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IDENTIFICATION OF THE REGULARITIES OF THE THERMOHYDRAULIC PROCESSES OF THE COOLING SYSTEM OF AN EXPERIMENTAL DEVICE BASED ON A MATHEMATICAL MODEL

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The article is devoted to the study of a nitrogen supply system for cooling an experimental device designed for testing in a pulsed reactor with a graphite moderator. To analyze emergency situations caused by disruption of the nitrogen supply system in the cooling paths of the fuel assembly cover and the experimental device power housing, a mathematical model has been developed to describe thermodynamic processes in a system of interconnected tanks that simulate individual sections of the experimental device hydrodynamic cooling system in a pulsed graphite reactor and implemented in the mathematical interactive package for engineering calculations in MATLAB/Simulink. To study the normal operation of the system and analyze possible emergencies, the cooling system of the experimental device was presented in the form of groups of interconnected sections of the hydrodynamic system-tanks, with specified volumes and hydraulic resistances of pipelines connecting these tanks. Verification of the model, calculations of the experimental device cooling system normal operation mode, calculations of emergency situations caused by a violation of the nitrogen supply system normal operation in the cooling paths of the fuel assembly cover were carried out, in particular, it was found that for the cooling system of the experimental device WF-2, the breakdown of the gearbox P-12 can cause depressurization of the fuel assembly cover and an increase in pressure in the power housing, the opening of the safety valve prevents exceeding the pressure limit in the housing, the device maintains integrity even in emergency situations, without being subjected to destruction of the power elements of the structure at a pressure of up to 8 MPa

Keywords: pulsed reactor with graphite moderator, emergency analysis, heterogeneous processes, mathematical modeling, model verification

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1. Introduction

Currently, mathematical modeling is an integral element of the process of creating any complex technical system, while its role is constantly increasing. A computational experiment based on mathematical modeling of the studied processes, numerical solution methods and various applied software products becomes an indispensable tool of a modern researcher, especially at the early stages of creating a technical system.

The role of modeling in nuclear physics and power engineering is exceptionally great. Suffice it to say that replacing full-scale nuclear tests with simulation not only saves huge amounts of money, but also has a beneficial effect on the ecology of the planet Earth.

In a fast neutron reactor in non-stationary and emergency modes of operation, various processes of heterogeneous physical nature occur – neutron-physical, thermal, hydraulic, thermomechanical and others. Since setting up large-scale experiments to study processes in an accident is extremely problematic, the development of programs for calculating individual stages of an accident and complex calculation of the entire accident is of particular importance.

At present, it is impossible to imagine modern design and construction of nuclear reactors without developing mathematical models of the processes, occurring in the future reactor. Technical systems that exist today can no longer be investigated by conventional theoretical methods.

All these factors confirm that the topic of such research is of scientific importance and an important and urgent task in the field of nuclear energy and reactor science, which includes the safety and reliability of nuclear reactors, efficient use of resources, maintenance of environmental safety, development of new technologies related to the development of mathematical models and numerical methods for modeling thermal processes in the nuclear industry, which can lead to the development of more efficient and innovative solutions.

2. Literature review and problem statement

The article [1] is devoted to the study of the isothermal process of gas compression in a compressor, which is considered depending on the change in the degree of gas compression, thereby representing a liquid piston with variable speed. Guided by the method of mathematical modeling and the laws of conservation in physics, the authors developed a mathematical model of the process under study. The numerical experiment performed makes it possible to determine the essence of the processes' physical component in the machine and analyze the parameters of the objects under study. The disadvantage of this work is that the use of a liquid piston may be limited in application only to certain types of compressors, which reduces its versatility. In general, the work presents interesting research aspects and can potentially lead to an increase in the efficiency of compressors, but it requires further research and experiments to confirm its effectiveness and practical applicability. The article [2] presents the main technical parameters of a pulsed graphite reactor (IGR), providing its outstanding experimental capabilities for studying the behavior of reactor components in various modes, including emergency situations. A brief overview of the experimental programs conducted at IGR highlights their importance for the safety of nuclear reactors, providing new and unique results that help identify key parameters for ensuring the safety and efficiency of reactors. Despite the success of the reactor and the long-term experience of the staff, there are some limitations and financial costs associated with its operation. The authors of [3] present the results of their experiment. The relevance of this experiment is to conduct a study of the created installation cooling system to reduce energy consumption under the considered conditions. Verification of the research results is confirmed by the developed mathematical model. The advantage of this work is the use of shallow geothermal energy, which is a sustainable energy source. In [4], the authors present the development of a new cooling system with a simpler design depending on solar energy. The results of the work are the calculation of the efficiency coefficients in the experiment and a comparative analysis of the obtained values. The experiments were carried out in laboratory conditions with a solar radiation simulator, which may differ from real conditions outside the laboratory.

The paper [5] provides information on the current state of development of fuel cells for electric vehicles and supports developers and manufacturers in increasing the efficiency and distribution of electric vehicles powered by fuel cells. High costs for the development and production of PEMFC systems may limit their availability to a wide audience. In [6], the effect of conversion on pulsed transient process with high energy consumption was studied, and a fuel cell model was developed, which is a simpler version of the considered case description. The obtained results emphasize the validity of the constructed model. However, switching to low-enriched uranium may complicate fitting management and require more complex models for analysis. In [7], the study of obtaining a high heat exchange rate depending on the reduction in the mass of metal hydrides inside the reactor is described in more detail. As a result, a numerical implementation by the finite element method is obtained and a comparative analysis is performed. The problem under consideration is of great relevance in the technology of hydrogen production. However, despite the fact that the introduction of copper plates and water coolers improves heat transfer, it can also increase the complexity of the design and cost of the reactor. In [8], a thermal model of a research nuclear reactor was presented, described by mathematical equations expressing the change in water temperatures at the inlet and outlet of the reactor tank, heat exchanger, depending on time. A comparative analysis of model data obtained using the thermal model and machine learning was performed. The use of machine learning algorithms for modeling the heat transfer coefficient will allow to more accurately determine the parameters of the system, however, it may require additional efforts and resources for analysis and evaluation. In the article [9], the simulation of the neutron transfer process inside the core of a nuclear reactor is considered, which more accurately describes the motion under study. This model is represented by an equation that describes its fractal walk in time. An important result of the study is a comparative study of the root – mean – square bias of the resulting model with other traditional transport models of integer and fractional programming. The use of fractional orders in modeling avoids unrealistic predictions, such as the infinite neutron velocity, which makes the model more physically grounded, but may complicate calculations and require additional analysis methods. The article [10] presents the development and analysis of some new versions and approximations of the fractional-order point reactor kinetics model for a nuclear reactor with a plate geometry. A comparative analysis of models with integer programming models has been carried out, however, the application of this model may require more complex calculations compared to classical integer models.

From these sources, it is possible to see that such problems remain unresolved as the limited use of a liquid piston in compressors, which reduces the versatility of this approach, the development of efficient cooling systems using shallow geothermal energy and possible design difficulties, the development of new cooling systems taking into account the simplicity of the design, depending on solar energy, the development of more accurate methods for modeling heat transfer, including the use of machine learning algorithms, the complexity of calculations and calculations when using a fractional-order point reactor kinetics model compared to integer models.

All this allows to assert that it is advisable to conduct research on the development of universal and effective methods and technologies in the field of thermal and nuclear engineering, in order to improve the efficiency and safety of technical devices such as compressors, nuclear reactors, cooling systems, and elements of power plants.

3. The aim and objectives of the research

The aim of this research is to evaluate the operability of the cooling system of an experimental device in a pulsed graphite reactor under normal operating conditions and under possible emergency scenarios.

The results obtained allow to determine the potential risks and safety of the cooling system, and also confirm the safety of the structural elements of the device in case of emergency situations.

To achieve this aim, the following objectives are performed:

– develop a mathematical model of the cooling system of the experimental device;

– build a computer model of the studied process in MATLAB/Simulink;

– evaluate the efficiency of the cooling system in various experimental modes and visualize the results.

4. Materials and methods of the research

The object of research in this work is the cooling system of an experimental device in a pulsed graphite reactor. The creation of a mathematical and computer model of the cooling system will allow analyzing it's functioning in various modes and conditions, as well as evaluating the effectiveness and safety of this system.

To research normal operating mode of the system and analyze possible emergency situations, the cooling system of the experimental device is presented in the form of groups of interconnected sections of the hydrodynamic system – tanks with specified volumes and hydraulic resistances of pipelines connecting these tanks. Hydraulic resistances are the main parameters in the modeling of this class of problems, since they determine the pressure drops and flow rate of the flowing gas between adjacent sections of the hydrodynamic system. During the calculations, the cooling system was conditionally divided into five «tanks» connected by pipelines with specified hydraulic resistances. Each of the tanks included blocks that described the initial data for calculating the main hydraulic and thermal parameters.

The pressure behind the gas gearboxes R-12 and RP-13 (in front of the flow nozzles) in the nitrogen supply systems to the cooling paths of the device during normal operation of the cooling systems was selected from the calculations of the critical gas flow through the flow nozzles, and are equal to 2 and 8 MPa, respectively.

The main requirement that determines the operating mode of the cooling path of the internal cavity of the power housing is to maintain the temperature of its walls in the range of permissible operating values.

Nitrogen supply for cooling the internal cavity of the power housing begins before the start of the experiment immediately after the completion of the fuel preheating procedure and continues after the reactor is shut down (in the cooling mode) until the guaranteed termination of the increase in the temperature of the walls of the power housing.

In the course of the research, theoretical methods were used: a pulsed graphite reactor (IGR), designs of experimental devices intended for testing in the IGR reactor, as well as a nitrogen supply system for cooling the experimental device, mathematical modeling of thermal and hydraulic processes.

To implement the algorithm of the mathematical model for optimizing the operation of the cooling system of the experimental device, a mathematical interactive package for engineering calculations Matlab/Simulink was used.

To validate the model of the cooling system, calculations of various emergency situations caused by a violation of the normal operation of the nitrogen supply system in the cooling paths of the fuel assembly cover were carried out, and the analysis of the results obtained was also carried out.

All the obtained scientific results are confirmed by numerical implementation and computational experiments in solving real test problems.

Validation of the results allows to conclude about the applicability of the developed computer model and the proposed solutions for the correct modeling of processes occurring when filling the cooling system with nitrogen.

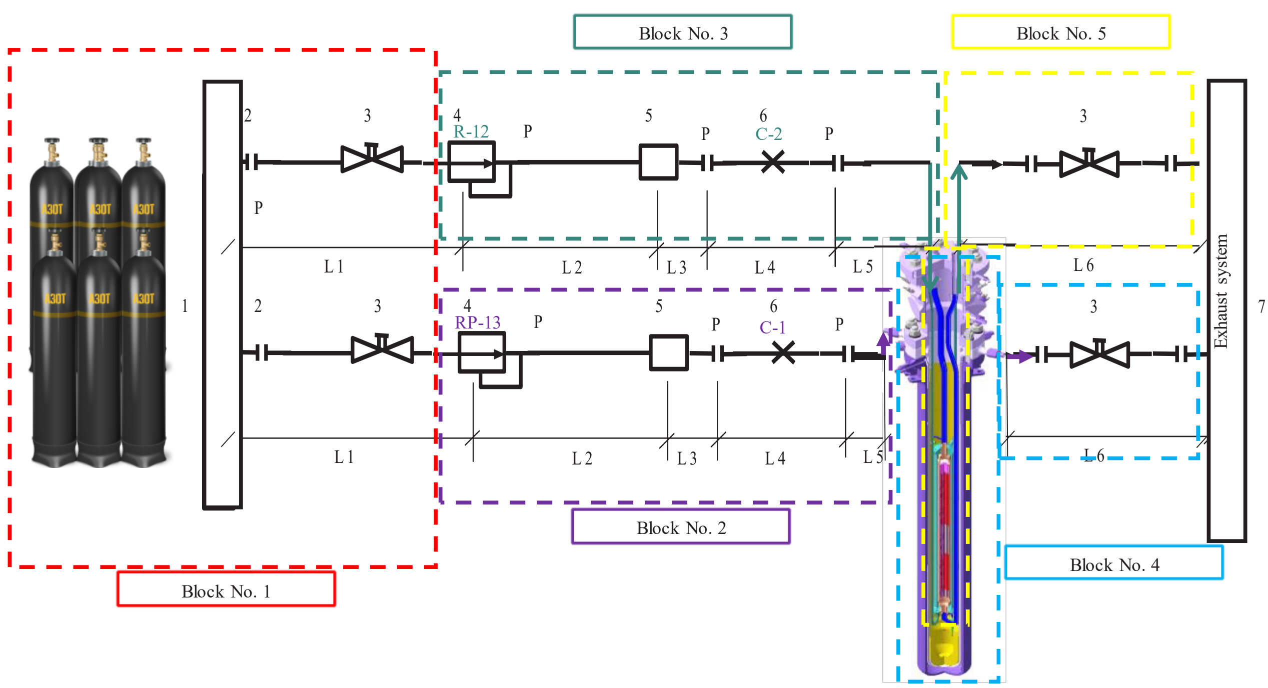


Fig. 1. Scheme of conditional separation of the cooling system of the experimental device

5. Results of the study of the model of the cooling system of an experimental device in the pulsed graphite reactor

5. 1. Mathematical description of the thermodynamic process

The model of the cooling system of the experimental device is recruited from separate modules, each of the modules describes a separate section of the hydrodynamic system, taking into account its geometric characteristics and hydrodynamic resistances of pipelines, as well as the relationship of this section with neighboring sections.

Hydraulic resistances are the main parameters in modeling this class of problems, since they determine the pressure drops and flow rate of flowing gas between adjacent sections of the hydrodynamic system (Fig. 1).

The pneumohydraulic systems involved (Fig. 1), which are important from the point of view of ensuring the safety of ED tests, include:

– nitrogen supply path for cooling the fuel assembly cover;

– nitrogen supply path for cooling the internal cavity of the power housing.

Nitrogen supply for cooling the fuel assembly cover is carried out from nitrogen tanks (Fig. 2, item 1) through a pipeline equipped with shut-off and control valves and a flow nozzle. Nitrogen for cooling the fuel assembly cover is supplied immediately after the implementation of the fuel assembly energy release diagram is completed. Premature cooling of the melting unit is unacceptable, as it may cause the temperature to drop below the set initial value of 670 K.

Nitrogen is released from the cooling path to the exhaust system of the stand.

Nitrogen is supplied to the fuel assembly cover cooling path after the reactor is shut down (in the cooling mode) until the safe temperature of the fuel assembly cover elements is reached (below the melting point of steel).

The main requirement that determines the operation mode of the internal cavity cooling path of the power housing is to maintain the temperature of its walls in the permissible operating values range.

The supply of nitrogen for cooling the internal cavity of the power housing begins before the start of the experiment immediately after the completion of the fuel preheating procedure and continues after the reactor operation is completed (in the cooling mode) until the guaranteed cessation of the increase in the temperature of the walls of the power housing.

Structurally, the nitrogen supply path for cooling the internal cavity of the power housing is similar to the nitrogen supply path for cooling the fuel assembly cover.

The path provides nitrogen supply for cooling the cavity of the power housing with a flow rate of up to 0.2 kg/s.

To analyze emergency situations caused by a violation of the normal operation of the nitrogen supply system in the cooling paths of the fuel assembly cover and the power housing of the electric power unit, a mathematical model should be used to describe thermodynamic processes in a system of interconnected tanks that simulate separate sections of the hydrodynamic cooling system of the experimental device as a whole.

The thermodynamic process in each of the blocks is described by the following (1)–(3):

– material balance equation:

$$\frac{dP}{dt}=\frac{RT}{V}\left(G_{in}-G_{out}\right)+R\rho\frac{dT}{dt}; \qquad (1)$$

– equation for calculating the gas flow rate flowing out of the tank:

$$G_{out}=\sqrt{\frac{P_{i-1}^2-P_i^2}{\xi\cdot zR\overline{T}}}; \qquad (2)$$

– energy balance equation:

$$C_p\rho V\frac{dT}{dt}=G_{in}\left(C_{pin}T_{in}-C_pT\right)-aF\left(T-T_W\right)+V\frac{dP}{dt}, \qquad (3)$$

where G_{in} – mass flow rate of gas at the entrance to the unit; G_{out} – mass flow rate of gas flowing out of the unit; $P_{Pi\text{-}1}$ – pressure inside the unit; P_i – pressure determined either by the pressure in the subsequent container or by atmospheric pressure (if there is no subsequent pressure); T_{in} – gas inlet temperature of the unit; t – time; z – compressibility factor; ξ – local hydraulic resistance of the pipeline at the outlet of the tank; S – cross-sectional area of the hydrodynamic section of the system; V – block size; C_{pin} – heat capacity of the gas flowing into the unit; C_p – heat capacity of the gas inside the unit; a – heat transfer coefficient; F – heat exchange surface area; T_w – temperature of the block wall.

Theoretical analysis and experimental results show that the power spent on mixing the liquid (N) depends on the dynamic viscosity coefficient (μ), density (ρ) of the liquid, gravity (g), speed of rotation of the mixer (n), its diameter (d_m) and other geometric characteristics (diameter of the device, height filling it with liquid, the height of placement of the agitator above the bottom of the vessel).

The maximum increase in the average mass temperature was estimated by the heat balance method according to the ratio:

$$Q_{integral}=\left(C_{p1}\cdot m_1+C_{p2}\cdot m_2\right)\cdot\Delta T+Q_{meltUO_2}+Q_{vaporNa}, \qquad (4)$$

where from:

$$\Delta T=\frac{Q_{integral}-Q_{meltUO_2}-Q_{vaporNa}}{(C_{p1}\cdot m_1+C_{p2}\cdot m_2)}, \qquad (5)$$

where ΔT – maximum increase in average mass temperature, K; $Q_{integral}$ – the integral energy that will be released in the fuel, J; Q_{meltUO_2} – latent melting heat of uranium dioxide for mass m_1, 605 kJ; $Q_{vaporNa}$ – the heat of vaporization in sodium for the mass m_2, 4773.4 kJ; C_{p1} – average specific heat of uranium dioxide, 618 J/(kg×K); m_1 – fuel weight, 2.17 kg; C_{p2} – average specific heat capacity of sodium, 1300 J/(kg×K); m_2 – mass of sodium, 1.1 kg.

Calculated estimates have shown that the maximum pressure increase caused by the interaction of molten fuel with sodium will be ≈0.2 MPa.

The pressure calculation was carried out depending on the average mass temperature of the gas (the maximum average mass temperature of the gas is 498 K). The initial argon pressure was assumed to be 0.1 MPa.

In this case, the pressure change can be calculated by the ratio:

$$P\cdot V=\frac{m}{\mu}R\cdot T, \qquad (6)$$

where P – the gas pressure, Pa; V – volume, m^3; m – the mass of the gas mixture, kg; μ – molar mass of gas, kg/kmol; R – the gas constant, J/(kmol K); T – the gas temperature, K.

When calculating the pressure in the power housing, an assumption was made that the housing cavity is filled with an ideal gas, since nitrogen is close to the ideal gas in properties [11].

In this case, the pressure change can be calculated by the ratio (6).

To estimate the nitrogen pressure change in the power housing, the volume of the graphite casing cavity was used, which is 0.089 m^3.

The initial gas temperature was assumed to be 300 K.

The change in the temperature of the gas in the cavity of the power housing will be:

$$\Delta T = \frac{Q}{c_p \cdot \rho \cdot V}, \quad (13)$$

where Q – energy released in gas, J; c_p – average specific heat, J/kg K; p – the average gas density, kg/m^3; V – the cavity volume of the power housing, m^3.

The maximum possible increase in pressure in the gas cavity of the power housing, due to the heating of the gas medium, will be ≈2 MPa. It should be noted that even with conservative estimates, that is, with a simple addition of pressure changes in the power housing caused by gas heating, as well as the interaction of sodium with fuel, there will not be a dangerous excess of pressure inside the power housing.

5. 2. Computer model of the thermophysical parameters of the cooling system of the experimental device

A computer model of the experimental device cooling system was implemented in the mathematical interactive package for engineering calculations MATLAB/Simulink.

A comprehensive overview of the developed model for the nitrogen cooling system within the power housing and the fuel assembly cover, implemented using the MATLAB/Simulink program, is shown in Fig. 2.

Each of the blocks includes modules that describe the initial data for calculating the main hydraulic and thermal parameters (Fig. 3).

Unlike blocks No. 2–5, block No. 1 (Fig. 3) includes two input parameter modules for calculating the gas flow rate flowing out of the blocks. This is due to the fact that from the same cylinders, nitrogen is supplied via two different pipelines to cool the fuel assembly cover and the power housing.

Fig. 5, 6 show blocks for the initial data «init» and thermal parameters «Value parameters».

The «Outflow calculation» block (Fig. 7) uses an equation to calculate the flow rate of gas flowing out of the tank.

The «Pressure calculation» block (Fig. 8) uses the material balance equation.

The «Temperature calculation» block (Fig. 9) uses the energy balance equation.

The block of thermophysical parameters «Value parameters» refers to the dialog box of the MATLAB program, in which, in order to calculate the thermodynamic parameters (density and thermal conductivity) of nitrogen as a function of temperature, the initial data for calculation is entered.

The pressures behind the R-12 and RP-13 gas reducers (in front of the flow-setting nozzles) in the nitrogen supply systems to the cooling paths of the device during normal operation of the cooling systems were selected from calculations of the critical gas flow through the flow-setting nozzles, and are equal to 2 and 8 MPa, respectively.

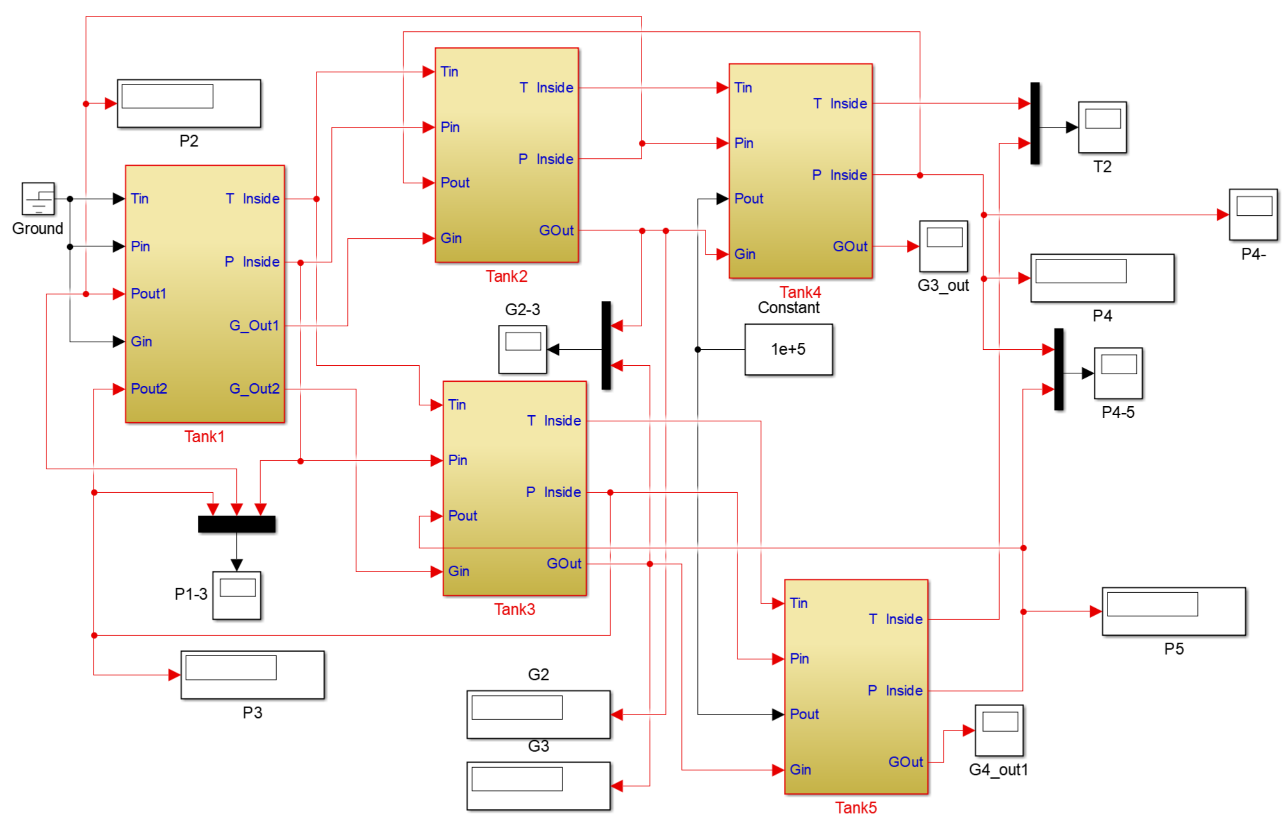


Fig. 2. Computer model of the cooling system of an experimental device

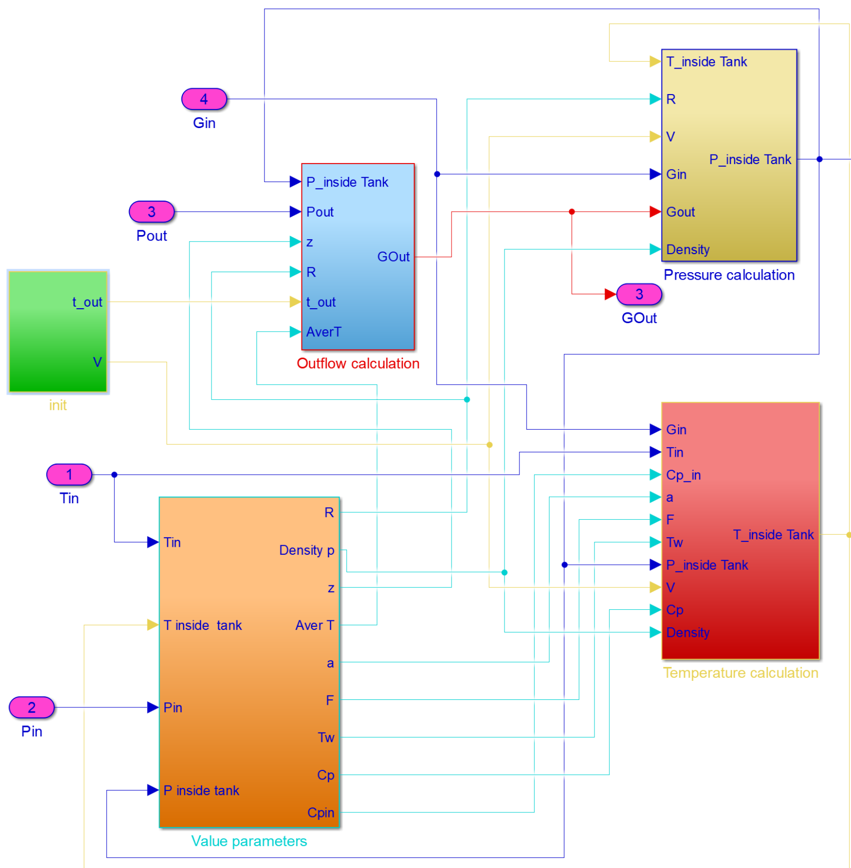


Fig. 3. Computer model of blocks No. 2, 3, 4, 5

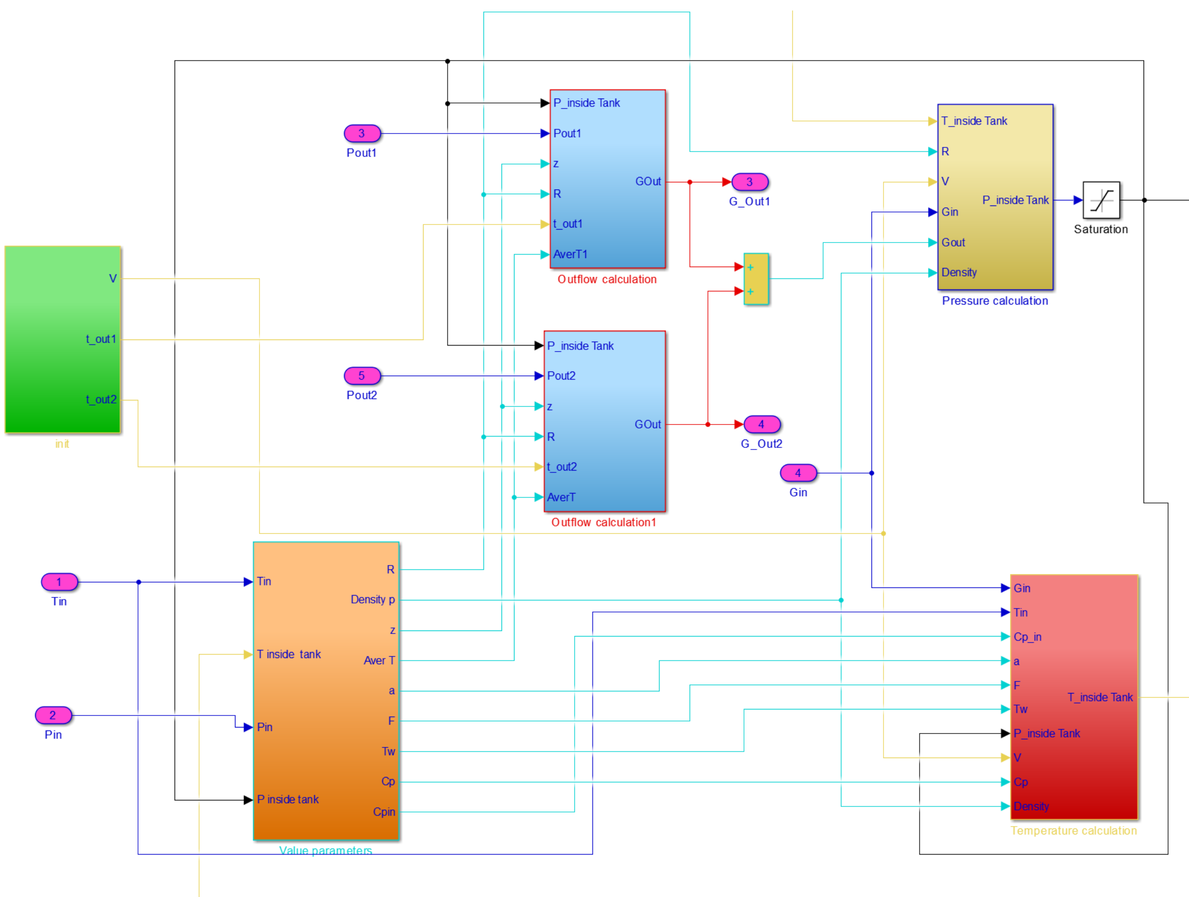


Fig. 4. Computer model of block No. 1

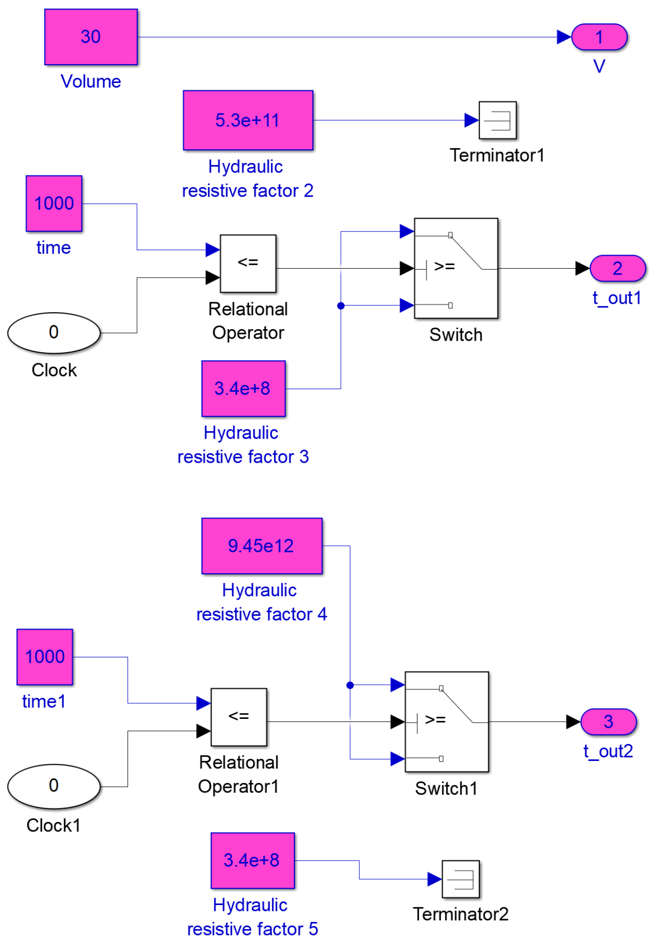


Fig. 5. Computer model for the «init» source data block

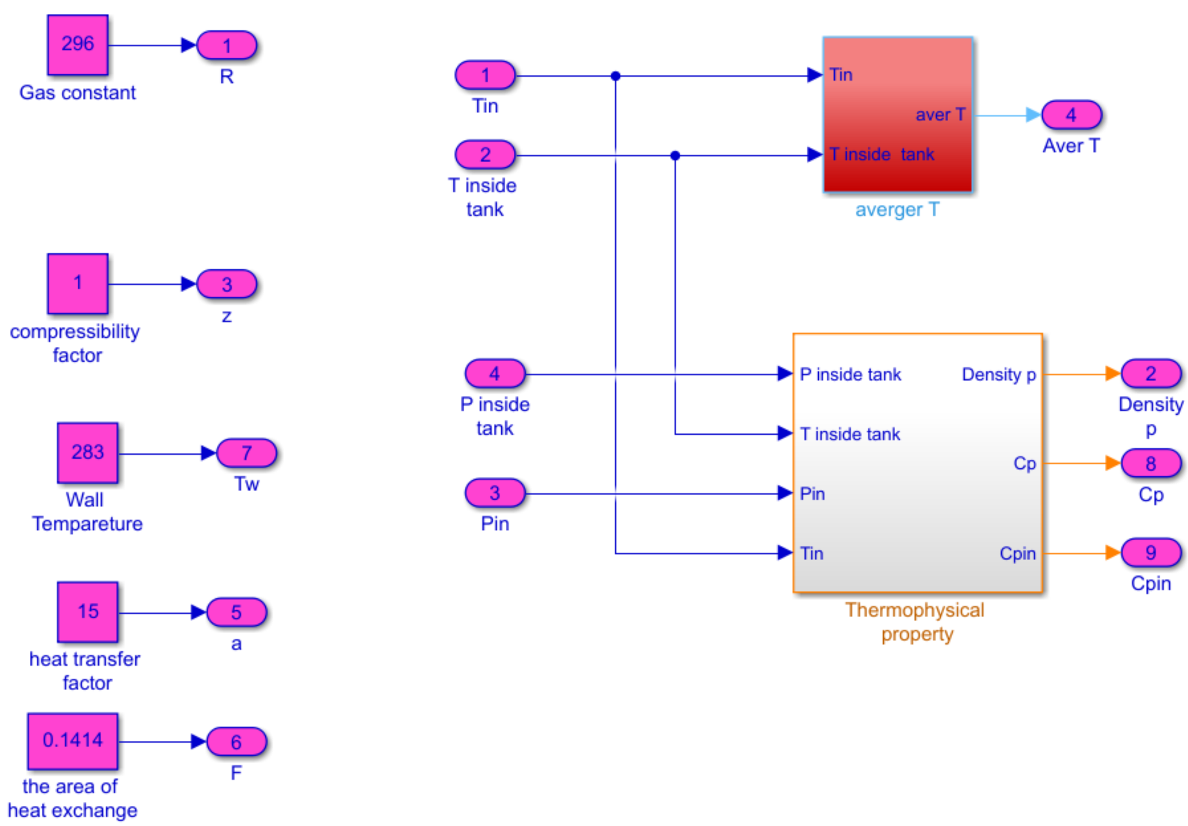


Fig. 6. Computer model of the thermal «Value parameters» block

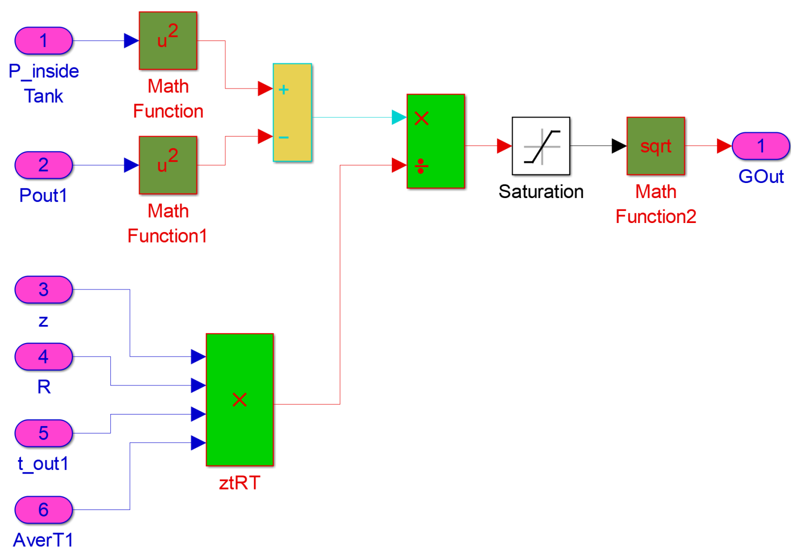


Fig. 7. Block of thermal parameters «Outflow calculation»

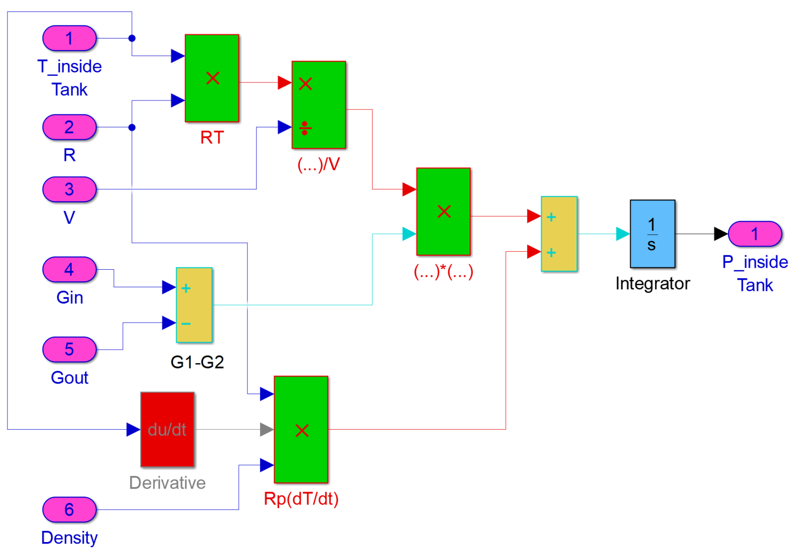


Fig. 8. Computer model of «Pressure calculation» thermophysical parameters block

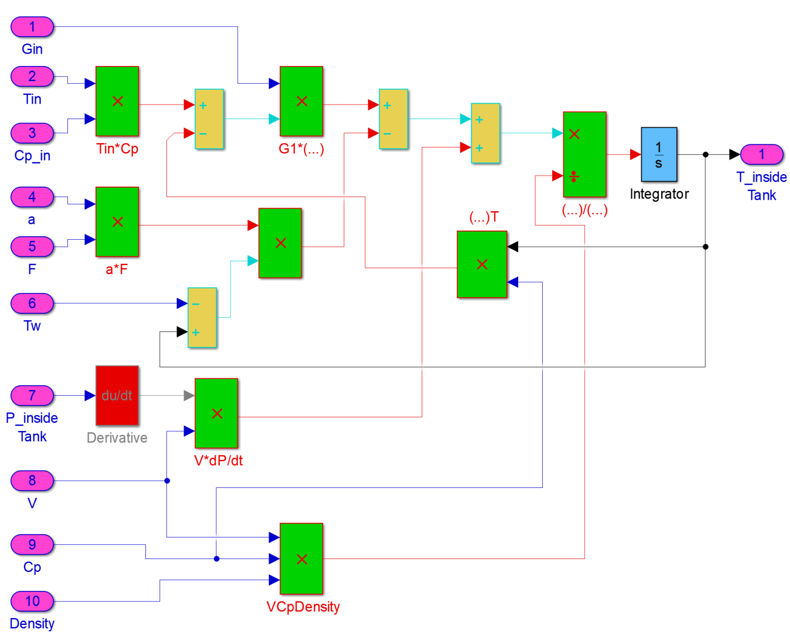


Fig. 9. Block of thermophysical parameters «Temperature calculation»

5. 3. Calculation of the normal operation mode of the cooling system of an experimental device

The pressures behind the R-12 and RP-13 gas reducers (in front of the flow-setting nozzles) in the nitrogen supply systems to the cooling paths of the device during normal operation of the cooling systems were selected from calculations of the critical gas flow through the flow-setting nozzles, and are equal to 2 and 8 MPa, respectively.

Initial conditions for carrying out the calculation of the normal operating mode of the system:

– the initial pressure in block No. 1 is 32 MPa;

– initial pressure in block No. 2–5 – 0.1 MPa;

– working pressure in front of unit No. 2 – 8 MPa;

– working pressure in front of unit No. 3 – 2 MPa;

– the pressure in the exhaust system is 0.065 MPa;

– gas consumption in the cooling path of the power housing is 0.2 kg/s;

– gas consumption in the cooling path of the fuel assembly cover is 0.05 kg/s;

– the initial temperature in all blocks was set to 290 K.

As a result of calculations, it was found that during the normal operation of the experimental device cooling system, the time of the system's output to stationary mode is ≈ 40 seconds (Fig. 10, *a*).

The pressure at the inlet to the cavity of the fuel assembly cover and the power housing is 0.16–0.22 MPa (Fig. 10, *b*).

When the pressure in front of the flow nozzles C1 and C2 of the device cooling paths is equal to 8 and 2 MPa, respectively, the flow rate of cooling nitrogen in the fuel assembly cover is 0.05 kg/s and in the power housing – 0.2 kg/s (Fig. 11).

The developed computer model shows the correct modeling of the processes that occur when the cooling system is filled with nitrogen. The required pressures and flow rates in the cooling paths of the fuel assembly cover and power housing were achieved.

During the calculations, 5 accidents were considered:

– failure of the R-12 gas gearbox;

– failure of the RP-13 gas gearbox;

– failure of the R-12 gas gearbox and overlap of the discharge line from the cooling path of the fuel assembly cover;

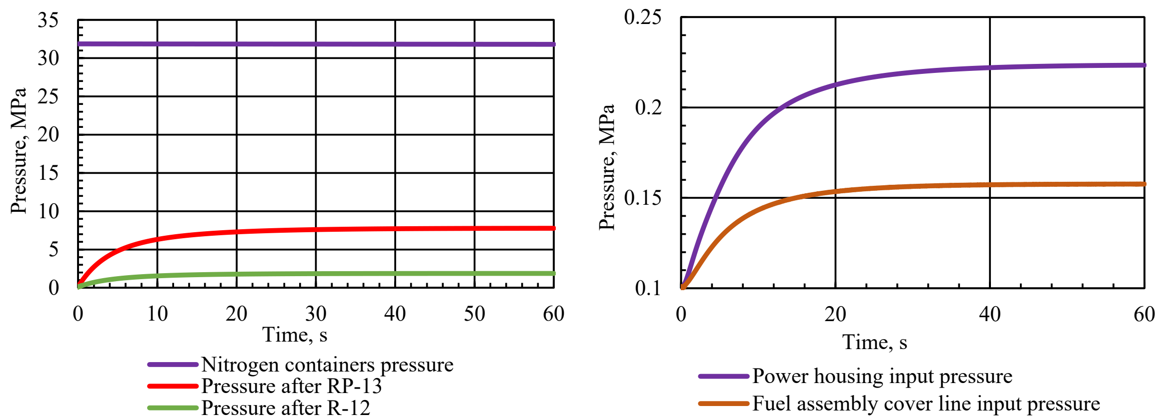
– failure of the RP-13 gas gearbox and overlap of the discharge line from the cooling path of the power housing;

– simultaneous overlap of discharge lines.

Table 1

System capacity parameters

Capacity number	Hydraulic circuit block described by «capacity»	Volume, m^3	Hydraulic resistance of «capacity», m^{-4}
1	Nitrogen storage tanks and pipeline to the gas reducer	30	5.3×10^{11} – for capacity No. 2; 9.45×10^{12} – for capacity No. 3
2	The pipeline from the gas reducer to the flow nozzle into the cooling path of the power housing	1.693×10^{-2}	1.52×10^{10}
3	The pipeline from the gas reducer to the flow nozzle into the cavity of the fuel assembly cover	1.693×10^{-2}	1.65×10^{10}
4	Internal cavity of the power case	0.115	1×10^{7}
5	The internal cavity of the fuel assembly cover and sections of pipelines for gas supply and discharge into the cavity of the fuel assembly cover	8×10^{-4}	6×10^{7}



a *b*

Fig. 10. Pressure in sections of the hydrodynamic system during normal operation: *a* – pressure change in the nitrogen storage tank and in the supply pipelines; *b* – pressure change in the cooling paths of the fuel assembly cover and the power housing

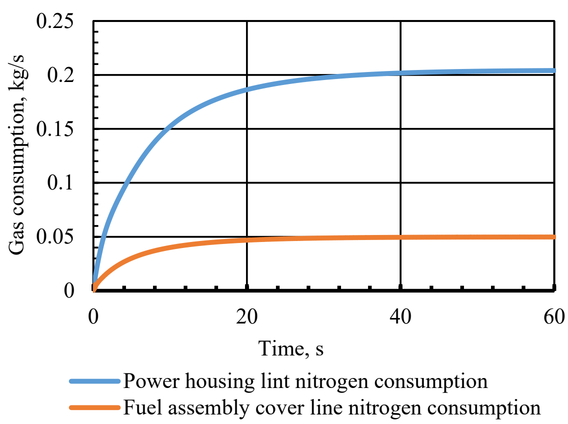


Fig. 11. Flow rate of cooling nitrogen entering the cooling paths of the fuel assembly cover and the power housing during normal operation of cooling systems

Determination of parameters of five particularly important sections of systems in case of malfunction and their calculation:

1) Calculation of system parameters in case of failure of the R-12 gearbox.

The breakdown of the R-12 gearbox was modeled by reducing the hydraulic resistance at the outlet of tank No. 1 from 9.45×10^{12} m^{-4} to 3.4×10^{8} m^{-4}.

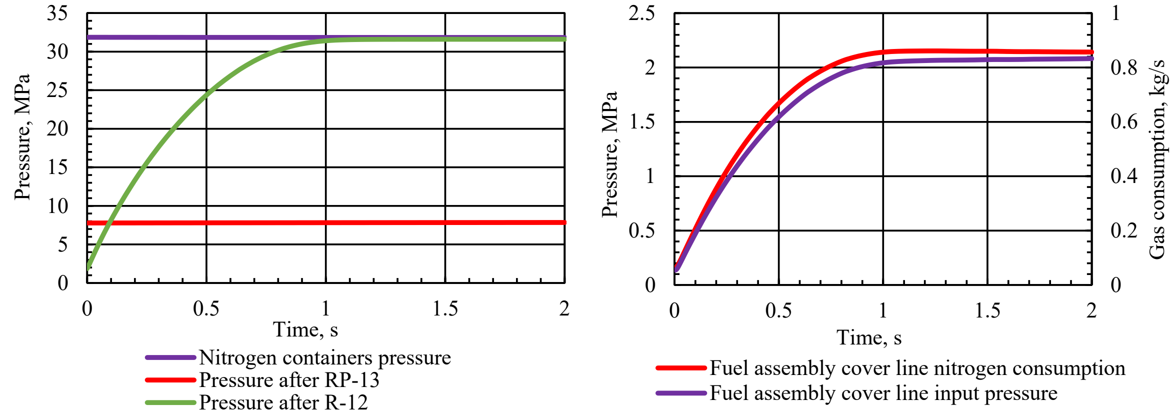
The results of calculating the system parameters during the breakdown of the R-12 gearbox are presented below (Fig. 12).

The time of the transient process in the system during the breakdown of the R-12 gearbox is ~1 second. In this case, the pressure in front of the flow nozzle C2 is practically compared with the pressure in the nitrogen storage tanks, which leads to an increase in the nitrogen flow rate and pressure in the cooling path of the fuel assembly cover. After ~1 second from the moment of gearbox failure, the expected nitrogen consumption in the cooling path of the fuel assembly cover will be 0.83 kg/s. In this case, the pressure at the inlet of the fuel assembly cover increases to 2.2 MPa. Since this pressure is higher than the maximum allowed value for the, it can be assumed that the fuel assembly cover will be depressurized, followed by gas entering the power housing.

If the R-12 gearbox fails, the pressure in the cavity of the fuel assembly cover reaches the maximum allowable value of 2 MPa in 0.7 seconds. It is necessary to analyze the situation in which the cooling path of the fuel assembly cover will be depressurized when the pressure reaches 2 MPa.

2) Calculation of system parameters in case of RP-13 gearbox failure.

The breakdown of the RP-13 gearbox was modeled by reducing the hydraulic resistance at the outlet of tank No. 1 from 5.3×10^{11} m^{-4} to 3.4×10^{8} m^{-4}.



a *b*

Fig. 12. Change in the cooling nitrogen flow rate and pressure in the system tanks during the breakdown of the R-12 gearbox: *a* – change in pressure in the nitrogen storage tank and in the supply pipelines; *b* – change in parameters in the internal cavity of the cooling path of the fuel assembly cover (FA)

The results of calculating the system parameters in case of failure of the RP-13 gearbox are presented below (Fig. 13).

The time of the transition process in the system when the RP-13 gearbox fails is ~5 seconds. The pressure in front of the flow nozzle C1 is practically compared with the pressure in the nitrogen storage tanks, which leads to an increase in the nitrogen flow rate and pressure in the cooling path of the power housing. After ~0.9 seconds from the moment of the gearbox breakdown, the nitrogen consumption in the cooling path of the power case will be 0.8 kg/s. At the same time, the pressure at the inlet of the power housing increases to 0.8 MPa in ~6 seconds.

3) Calculation of system parameters in case of failure of the R-12 gas gearbox and overlap of the discharge line from the cooling path of the fuel assembly cover.

In this version of the calculation, two emergency situations were simulated simultaneously: the failure of the R-12 gas gearbox and the overlap of the discharge line from the cooling path of the fuel assembly cover.

The results of calculating the system parameters are presented below (Fig. 14).

The time of the transition process in the system during the breakdown of the R-12 gearbox and the overlap of the discharge line from the cooling path of the fuel assembly cover is ~0.8 seconds. In this case, the pressure before and after the flow nozzle C2 is practically compared with the pressure in the nitrogen storage tanks. Nitrogen consumption first increases to 0.3 kg/s in 0.24 seconds, and then decreases to zero in ~0.9 seconds after the emergency occurs.

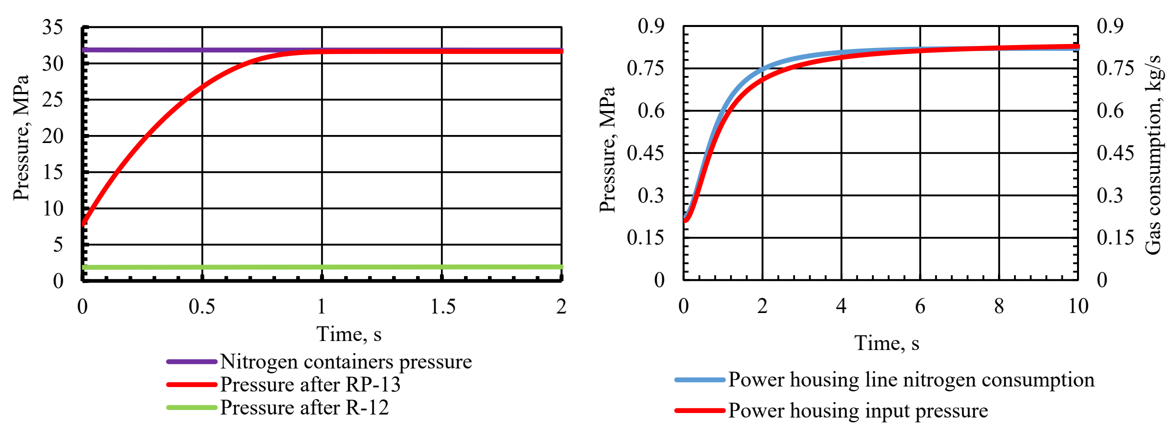
If the R-12 gearbox fails, the pressure in the cavity of the fuel assembly cover reaches the maximum allowable value of 2 MPa in 0.12 seconds. Below is an analysis of the situation in which the cooling path of the fuel assembly cover will be depressurized when the pressure reaches 2 MPa.

4) Calculation of system parameters in case of failure of the RP-13 gas gearbox and overlap of the discharge line from the cooling path of the power housing.

In the calculation, two emergency situations were simulated simultaneously: the breakdown of the RP-13 gas gearbox and the overlap of the discharge line from the cooling path of the power housing.

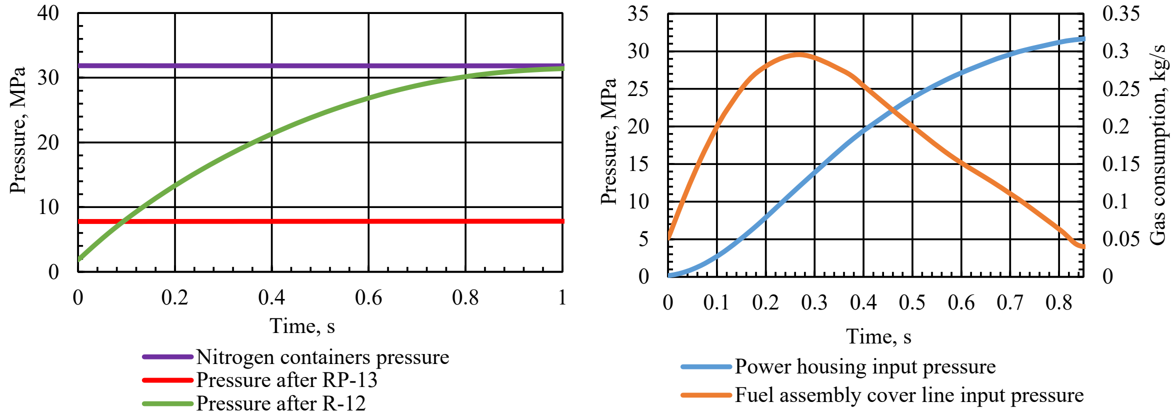
The results of calculating the system parameters are presented below (Fig. 15).

The time of the transition process in the system during the breakdown of the RP-13 gearbox and the overlap of the discharge line from the cooling path of the power housing is ~58 seconds.



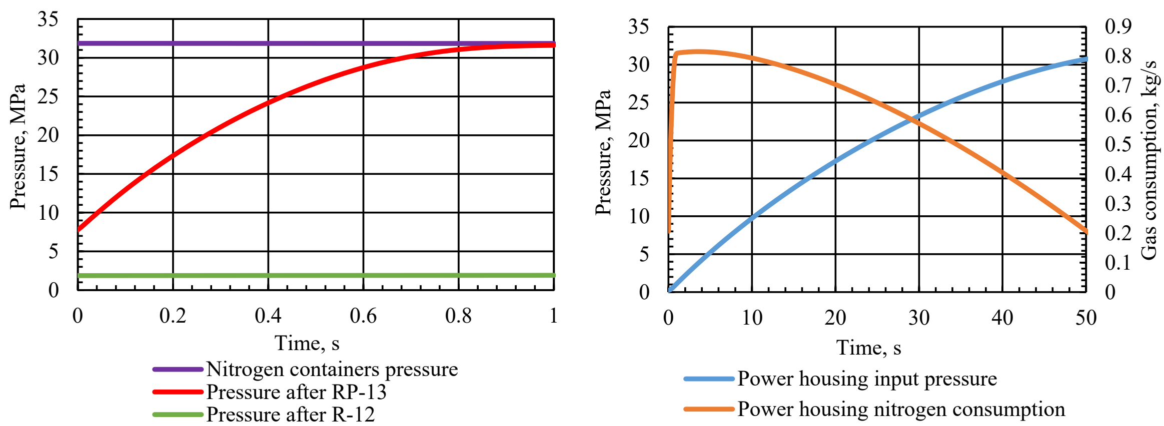
a *b*

Fig. 13. Change in the cooling nitrogen flow rate and pressure in the system tanks when the RP-13 gearbox fails: *a* – change in pressure in the nitrogen storage tank and in the supply pipelines; *b* – change in parameters in the internal cavity of the cooling path of the power housing



a *b*

Fig. 14. Change in the cooling nitrogen flow rate and pressure in the system tanks during the breakdown of the R-12 gearbox and the overlap of the discharge line from the cooling path of the fuel assembly cover: *a* – change in pressure in the nitrogen storage tank and in the supply pipelines; *b* – change in parameters in the internal cavity of the cooling path of the fuel assembly cover (FA)



a *b*

Fig. 15. Change in the cooling nitrogen flow rate and pressure in the system tanks during the breakdown of the RP-13 gearbox and the overlap of the discharge line from the cooling path of the power housing: *a* – change in pressure in the nitrogen storage tank and in the supply pipelines; *b* – change in parameters in the internal cavity of the cooling path of the power housing

The pressure before and after the flow nozzle C1 is practically compared with the pressure in nitrogen storage tanks. Nitrogen consumption first increases to 0.81 kg/s in 1.8 seconds, and then decreases to zero in ~58 seconds after the occurrence of the considered emergencies. In this case, the pressure at the entrance to the power housing reaches the maximum allowable value – 8 MPa in 8 seconds. Emergency pressure relief devices must be provided for the power housing cavity.

5) Calculation of system parameters in case of discharge lines overlap of the device cooling paths.

To simulate the overlap of the discharge lines for the device cooling paths, the hydraulic resistance at the output of the fuel assembly cover and the power housing was set infinitely large (equal to $1.10 \cdot 10^{100}$ m^{-4}). The calculation of changes in hydraulic parameters for this case was carried out under the condition that the gas reducers of the system continue to provide a constant pressure in front of the flow nozzles of the cooling paths, equal to 2 and 8 MPa.

The calculation results show that if the discharge line of the cooling path of the housing is blocked, the pressure in the internal cavity of the power housing of the device increases relatively slowly. For 250 seconds of the process, the pressure in the cavity increases to 8 MPa (Fig. 16, *a*). The situation is not dangerous for the power housing.

When the discharge line of the cooling path of the fuel assembly cover of the device is closed, the cavities of the cooling path are quickly filled with nitrogen, and in ≈0.5 seconds the pressure in the cavity of the cooling jacket of the fuel assembly cover rises to 2 MPa (Fig. 16, *b*). In this case, the cooling jacket of the fuel assembly cover may be depressurized, followed by gas entering the cavity of the power housing.

Calculated estimates of the system behavior during depressurization of the fuel assembly cover cooling jacket were carried out under the condition that nitrogen is discharged from the body cavity through the standard discharge line and through the discharge line of the fuel assembly cover, and the gas reducers of the system continue to provide a constant pressure in front of both flow-setting nozzles of the cooling paths equal to 8 MPa (conservative approach).

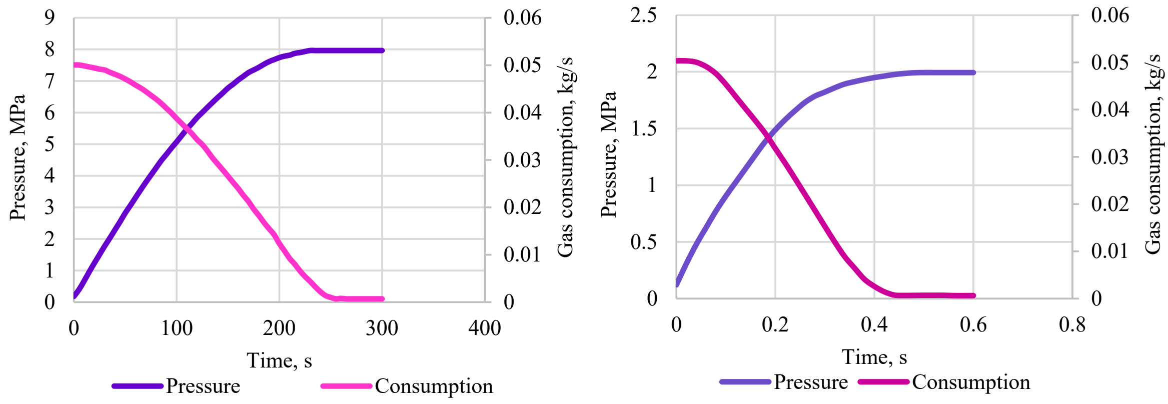


Fig. 16. Changes in the cooling nitrogen flow rate and pressure in the system tanks when the discharge lines of the cooling paths are closed: *a* — change of parameters in the cooling path of the power housing; *b* — change of parameters in the cooling path of the fuel assembly cover

6. Discussion of results of the study of the cooling system model of an experimental device in the pulsed graphite reactor

The choice of the IGR reactor for research in the field of nuclear power safety justification is due to the fact that the technical characteristics of the reactor provide the possibility of modeling severe accidents in a wide range of basic determining quantities such as time (from one tenth to hundreds of seconds), fluence of the thermal neutron flux (up to 3.7×10^{16} n/cm^2), maximum thermal neutron flux in the neutron flash mode (up to 0.7×10^{17} n/cm^2 s).

Graphite is a good moderator, has a high heat capacity, is resistant to high temperature and thermal shocks, well removes and absorbs heat from uranium fuel particles. These properties of graphite made it possible to dispense with a special core cooling system (coolant circuit) – the energy released in the core during reactor start-up is accumulated in graphite and then discharged by water cooling experimental devices (fixed ampoules of the central and lateral experimental channels) and the reactor vessel.

The unique characteristics of the IGR reactor and its bench technological systems predetermined the deployment of a test program for fuel rods and fuel assemblies of power reactors in the IGR reactor. Currently, in-reactor experiments are being conducted at the IGR reactor to study the processes accompanying severe accidents of fast neutron power reactors with core melting.

To study the normal operation of the system and analyze possible emergency situations, the cooling system of the experimental device was presented in the form of groups of interconnected sections of the hydrodynamic system – tanks with specified volumes and hydraulic resistances of pipelines connecting these tanks. Hydraulic resistances are the main parameters in the modeling of this class of problems, since they determine the pressure drops and flow rate of the flowing gas between adjacent sections of the hydrodynamic system. During the calculations, the cooling system was conditionally divided into five «tanks» connected by pipelines with specified hydraulic resistances (Fig. 1).

The model of the cooling system of the experimental device is recruited from separate modules, each of the modules describes a separate section of the hydrodynamic system, taking into account its geometric characteristics and hydrodynamic resistances of pipelines, as well as the relationship of this section with neighboring sections.

A mathematical model has been obtained for this model, which is described by equations (1)–(3) and a computer model has been developed (Fig. 3–10).

Based on the results of calculations of the parameters of the normal operation of the cooling systems of the channel of the experimental device and an assessment of the consequences of possible failures in the operation of the system, it was obtained:

– breakdown of the R-12 gearbox leads to a sharp increase in the nitrogen pressure at the inlet of the cooling path of the fuel assembly cover above the maximum permissible value (2 MPa) for it, as a result of which the fuel assembly cover may be depressurized with subsequent entry of cooling gas into the cavity of the power housing of the inner housing of the ampoule;

– breakdown of the R-12 gearbox and overlap of the discharge pipeline (superposition of two initial events) leads to an increase in pressure in the fuel cover path to the maximum allowable value of 2 MPa for it in 0.09 seconds, followed by depressurization of the fuel cover cooling path;

– breakdown of the RP-13 gearbox leads to a slight increase in pressure, which does not exceed the maximum permissible value (8 MPa) for the power housing; the situation is not dangerous;

– breakdown of the RP-13 gearbox with the overlap of the discharge line of the power housing (superposition of two initial events) leads to an increase in pressure at the inlet to the cooling path of the ampoule to the maximum allowable value of 8 MPa in 8 seconds;

– in the event of both the cooling nitrogen supply pipeline to the fuel assembly cover and the discharge lines breaking simultaneously, the power housing's pressure increases to 8 MPa within 60 seconds.

Based on the fact that the power housing is designed to withstand a pressure of 8 MPa, it can be concluded that, in emergency situations affecting the cooling system, the structural integrity of the device remains intact, and the power elements are not destroyed.

The main feature of this study is the creation of a mathematical model of the cooling system of an experimental device in IGR reactor and conducting computer experiments to analyze its operation. This allows to study the system in more detail and accurately than existing methods, and evaluate its performance in various scenarios.

One of the limitations is abstracting the model, which may not take into account all the details and complexities of a real cooling system. Simulation data may be limited by the accuracy of mathematical models and input parameters.

The results obtained can serve as a basis for improving the safety and efficiency of the IGR reactor and similar cooling systems.

Further development of the study may include expanding the model to account for additional parameters and more complex scenarios.

In general, this study represents an important step in the analysis of the cooling system of the experimental device in the IGR reactor.

Thus, this study made it possible to develop a model of the cooling system in the IGR reactor, identify the features of its operation and analyze emergency scenarios.

The results obtained can serve as a basis for improving the safety and efficiency of the IGR reactor and similar cooling systems.

7. Conclusions

1. A mathematical model of the cooling system of the experimental device has been developed, which takes into account the geometric characteristics and hydraulic resistance of pipelines. The model of the cooling system of the experimental device allows to study its functioning in detail and assess the consequences of possible failures in the system. The developed mathematical model showed the correct modeling of the processes occurring when filling the cooling system with nitrogen. The required pressures and flow into the cooling paths of the fuel assembly cover and the power housing were achieved.

As a result of the study, the following regularities of the cooling system were revealed: the breakdown of the R-12 gearbox causes depressurization at a pressure of more than 2 MPa, and the breakdown of the RP-13 remains safe, reaching a maximum of 8 MPa. The breakdown of the RP-13 gearbox with the overlap of the discharge line of the power housing led to an increase in pressure at the inlet to the cooling path of the ampoule to a maximum of 8 MPa in 8 seconds. In case of simultaneous breakage of the cooling nitrogen supply pipeline and closure of the discharge lines, the pressure in the power housing increased to 8 MPa within 60 seconds. It is important to note that the power housing of the device remained inaccessible to destruction, confirming its resistance to emergency situations.

2. A computer model of the cooling system of an experimental device in a pulsed graphite reactor in a mathematical interactive package Matlab/Simulink has been developed. The model made it possible to analyze the operation of the cooling system in various modes and conditions. The obtained results showed that in emergency scenarios, such as breakdown of gearboxes R-12 and RP-13, the pressure in the system may exceed the maximum permissible values (2 and 8 MPa, respectively).

As part of the study, the peculiarities of the cooling system operation in normal and emergency situations were revealed. This includes the supply of nitrogen to cool the internal cavity of the power housing and the need to maintain the temperature of its walls within acceptable values.

3. To evaluate the model of the cooling system, calculations of various emergency situations caused by a violation of the normal operation of the nitrogen supply system in the cooling paths of the fuel assembly cover were carried out. The results obtained were confirmed by numerical implementation and computational experiments in solving real test problems. Validation of the results allowed to conclude that the developed computer model is applicable for the correct modeling of processes occurring when filling the cooling system with nitrogen.

During the validation of the cooling system model, calculations of various emergency scenarios were carried out, including the breakdown of the R-12 gearbox, the overlap of the discharge pipeline, the breakdown of the RP-13 gearbox and its combination with the overlap of the discharge line of the power housing. The numerical results obtained were carefully compared with real test tasks, which confirmed the accuracy and applicability of the developed computer model for reliable modeling of processes associated with filling the cooling system with nitrogen. These calculations included the following numerical estimates: nitrogen pressure, time parameters of pressure growth, and maximum pressure values in various parts of the cooling system, which ensured the reliability of the results and confirmed the applicability of the developed model to real conditions.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorial or otherwise, which could affect the research and its results presented in this article.

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The study was conducted without financial support.

Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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