The object of this study is the process of functioning of the hydrogen storage and supply system. The issue of fire-explosive events in the hydrogen storage and supply system is investigated. A set of mathematical models has been built to determine the probability of a combustible medium in the hydrogen storage and supply system. This set includes partial mathematical models for the main elements of the system, which are united by a generalized mathematical model. When constructing partial mathematical models, the probabilities of trouble-free operation of the main elements of the system are used, which include a pipeline and a gas generator with a pressure stabilization circuit. The probability of trouble-free operation is represented in the form of two multiplicative components that take into account catastrophic and parametric failures of the main elements of the system. When determining the probability of trouble-free operation of the main elements of the system in relation to parametric failures, the integral (generalized) parameters were used. In particular, for a gas generator, such parameters are its time constants. The current values of time constants of the gas generator are determined according to the developed algorithm whose feature is the use for its implementation of the values of the amplitude-frequency characteristics of the system, which are determined at three a priori given frequencies. For a typical version of the on-board hydrogen storage and supply system, quantitative indicators of the likelihood of a combustible medium are given. It is shown that if the parametric failures of the main elements of the system are not taken into account, an error occurs, the value of which is 30.0 %.

The results could be used to obtain an express assessment of the level of fire hazard of hydrogen storage and supply systems at different stages of their life cycle

Keywords: hydrogen storage and supply system, combustible environment, catastrophic failures, parametric failures

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DETERMINING THE POSSIBILITY OF THE APPEARANCE OF A COMBUSTIBLE MEDIUM IN THE HYDROGEN STORAGE AND SUPPLY SYSTEM

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1. Introduction

Among all the «green» alternatives available, hydrogen, due to its large amounts and diverse production technologies, is becoming a more viable environmentally friendly source of energy [1]. It is expected to become one of the most important energy carriers in the 21st century [2]. This area of activity is termed hydrogen economy [3] – a system in which hydrogen is produced and used as the main energy carrier. One of the main keys to the full development of the hydrogen economy is the safe, compact, and cost-effective storage of hydrogen, which is provided through hydrogen storage systems (HSS). A traditional gaseous storage system and a liquid storage system create cost and safety problems for onboard applications, resulting in them not meeting future hydrogen economy targets. Solid-state hydrogen storage and supply systems are becoming an increasingly attractive option for hydrogen applications. However, during the storage, transportation, and use of hydrogen, the influence of various factors, such as material damage, structural defects, operating errors or external collisions and impacts, can lead to fire-explosive events [4]. In this regard, there is a need for research aimed at determining the possibility of fire-explosive events in the hydrogen storage and supply system.

2. Literature review and problem statement

Hydrogen has extreme properties in many aspects [5]. It is floating in the gas phase, the reactivity is higher, the flammable range is wider, the ignition energy is lower than that of traditional fuels. To ensure the safety of hydrogen systems, it is proposed to use the inherently safe properties of hydrogen, starting with the design stages of such systems. Various options for the consequences of the implementation of dangerous events in hydrogen systems are considered but quantitative indicators that reflect the possibility of such events are not addressed. In [6], attention is drawn to the fact that there are serious safety problems associated with the hydrogen process. To conduct risk analysis, it is proposed to perform consequence modeling and risk assessment using computational fluid dynamics (CFD). Hydrogen emission ranges and scenarios for their distribution are considered. As for quantitative assessments of risks, they are considered only in fragments. Paper [7] provides possible scenarios for accidents related to hydrogen infrastructure. These scenarios are based on the use of a dynamic Bayes network model (DBN), and its demonstration is carried out in the process of electrolysis of water. It should be noted that the scenarios for the release of hydrogen are modeled by the worst-best methods. This approach does not provide estimates that characterize the possibility of implementing a particular scenario but only provides a better understanding of the action of such scenarios. One of these scenarios was investigated in [8], where the spill of a combustible cloud of liquid hydrogen is considered. In the study, a heterogeneous equilibrium model (NHEM) was used, the adequacy of which was confirmed experimentally. The paper does not provide data on the causes (and their characteristics) that determine the implementation of such a scenario. In [9], the results of research on the analysis of risk factors that lead to hydrogen logistical incidents are reported. To identify significant factors, network analysis was used. The constructed model, which belongs to the class of regression models, makes it possible to obtain quantitative estimates of the influence of each of the factors on the hydrogen logistic incident. But this approach does not make it possible to get an answer to the question regarding the possibility of the appearance of a factor for implementation of a hydrogen logistical incident. In [10], the results of studies into the influence of the size of the hydrogen storage, its mass consumption, pressure, and storage temperature on the safety of the hydrogen storage and supply system are given. It has been shown that the capacity and pressure of the storage system have the greatest impact on the risk assessment of the hydrogen storage and supply system. A feature of these studies is that they extend to gaseous hydrogen systems. For other types of hydrogen storage and supply systems, additional research is necessary. In particular, paper [11] reports data on studies of failure behavior, criteria, and forecasting models for composite containers exposed to high pressure and extreme temperatures. Such containers are the main functional elements of the hydrogen storage and supply system. It should be noted that such studies are local, they do not include other functional elements of the hydrogen storage and supply system and do not make it possible to obtain estimates of the level of fire and explosion hazard of such systems. In [12], quantitative indicators are given for risk assessments in relation to onboard hydrogen storage and supply systems. As such indicators, the cost of human life per vehicle fire and the annual mortality rate per vehicle are used and indicators that characterize the possibility of fire-explosive events on vehicles are not used. The emergence of fire-explosive events during the operation of tanks as elements of hydrogen storage and supply systems was investigated in [13] theoretically, and in [14] experimentally. Quantitative estimates have been obtained that characterize the conditions under which there is an explosion of tanks and a hydrogen spill. In [15], a new sensor array based on MXene film and flexible printed circuit (FPC) is proposed, which is integrated with pressure tanks during its manufacturing process. This sensor array makes it possible to receive real-time information regarding the characteristics of the tank of the hydrogen storage and supply system in the context of its fire and explosion hazard. A feature of the research, the results of which are given in these three works, is that that they are not integrated into the overall task of ensuring the fire and explosion hazard of the hydrogen storage and supply system. In works [13, 14], there is an answer to the question of «what will happen if» but there is no answer to the question of what is the probability of the appearance of conditions leading to tank explosions. Regarding the requirements for quantitative assessment of the risks of hydrogen storage and supply systems, for systems that are focused on the use of liquid hydrogen, they are provided in [16, 17]. In [16], it is noted that there is a lack of data on the reliability of the liquid hydrogen storage system. In this regard, the mode and consequences of failures (FMEA) analysis was carried out using event sequence diagrams (ESI) and fault tree analysis (FTA). The results are used to identify, rank, and model risk scenarios associated with the release of liquid hydrogen (LH_2). Based on the analysis of these scenarios, data on the reliability and quantitative indicators of the risk of hydrogen systems are determined. A feature of these studies is that they apply to liquid hydrogen storage systems, which are located at filling stations. In relation to other hydrogen storage and supply systems, in particular, systems based on metal hydrides, additional research is necessary. In [17], studies are also focused on hydrogen storage systems in the liquid state, which are located at filling stations. The research results are aimed at improving the reliability of the hydrogen storage and supply system. The studies, the results of which are given in [16, 17], are characterized by the absence of a link between the indicators characterizing the level of fire and explosion hazard of the hydrogen storage system and indicators of their reliability.

All this gives grounds to argue that it is expedient to conduct a study on the possibility of forming a combustible environment in the hydrogen storage and supply system as one of the conditions for ensuring its fire and explosion safety.

3. The aim and objectives of the study

The aim of our work is to build a set of mathematical models for obtaining quantitative indicators that characterize the possibility of the formation of a combustible medium in the system of storage and supply of hydrogen. In practice, this will make it possible to derive express assessments of the level of fire hazard of such systems at different stages of their life cycle.

To accomplish the aim, the following tasks have been set:

– to construct a generalized mathematical model for the probability of the formation of a combustible medium in the hydrogen storage and supply system;

– to determine partial mathematical models for the probabilities of trouble-free operation of the main elements of the hydrogen storage and supply system, taking into account catastrophic and parametric failures;

– to derive quantitative indicators for the probability of formation of a combustible medium in the system of storage and supply of hydrogen.

4. The study materials and methods

The object of this study is the process of functioning of the hydrogen storage and supply system. The main hypothesis of the study assumes that a generalized mathematical model is used to determine the probability of formation of a combustible medium in the hydrogen storage and supply system. The elements of the model are the probabilities of trouble-free operation of its main elements, taking into account catastrophic and parametric failures.

The main assumptions are:

– the possibility of forming a combustible medium in the system of storage and supply of hydrogen is associated with the level of reliability of its elements;

– catastrophic refusals have an exponential law of distribution;

– parametric failures according to Lyapunov's theorem follow a normal law of distribution.

When constructing mathematical models (generalized and partial), the methods of probability theory and reliability theory were used. To determine the integral parameters of the gas generator, the methods of the theory of functions of a complex variable were used, as well as methods of the theory of automatic control. When deriving quantitative indicators for the probability of the appearance of a combustible medium in the system of storage and supply of hydrogen, a typical version of the construction of such a system (solid-state type based on sodium hydride) was used.

5. The results of research to determine the possibility of the appearance of a combustible environment in the system of storage and supply of hydrogen

5. 1. Construction of a generalized mathematical model for the probability of formation of a combustible medium in the hydrogen storage and supply system

The formation of a combustible environment in the system of storage and supply of hydrogen is a prerequisite for the occurrence of a fire-explosive situation. An event that corresponds to the formation of a combustible medium in the k-th element of the hydrogen storage and supply system can be described by the operator A_k. To implement this event, it is necessary and sufficient to meet two conditions, the formalization of which is described by the following expression:

$$A_k = A_{k1} \cap A_{k2}, \tag{1}$$

where A_{k1} is an operator that corresponds to the appearance in the k-th element of the hydrogen storage and supply system of a sufficient amount of combustible substance; A_{k2} is an operator that corresponds to the appearance in the k-th element of the hydrogen storage and supply system of a sufficient amount of oxidizing agent.

For operators A_{k1} and A_{k2}:

$$A_{k1} = A_{k11} \cup A_{k12} \cup A_{k1i} \ldots A_{k1n}; \tag{2}$$

$$A_{k2} = A_{k21} \cup A_{k22} \cup A_{k2j} \ldots A_{k1m}, \tag{3}$$

where A_{k1i} is the operator of the implementation of the i-th reason for the appearance in the k-th element of the hydrogen storage and supply system of a sufficient amount of combustible substance (i=1, 2, ..., n); A_{k2j} is the operator of the implementation of the j-th reason for the appearance in the k-th element of the hydrogen storage and supply system of a sufficient amount of oxidizer (j=1, 2, ..., m).

It should be noted that the identification of i-th and j-th causes is subjective and determining the probability of occurrence of fragments of a combustible medium, which are formalized using the operators A_{k1i} and A_{k2j}, requires statistical data. As a rule, such statistics are absent, or their sample is very small. One of the ways out of this situation is to use the hypothesis, according to which these probabilities (or part thereof) correspond to the probability of failures of the elements of the system, which make it impossible for the occurrence of relevant events [18]. However, in this case, the influence of parametric failures of the elements of the hydrogen storage and supply system is not taken into account, and the influence of the subjective factor is not excluded. It is possible to significantly weaken the influence of the subjective factor if we move to a higher hierarchical level when obtaining estimates of probability failures. To do this, it is advisable to use instead of the probabilities of the appearance of fragments of a combustible medium in the k-th element of the hydrogen storage and supply system due to the manifestation of i-th and j-th reasons integral indicators – the probability of the formation of a combustible medium in the k-th element of such a system. These probabilities can be determined due to the probability of uptime of the corresponding elements of the hydrogen storage and supply system.

In the system of storage and supply of hydrogen in the first approximation, the most important functional elements can be distinguished, which can cause the appearance of a combustible medium in it. Such elements include pipeline T and gas generator G with pressure stabilization circuit S.

The probability of the formation of a combustible medium in the system of storage and supply of hydrogen in this case will be determined by the following expression:

$$Q = Q_1 + (1 + Q_1) Q_2, \tag{4}$$

where Q_1, Q_2 – probability of formation of a combustible medium in the pipeline and in the gas generator with a pressure stabilization circuit, respectively.

The appearance of a combustible substance in the pipeline and in the gas generator with a pressure stabilization circuit in a formalized form can be represented as follows:

$$P_{V1} = P_T P_G P_S; \;\; P_{V2} = P_G P_S, \tag{5}$$

where P_T, P_G, P_S is the probability of trouble-free operation of elements T, G, and S, respectively.

The appearance of an oxidizing agent in a pipeline and gas generator with a formalized pressure stabilization circuit can be represented by expressions:

$$P_{O1} = 1 - P_T;$$

$$P_{O2} = (1 - P_G) + (1 - P_S) + (1 - P_G)(1 - P_s) = \\ = 3 - 2(P_G + P_S) + P_G P_S. \tag{6}$$

The formation of a combustible medium in the elements of the hydrogen storage and supply system has the following formalization:

$$Q_1 = P_{V1} P_{O1}; \;\; Q_2 = P_{V2} P_{O2}. \tag{7}$$

Concatenation of (4)÷(7) results in the following expression:

$$Q=P_G P_S\begin{bmatrix} P_T\left(1-P_T\right)+\left(1+P_T P_G P_S\left(1-P_T\right)\right)\times \\ \times\left(3-2\left(P_G+P_S\right)+P_G P_S\right)\end{bmatrix}. \tag{8}$$

This expression is a mathematical model that describes the probability of formation of a combustible medium in the hydrogen storage and supply system, depending on the probabilities of trouble-free operation of its elements – a pipeline and a gas generator with a pressure stabilization circuit.

Fig. 1 shows the dependence $Q=Q(P_G)$ for P_S=0.9 at P_T=var.

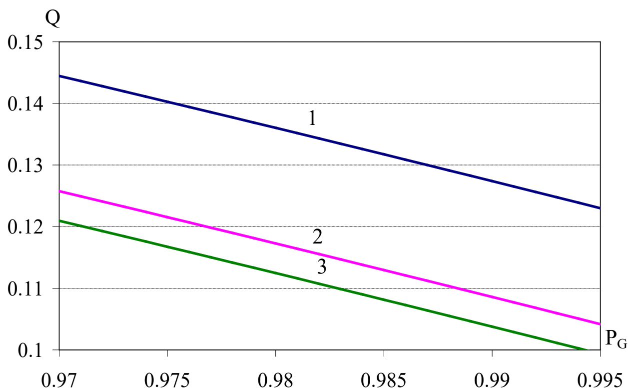

Fig. 1. Dependence $Q=Q(P_G)$ at P_S=0.9 and P_T=var: 1 – P_T=0.97; 2 – P_T=0.99; 3 – P_T=0.995

With an increase in the probabilities P_T and P_G, there is a decrease in the probability Q_1, which does not contradict the physical interpretation of the probability of the formation of a combustible medium.

5. 2. Taking into account catastrophic and parametric failures

When taking into account catastrophic and parametric failures, the expression for the probability of trouble-free operation of the pipeline is:

$$P_T=\exp\left(-\lambda_1 t\right)F\left[\left(m_R-m_P\right)\left(\sigma_R^2+\sigma_P^2\right)^{-0.5}\right], \tag{9}$$

where λ_1 is the intensity of catastrophic failures; $F(z)$ is the function of the standard normal distribution:

$$F\left(z\right)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{z}\exp\left(-0.5t^2\right)\mathrm{d}t; \tag{10}$$

m_R, σ_R is the mathematical expectation and standard deviation of the bearing capacity, respectively; m_P, σ_P is the mathematical expectation and standard deviation of pressure in the pipeline, respectively.

Expressions for the mathematical expectation m_R and for the standard deviation σ_R can be represented as follows:

$$m_R=2m_B m_d m_D^{-1}; \tag{11}$$

$$\sigma_R=V_R m_R, \tag{12}$$

where m_B is the mathematical expectation of the strength limit of the pipeline material; m_d, m_D – mathematical expectation of wall thickness and pipeline diameter, respectively; V_R – coefficient of variation:

$$V_R=\left(V_B^2+V_d^2+V_D^2\right)^{0.5}; \tag{13}$$

V_B is the coefficient of variation of the tensile strength of the pipeline material; V_d, V_D – coefficient of variation of wall thickness and diameter of the pipeline, respectively.

If Δ_P, Δ_d, Δ_D are the absolute errors of pressure, thickness, and diameter of the pipeline, then:

$$\sigma_P=\frac{\Delta_P}{3};\ V_d=\Delta_d\left(3m_d\right)^{-1};\ V_D=\Delta_D\left(3m_D\right)^{-1}. \tag{14}$$

If the current values of pressure p_i in the pipeline are measured, then the parameters m_P and σ_P are determined by the following expressions:

$$m_P=n^{-1}\sum_{i=1}^{n}p_i;\ \sigma_p=\left[\left(n-1\right)^{-1}\sum_{i=1}^{n}\left(p_i-m_p\right)^2\right]^{0.5}. \tag{15}$$

The gas generator is the main element of the hydrogen storage and supply system. There are many reasons that cause its refusal. These reasons depend on the quality of materials, design, manufacturing technology, mode, working conditions, etc. [4]. For example, for some gas generators, the cavity pressure of which is 50 MPa, the presence of a radial temperature gradient ΔT=1 K leads in a few seconds to a thermal explosion. To take into account these reasons, information is a priori needed regarding the functional dependence of the probability of failure of the gas generator on the relevant factors. Determining such a functional dependence is not always possible.

In the gas generator of the hydrogen storage and supply system, the influence of various factors on its reliability indicators can be taken into account through integral (generalized) parameters. Such integral parameters are determined using the transfer function of the gas generator, which takes the following form [19]:

$$W\left(p\right)=K\left(1-\tau_1 p\right)\left[\left(\tau_2 p+1\right)\left(\tau_3 p+1\right)\right]^{-1}, \tag{16}$$

where K is the transmission coefficient; τ_i is the i-th time constant (i=1, 2, 3); p is a complex variable.

Time constants τ_i depend on the corresponding physical parameters (factors), fully determine the dynamic properties of the gas generator, as a result of which they can act as its integral parameters.

The probability of trouble-free operation of the gas generator, in this case, is determined by the following expression:

$$P_G=\exp\left(-\lambda_2 t\right)\prod_{i=1}^{3}\left[\Phi\left(\frac{\tau_{2i}-\tau_{0i}}{\sigma_i}\right)-\Phi\left(\frac{\tau_{1i}-\tau_{0i}}{\sigma_i}\right)\right], \tag{17}$$

where λ_2 is the intensity of catastrophic failures; τ_{0i} – mathematical expectation of the i-th time constant; σ_i – RMS deviation of the i-th time constant; τ_{1i}, τ_{2i} – limit values of the i-th time constant ($\tau_{2i}>\tau_{1i}$); $\Phi(x)$ is the Laplace function,

$$\Phi\left(x\right)=\frac{1}{\sqrt{2\sigma}}\int_{0}^{x}\exp\left(-0.5z^2\right)dz; \tag{18}$$

$$z=\frac{\tau_i-\tau_{0i}}{\sigma_i}. \tag{19}$$

Determination of current values of i-th time constant of the gas generator is carried out when monitoring its technical condition using the appropriate algorithms. For the construction of such algorithms, one can use, in particular, the frequency characteristics of the gas generator [20].

Thus, from (16) it follows that the amplitude-frequency characteristic of the gas generator is described by the following expression:

$$A(\omega)=K\left[\left[1+(\omega\tau_1)^2\right]\left[\left[1+(\omega\tau_2)^2\right]\left[1+(\omega\tau_3)^2\right]\right]^{-1}\right]^{0.5}, \quad (20)$$

where ω is the angular frequency.

According to this expression, for the integral parameter τ_1:

$$\tau_1^2=(K\omega)^{-2}\left[A^2(\omega)\left[\omega^4\tau_2^2\tau_3^2+\omega^2\left(\tau_2^2+\tau_3^2\right)+1\right]-K^2\right], \quad (21)$$

as a result, for three frequencies ω_i, the following ratio can be written:

$$\begin{aligned}&\omega_1^{-2}\left[A^2(\omega_1)\left[\omega_1^4\tau_2^2\tau_3^2+\omega_1^2\left(\tau_2^2+\tau_3^2\right)+1\right]-K^2\right]=\\&=\omega_2^{-2}\left[A^2(\omega_2)\left[\omega_2^4\tau_2^2\tau_3^2+\omega_2^2\left(\tau_2^2+\tau_3^2\right)+1\right]-K^2\right]=\\&=\omega_3^{-2}\left[A^2(\omega_3)\left[\omega_3^4\tau_2^2\tau_3^2+\omega_3^2\left(\tau_2^2+\tau_3^2\right)+1\right]-K^2\right]. \quad (22)\end{aligned}$$

If we introduce the notation:

$$B_1=\left[A^2(\omega_1)-K^2\right]\left[\omega_1^2\left(A^2(\omega_1)-A^2(\omega_2)\right)\right]^{-1};$$

$$B_2=\left[A^2(\omega_2)-K^2\right]\left[\omega_2^2\left(A^2(\omega_1)-A^2(\omega_2)\right)\right]^{-1};$$

$$B_3=\left[A^2(\omega_2)\omega_2^2-A^2(\omega_3)\omega_3^2\right]\left[A^2(\omega_2)-A^2(\omega_3)\right]^{-1};$$

$$D_1=\left[A^2(\omega_2)-K^2\right]\left[\omega_2^2\left(A^2(\omega_2)-A^2(\omega_3)\right)\right]^{-1};$$

$$D_2=\left[A^2(\omega_3)-K^2\right]\left[\omega_3^2\left(A^2(\omega_2)-A^2(\omega_3)\right)\right]^{-1};$$

$$D_3=\left[A^2(\omega_1)\omega_1^2-A^2(\omega_2)\omega_2^2\right]\left[A^2(\omega_1)-A^2(\omega_3)\right]^{-1}, \quad (23)$$

then for the time constants τ_i of the gas generator there are the following expressions:

$$\tau_2=\left[\left[-C_2+\left(C_2^2-4C_1C_3\right)^{0.5}\right]\left(2C_1\right)^{-1}\right]^{0.5}; \quad (24)$$

$$\tau_3=\left[\left(\tau_2^2+B_1-B_2\right)\left(1+D_3\tau_2^2\right)^{-1}\right]^{0.5}; \quad (25)$$

$$\tau_1=\left[\left[A^2(\omega_i)\begin{bmatrix}\omega_i^4\tau_2^2\tau_3^2+\\+\omega_i^2\left(\tau_2^2+\tau_3^2\right)+1\end{bmatrix}-K^2\right]\left(K\omega_i\right)^{-2}\right]^{0.5}, \quad (26)$$

where

$$C_1=B_3-D_3;\quad C_2=B_3\left(B_1-B_2\right)-D_3\left(D_1-D_2\right);$$

$$C_3=B_1-B_2-D_1+D_2 \quad (27)$$

The values $A(\omega_i)$, K are determined in accordance with the method given in [21].

The reliability of the pressure stabilization circuit is determined by the electric motor and reducer. The probability of trouble-free operation of this circuit will be determined by the following expression:

$$P_S=\prod_{i=1}^{4}P_{Si}, \quad (28)$$

where P_{S1}, P_{S2}, P_{S3}, P_{S4} is the probability of trouble-free operation of the winding, bearings, brush assembly of the electric motor, and reducer, respectively.

For probability P_{S1}:

$$P_{S1}=\exp(-\lambda_3 t), \quad (29)$$

where λ_3 is the equivalent failure intensity of the winding of an electric motor, which is described by the following expression:

$$\lambda_3=\lambda_{30}\exp\left[-\alpha\left(\theta-\theta_0\right)+\alpha R_\theta P\right]; \quad (30)$$

λ_{30} is the intensity of catastrophic winding failures; θ – ambient temperature; θ_0 – temperature at which λ_{20} was determined; R_θ – thermal resistance for the return of heat of the winding to the environment; P – winding heating power; α – coefficient, the value of which is determined by the insulation class (Table 1).

Table 1

Coefficient α values

Insulation class	0	A	B	H	C
α, K^{-1}	0.057	0.032	0.073	0.085	0.055

For probabilities P_{S2}, P_{S3}, one can write:

$$P_{S2}P_{S3}=\exp(-\lambda_4 t), \quad (31)$$

where λ_4 is the equivalent failure intensity of the bearings and brush assembly, which is determined by the following expression:

$$\lambda_4=\lambda_{40}\left(n\cdot n_0^{-1}\right)^2. \quad (32)$$

In this expression, n_0=10^3 rpm; λ_{40}=$8.5\cdot10^{-6}$ h^{-1}; n – rotational speed.

The probability P_{S4} is described by the following expression:

$$P_{S4}=\prod_{i=1}^{m}\exp(-\lambda_{5i}t)\left[0.5-\Phi\left(\frac{t-T_i}{\sigma}\right)\right], \quad (33)$$

where m is the number of gears; λ_{5i} – intensity of catastrophic failures; T_i – normative value of durability of gears; σ – RMS deviation of the failure-free operation of gears, $\Phi(x)$ is the Laplace function.

Parameters T_i are defined by the following expression:

$$T_i=N_i\left(60n_i\right)^{-1}, \quad (34)$$

where N_i is the number of load cycles of the i-th gear wheel; n_i – speed of rotation of the i-th gear wheel.

The expression for the probability P_S after merging (28), (29), (31), and (33) is:

$$P_S = \exp\left(-\left(\lambda_3+\lambda_4\right)t\right)\prod_{i=1}^{m}\exp\left(-\lambda_{5i}t\right)\left[0.5-\Phi\left(\frac{t-T_i}{\sigma}\right)\right]. \quad (35)$$

In this expression, max σ=0.3t.

5. 3. Establishing quantitative indicators for the probability of formation of a combustible medium

To establish quantitative indicators, a typical version of the on-board hydrogen storage and supply system with a hydroreacting composition (IPMash NAS of Ukraine, Ukraine) at a time interval t=10^3 hours was considered. In such a system, pipeline T has the following parameters: D=(25.0±0.3) mm; d=(2.1±0.1) mm; m_B=180 MPa; V_B=0.07; λ_1=$3.0\cdot10^{-6}$ h^{-1} and is under pressure of (22.0±3.0) MPa. In this case, m_p=22.0 MPa; σ_R=2.2 MPa; σ_p=1.0 MPa and, according to (9), P_T=0.993. Excluding parametric failures P_T=0.997.

Gas generator (IPMash NAS of Ukraine, Ukraine) G has the following parameters: λ_2=$2.0\cdot10^{-6}$ h^{-1}; σ_i=σ= =$2.0\cdot10^{-3}$ s; τ_{21}=$14.0\cdot10^{-3}$ s; τ_{22}=$12.0\cdot10^{-3}$ s; τ_{23}=$25.0\cdot10^{-3}$ s; τ_{11}=$2.0\cdot10^{-3}$ s; τ_{12}=$2.0\cdot10^{-3}$ s; τ_{13}=$5.0\cdot10^{-3}$ s; τ_{01}=$8.0\cdot10^{-3}$ s; τ_{02}=$7.0\cdot10^{-3}$ s; τ_{03}=$15.0\cdot10^{-3}$ s. According to expression (17), P_G=0.984, and without taking into account parametric failures, P_G=0.998.

The pressure stabilization circuit S uses an electric motor of the DPR series, in particular, DPR-62-08 (Electric Appliance, Ukraine). Its parameters: electrical supply voltage U=12 V; armature current I=0.73 A; electrical resistance of the armature R=4.0 Ohm; transient electrical voltage on brushes ΔU=0.5 V; rotation speed $2.5\cdot10^3$ rpm; service life $2.0\cdot10^3$ hours; $\theta-\theta_0$=30 K; α=$3.2\cdot10^{-2}$ K^{-1}; λ_{30}=$1.4\cdot10^{-5}$ h^{-1}; R_θ=25.0 K/W. For reducer, λ_{5i}=λ_5=$3.0\cdot10^{-5}$ h^{-1}; m=2; $n_{i\ \max}$=240 rpm; $T_{i\max}$=$1.74\cdot10^3$ h. The heating power is determined by the following expression:

$$P=\left(U-E\right)I, \quad (36)$$

where E is the e.r.s. of the armature,

$$E=U-IR-\Delta U. \quad (37)$$

In this case, P=1.76 W.

For the pressure stabilization circuit S, P_S=0.913, and without taking into account the parametric failures, P_S=0.919.

The probability of formation of a combustible medium in the system of storage and supply of hydrogen according to (8) will be equal to 0.102, and without taking into account parametric failures – 0.079 at a time interval of 10^3 hours. Thus, if we do not take into account the parametric failures in the elements T, G, and S of the hydrogen storage and supply system, then there will be a relative error of 30.0 %.

The gas generator contributes the greatest weight in this error, for which the discrepancy between probabilities that take into account catastrophic and parametric failures, and which do not take into account parametric failures is ΔP_G=0.014. At the same time, ΔP_T=0.004 is for the pipeline, and for the pressure stabilization circuit ΔP_S=0.006.

Fig. 2 shows the nature of change in the dependence Q=Q(P_G, P_S) at P_T=0.995.

Improving the reliability of the hydrogen storage and supply system reduces the possibility of forming a combustible environment in it.

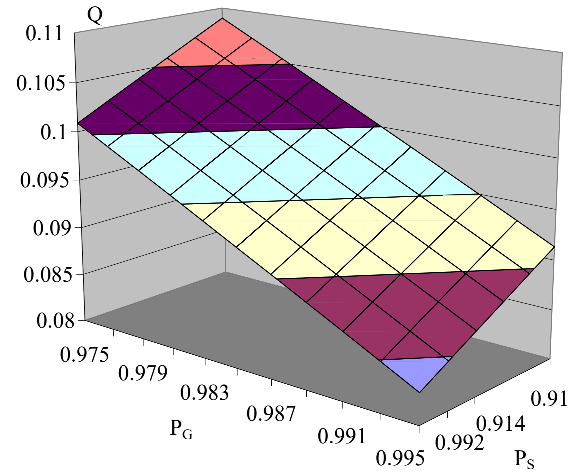

Fig. 2. Dependence Q=Q(P_G, P_S) at P_T=0.995

6. Discussion of research results to determine the possibility of a combustible environment in the hydrogen storage and supply system

Determining the possibility of the emergence of the environment of the hydrogen storage and supply system is based on the use of a generalized mathematical model, which is built in terms of probability theory. A necessary and sufficient condition for the appearance of a combustible medium in the hydrogen storage and supply system is the presence of a combustible substance and an oxidizing agent in it. The presence of a combustible substance – hydrogen is due to the trouble-free operation of the main elements of the hydrogen storage and supply system, which in the first approximation include a pipeline and a gas generator with a pressure stabilization circuit. The appearance of an oxidizing agent – oxygen is possible in the case of failure of the main elements of the hydrogen storage and supply system. This approach makes it possible to build a generalized mathematical model that formalizes the possibility of the appearance of a combustible medium in the hydrogen storage and supply system. The mathematical model represents the nonlinear functional dependence of the probability of the appearance of a combustible medium on the probability of uptime of the main functional elements – expression (8).

When constructing the components of this mathematical model, assumptions are used regarding the failures of the main elements of the system – catastrophic failures have an exponential law of distribution, and parametric failures according to Lyapunov's theorem follow a normal law of distribution. The probability of trouble-free operation of the main elements of the hydrogen storage and supply system relative to parametric failures is represented through the Laplace functions. These functions reflect the fact of taking into account various factors on the reliability indicators of the main elements of the hydrogen storage and supply system. A feature of the constructed partial mathematical models is that the influence of various factors on the reliability indicators of the main elements of the system is taken into account integrally. In particular, in relation to the gas generator, its time constants are used as integral (generalized) parameters, which fully characterize its dynamic properties (16). The current values of time constants of the gas generator, which are used as arguments for the Laplace function (18), (19), are determined according to the developed algorithm (24) to (26). A feature of this algorithm is that for its implementation, the values of the amplitude-frequency characteristics of the gas generator are used, which are determined at three a priori given frequencies. A feature of the partial mathematical model of the probability of trouble-free operation of the pressure stabilization circuit (35) is to take into account the conditions of its operation. Such conditions include the ambient temperature, the thermal effect on the side of the winding of the electric motor, the speed of rotation of the shaft of the electric motor, the number of load cycles of the gears of the reducer.

An illustration of mathematical models focused on determining the possibility of the appearance of a combustible medium in the hydrogen storage and supply system was carried out on the example of a typical version of a non-stationary type on-board system. The largest contribution to this error is made by the gas generator, and the smallest – by the pipeline. Improving the reliability of the hydrogen storage and supply system reduces the possibility of forming a combustible medium in it (Fig. 2).

Thus, the construction of a generalized mathematical model allows us to determine the probability of the formation of a combustible medium in the hydrogen storage and supply system, which is one of the conditions for ensuring fire and explosion safety.

The advantage of this approach to determining the possibility of the appearance of a combustible environment in the system of storage and supply of hydrogen over the known ones is that quantitative indicators of the level of fire hazard can be obtained using reliability indicators. For example, in [16, 17], the estimates of indicators of reliability of hydrogen systems are determined, but these estimates are not related to the level of their fire hazard. This became possible due to the construction of a generalized mathematical model to obtain the probability of the appearance of a combustible medium in the hydrogen storage and supply system. The components of this model are indicators of the reliability of the elements of the hydrogen storage and supply system. Another advantage of this approach is that its implementation has a reasonable use of both the probability of catastrophic failures and the probability of parametric failures. For example, in [11], only catastrophic failures are taken into account when obtaining estimates of the reliability of composite containers.

The limitations of the developed procedure for determining the possibility of the appearance of a combustible medium in the hydrogen storage and supply system include the fact that this determination is carried out within the accepted assumptions.

The disadvantage of the study is that when determining the probability of a combustible environment in the hydrogen storage and supply system, the influence of its non-basic functional elements – sensors, amplifiers, etc. is not taken into account.

Further development of this area of research should be directed to the development of algorithms for predicting the level of fire hazard of the hydrogen storage and supply system.

7. Conclusions

1. It is shown that the formalization of the possibility of the formation of a combustible medium in the system of storage and supply of hydrogen can be represented in the form of a generalized mathematical model for the probability of the formation of a combustible medium. This generalized mathematical model is given in the form of a nonlinear functional dependence of the probability of the formation of a combustible medium on the probabilities of the trouble-free operation of its main elements. As such elements of the hydrogen storage and supply system, a gas generator with a pressure stabilization circuit and a pipeline are considered.

2. Partial mathematical models have been defined for the probability of trouble-free operation of the main elements of the hydrogen storage and supply system, in which parametric failures are taken into account as a multiplicative component, which is a function (functions) of Laplace. For a gas generator, the arguments of the Laplace functions are the integral parameters, which use its time constants. These integral parameters fully characterize the dynamic properties of the gas generator, and their current values are determined, for example, using its amplitude-frequency characteristic at three a priori given frequencies.

3. For a typical version of the on-board hydrogen storage and supply system, quantitative indicators of the probability of formation of a combustible medium were established. It is shown that if the parametric component of failures is not taken into account to obtain an estimate of the probability of formation of a combustible medium in the hydrogen storage and supply system, an error occurs, the value of which is 30.0 %.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

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