843	0.004922	0.004687	0.009064	0.002473
Design parameters of the biological purification system						
Q : the rate of hydrogen sulfate inflow to the collector in terms of volume, m ³ /h	0.003249	0.003249	0.003249	0.003249	0.003249	0.003249
g_o : the rate of hydrogen sulfate inflow to the collector in terms of weight, g/h	5	5	5	5	5	5
ρ_0^* : hydrogen sulfate concentration at the bioreactor entry, g/m ³	0.006498	0.006498	0.006498	0.006498	0.006498	0.006498
ρ_1 : hydrogen sulfate concentration at the bioreactor exit, g/m ³	1.567	1.567	1.567	1.567	4.682	0.535
g_1 : intensity of hydrogen sulfate release at the bioreactor exit, g/h	0.1567	0.1567	0.0784	0.3134	0.4682	0.0535
t_d : duration of the biological purification process, h	0.06286	0.01571	0.06286	0.01571	0.01571	0.06286
μ_0 : initial concentration of biomass, g _b /m ³	1,000	1,000	1,000	1,000	1,000	1,000
R_b : the calculated volume of water on the bed, m ³	0.006286	0.001571	0.003143	0.003143	0.001571	0.006286
r : the rate of the bed irrigation with water, m ³ /h	0.1	0.1	0.05	0.2	0.1	0.1
K_s : the required gas solubility in water, m ³ _{gas} /m ³ _{water}	0.03249	0.03249	0.06498	0.01624	0.03249	0.03249

An increase in the rate of irrigating the bed with water, r , (versions 3 and 4 in Table 4) resulted in an increase in the rate of hydrogen sulfide release at the exit from the bioreactor, g_1 and, as a consequence, a decrease in the specific bio oxidation power, W , and the purification degree, η , (from 98.4 % to 93.7 %).

The increase in the bioreactor capacity, R , (versions 5 and 6 in Table 4) caused a decrease in concentration of hydrogen sulfide in water at the exit from the bioreactor, ρ_1 , accompanied by an increase in the purification degree, η , and a decrease in the specific bio oxidative power, W . The maximum purification degree of 98.9 % was achieved in version 6.

The bioreactor of the type under consideration features a practical impossibility of achievement of zero concentrations of the contaminant dissolved in water at its concentration in the air-gas mixture not equal to zero.

5. 3. Influence of design and operation mode parameters of the biological purification systems on efficiency of the formaldehyde elimination process

Tables 5, 6 show the results of calculations applied to the anaerobic bio oxidation of formaldehyde until it was completely removed. The observed effects were evaluated for variation of the vessel filling time, that is, a variation in its working volume and a variation of the rate of pollutant inflow at a constant initial amount of biomass.

The data presented demonstrate an almost proportional increase in duration of the stationary stage of the process at an increase in the working capacity of the vessel. This effect is explained by a corresponding decrease in concentration of biomass and, consequently, the rate of the stationary process. In general, duration of the stationary stages is relatively short since an active, nonstationary process with low concentrations at its completion was realized in all cases.

Table 5

The versions of realization of the process of anaerobic bio oxidation of formaldehyde in water at a constant rate of its inflow to the vessel (the design parameters of the facility)

Indicator meaning	Calculation versions		
	1	2	3
<i>D</i> : the vessel diameter, m	3	3,5	4
<i>H</i> : the vessel height, m	0.849	1.143	1.273
<i>R</i> : the vessel capacity, m ³	6	11	16
<i>R</i> ₀ : the initial filling, m ³	1	1	1
<i>m</i> _b : the amount of biomass, g	30,000	30,000	30,000
δG_V : the weight of eliminated formaldehyde, g	15,000	30,000	45,000
η : purification degree, %	100	100	100
<i>t</i> _d : duration of the biological purification process, h	6.18	12.16	18.14
<i>N</i> : efficiency in terms of water solution, m ³ /h	0.8095	0.8225	0.827
<i>W</i> : mean specific bio oxidative power, g/m ³ h	404.7	224.3	155.1
<i>V</i> : mean specific rate of oxidation, g/g _b h	0.002447	0.009532	0.004843

It should be noted that the average specific bio oxidative power decreases significantly with the growth of the working space in which the final stage of the process takes place. This fact shows economic inexpediency of an unlimited increase in the vessel capacity. If there are two vessels in the facility that provide the technological continuity, its value is limited by satisfaction of the correlation:

$$t_f \geq t_r + t_m + t_s, \tag{19}$$

where *t_f* is the vessel filling time, h; *t_r* is the duration of removal of regenerated water from the vessel, h; *t_m* is the duration of the vessel maintenance, h; *t_s* is the duration of the final stationary stage of the process with a filled vessel, h.

The equality sign in relation (19) corresponds to the minimum capacity providing the process continuity. The above described regularity indicates that the minimum volume will simultaneously correspond to the maximum specific bio oxidative power under these conditions. Thus, the calculated minimum capacity can be considered an optimal design choice.

Tables 7, 8 present the results of calculations applied to the anaerobic bio oxidation of formaldehyde for the case of two stages of the nonstationary process with different pollution inflow rates during the vessel filling process. Durations of the stages are assumed to be equal, a complete removal of the contaminant was preset at an unchanged vessel capacity and the initial amount of biomass.

Table 7

Versions of realization of the process of anaerobic bio oxidation of formaldehyde in water at a varying rate of its inflow to the vessel (the design parameters of the facility)

Indicator meaning	Calculation version		
	1	2	3
<i>D</i> : the vessel diameter, m	4.5	4.5	4/5
<i>H</i> : the vessel height, m	1.32	1.32	1.32
<i>R</i> : the vessel capacity, m ³	21	21	21
<i>R</i> ₀ : initial filling, m ³	1	1	1
<i>m</i> _b : the biomass amount, g	10,000	10,000	10,000
δG_V : the weight of eliminated formaldehyde, g	60,000	70,000	80,000
η : the purification degree, %	100	100	100
<i>t</i> _d : the duration of the biological purification process, h	38.66	41.37	44.52
<i>N</i> : the efficiency in terms of the water solution, m ³ /h	0.5173	0.4835	0.4493
<i>W</i> : the average specific bio oxidative power, g/m ³ h	73.91	80.58	85.58
<i>V</i> : the average specific rate of oxidation g/g _b h	0.1552	0.1692	0.1797

Table 6

Versions of realization of the process of anaerobic bio oxidation of formaldehyde in water at a constant rate of its inflow to the vessel (the design parameters of the biological purification process)

Process stage	Initial state: the vessel partially filled, formaldehyde does not enter			Nonstationary process: the vessel is being filled, formaldehyde enters the vessel at a constant rate			Stationary process: the vessel is filled, formaldehyde does not enter		
	0	1	2	1	2	3	1	2	3
<i>j</i> : the stage index	0			1			2		
Version	1	2	3	1	2	3	1	2	3
<i>r_j</i> : the rate of water solution inflow, m ³ /h	0	0	0	1	1	1	0		
<i>g_j</i> : the rate of formaldehyde inflow, g/h	0	0	0	3,000	3,000	3,000	0	0	0
ρ_{g_j} : initial formaldehyde concentration, g/m ³	0	0	0	3,000	3,000	3,000	0	0	0
<i>V_{g_j}</i> : specific rate of formaldehyde inflow, g/g _b h	0	0	0	0.1	0.1	0.1	0	0	0
δG_{g_j} : weight of formaldehyde entered, kg	0	0	0	15	30	45	0	0	0
<i>t_j</i> : the stage duration, h	0	0	0	5	10	15	1.18	2.16	3.14
μ : the biomass concentration, g/m ³	30,000	30,000	30,000	5,000	2,727	1,875	5,000	2,727	1,875
ρ_f : formaldehyde concentration, g/m ³	0	0	0	95.5	95.5	95.5	0	0	0

Table 8

Versions of realization of the process of anaerobic bio oxidation of formaldehyde in water at a varying rate of its inflow to the vessel (the design parameters of the biological purification process)

The process stage	Initial state: partial filling, formaldehyde does not enter			Nonstationary process: the vessel is being filled, formaldehyde enters at the j -th rate						Stationary process: the vessel is filled, formaldehyde does not enter		
	0			1			2			3		
j is the stage index												
Version	1	2	3	1	2	3	1	2	3	1	2	3
$r_j, \text{m}^3/\text{h}$	0	0	0	1	1	1	1	1	1	0		
$g_j, \text{kg}/\text{h}$	0	0	0	2	2	2	4	5	6	0	0	0
$\rho_{gj}, \text{kg}/\text{m}^3$	0	0	0	2	2	2	4	5	6	0	0	0
$V_{gj}, \text{g}/\text{g}_b \text{ h}$	0	0	0	0.2	0.2	0.2	0.4	0.5	0.6	0	0	0
$\delta G_{rj}, \text{kg}$	0	0	0	20	20	20	40	50	60	0	0	0
t_j, h	0	0	0	10	10	10	10	10	10	18.66	21.37	24.52
$\mu_j, \text{g}/\text{m}^3$	10,000	10,000	10,000	909.1	909.1	909.1	476.2	476.2	476.2	476.2	476.2	476.2
$\rho_j, \text{g}/\text{m}^3$	0	0	0	229.3	229.3	229.3	764.8	1,224.8	1,796.8	0	0	0

As it follows from the data given, an increase in the rate of formaldehyde inflow at the second stage corresponds to a long duration of the stationary process. Its value may exceed the vessel filling time. This effect is explained by the fact that the ratio of the ρ_{gj} and V_{gj} parameters exceeds the range of realization of the active nonstationary process and, as a consequence, the contaminant concentrations are already high at the moment of completion of the vessel filling.

Comparison of the versions with different rates of formaldehyde inflow at the second stage of the nonstationary process shows that a relatively smaller increase in the total duration of the process corresponds to an increase in the weight of the contaminant entered the vessel. As a result, there is a noticeable increase in the bio oxidation power, W , and a decrease in efficiency in terms of processed volume of the aqueous solution of the harmful substance, N .

In general, the results obtained in quantitative terms indicate the necessity of taking into account the variation of the rate of pollutant inflow during the process of filling.

It is important to note that the design versions given in Table 8 cannot be recommended for realization because of the failure of meeting condition of (19). In this case, an acceptable design solution can be obtained by a corresponding enlargement of the vessel capacity.

The effect of such a parameter as the amount of biomass intensifying the process is obvious. In particular, it is possible to achieve transition to the region of an active nonstationary process by increasing the initial amount of biomass. Thus, it is possible to influence characteristics of the facility of bio oxidation of the harmful substance dissolved in water both at the design stage and during operation. At the design stage, efficiency of the facility can be changed, for example, by a choice of the vessel capacity.

At the same time, it is necessary to strive for a minimum capacity that ensures compliance with condition of the technological continuity. In operation, it is possible to improve the unit characteristics by changing the initial amount of biomass during maintenance service.

6. Discussion of results obtained in the study of influence of design and operation mode parameters on efficiency of biological purification facilities

The presented calculation results as well as the methods for studying the effect of design and operation mode parameters can be useful in designing systems of biological gas purification. The advantages of the presented approach include simplicity of analysis and economic feasibility of the numerical experiment in comparison with the actual industrial experiments which require creation of a pilot facility and significant capital expenditures. Another advantage of the proposed method is that it is based on the mathematical models created with taking into account the results of real experimental data and the ideas of kinetics of methane, hydrogen sulfide and formaldehyde destruction elucidated in laboratory conditions and described earlier in [18–22].

In general, the data obtained in numerical modeling (Tables 1–8) indicate the possibility of controlling the bioreactor characteristics both at the design stage and in operation.

At the design stage, the possibility of controlling consists in choosing the bioreactor capacity. However, it should be noted that this control is known to be limited for economic and design reasons. For example, when choosing the design parameters of the bio oxidation systems, a smaller bioreactor is preferred.

During routine maintenance, it is possible in principle to make corrections to the bioreactor characteristics by changing the initial biomass concentration, μ_0 . The possibility of a prompt control of the bioreactor during its operation consists in a change of concentration of the incoming contaminants by changing capacity, N , of the ventilator supplying the gas-air mixture (in the case of a bubbling-type reactor) or the rate of bed irrigation with water (in the case of using a reactor with a washed layer).

A common drawback of the above studies is that the data of mathematical modeling cannot take into account the entire specifics of the process in real production conditions. Therefore, in the future, it is expedient to carry out experi-

ments in industrial conditions using an experimental-industrial reactor.

7. Conclusions

1. A procedure for analyzing efficiency of biological purification systems as the objects of design and operation has been developed. The procedure is based on the proposed mathematical models of nonstationary processes of bio oxidation of gaseous harmful substances that are soluble and insoluble in water as well as the contaminants dissolved in water.

2. The influence of design and operation mode parameters on efficiency of the systems of bio destruction of gaseous methane and hydrogen sulfide as well as formaldehyde dissolved in water was calculated and analyzed. The obtained regularities are the tool of efficiency control in designing and operation of biological purification facilities of corre-

sponding types by variation of the bioreactor size, the initial concentration of biomass or the technological parameters of supply of air to be purified or a washing liquid.

3. The data obtained in numerical experiments quantitatively indicate the necessity of taking into account the variation of the rate of pollution inflow during filling of the vessel. It has been established that an increase in efficiency of the facility in terms of the air-gas mixture, N , causes a decrease in methane concentration at the entry to the bioreactor and leads to a reduction in the degree of purification, η , to 62 %. An increase in the rate of hydrogen sulfide inflow to the reactor leads to a reduction in purification degree from 98 to 95 % and an increase in the initial concentration of biomass by a factor of 1.7 and causes a decrease in the concentration of hydrogen sulfide in water from 2.5 to 1.1 g/m³. It should also be noted that there is a significant decrease in the average specific bio oxidative power with an increase in the working space in which the final stage of formaldehyde elimination from emissions takes place.

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