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Создан в целях освещения результатов исследований и реальных достижений по актуальным вопросам машиностроения, техносферной безопасности, современной металлургии и материаловедения. В журнале освещаются проблемы развития фундаментальных исследований и инженерных разработок в ряде важнейших областей технических наук. Одним из главных направлений деятельности журнала является интеграция в международное информационное пространство.

Журнал включен в перечень рецензируемых научных изданий, в котором должны быть опубликованы основные научные результаты диссертаций на соискание ученой степени кандидата наук, на соискание ученой степени доктора наук (Перечень ВАК) по следующим научным специальностям:

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2.6.5 – Порошковая металлургия и композиционные материалы (технические науки)
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Original Empirical Research

Development of a Calculation Method for a Combined Filter

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EDN: URXCEZ

Abstract

Introduction. If wastewater treatment becomes less effective, the intensity of treatment facilities should be increased. Several approaches to solving this issue have been described in the literature. For example, to intensify the coagulation process, researchers have used controlled mechanical mixing of coagulants with effluents, mixing with air, and injecting the coagulant using jet or chamber mixers. The authors of this paper propose integrating a vertical clarifying filter (VCF) and a mixing chamber into one housing. This is a novel approach that eliminates the disadvantages of operating separate devices, such as the need for additional space, the possibility of forming aggregates close to the area where they are removed on filters, and avoiding breakage of flakes in connecting pipelines. Experimental evidence has previously demonstrated the effectiveness of this installation. The aim of this study is to develop a scientific methodology for calculating the combined filter, which is essential for widespread adoption.

Materials and Methods. The mixing efficiency of the fluidized bed was determined using the Camp criterion, which characterized the energy spent on mixing. Relevant publications on the subject were also taken into account. Special attention was paid to the description of coagulation. Before developing the calculation method, the authors conducted experiments and created a mathematical model of the installation. The operation of a combined filter with a mixing chamber consisting of a rapid mixing tank with a floating load and a settling tank was considered. The main initial data for the calculation method included: maximum wastewater flow rate, water viscosity, filter diameter, distance from load to housing, backwash intensity, and the volume of expansion of load during backwashing.

Results. The paper shows that the Camp criterion depends on various factors, including mass, area, contact time, and viscosity of particles in a fluidized bed. The calculation of the mixing chamber of the filter was based on this dependence. The regeneration of filters related to the efficiency of backwashing was taken into account. The method for calculating the mixing chamber was presented, and factors that could reduce the effectiveness of backwashing were discussed. As compensation, it was proposed to increase the intensity of backwashing or reduce the height of the filter layer. It was shown how to calculate the dimensions of the mixing chamber elements — the diameter and height of the tanks. A self-check was included in the calculation to avoid errors.

Discussion and Conclusion. For the first time, an improved combined filter design and a method for calculating it are described. The proposed approach makes it possible to determine the dimensions of the mixing chamber and ensure the necessary backwash efficiency. The new solution is of practical interest for enterprises that operate wastewater treatment plants with VCF.

Keywords: vertical clarifying filter, combined filter, calculation of a combined filter, Camp criterion for fluidized bed, filtration intensification

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Оригинальное эмпирическое исследование

Разработка методики расчета комбифильтра

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Аннотация
Введение. При ухудшении очистки стоков следует повысить интенсивность работы очистных сооружений. Некоторые подходы к решению данной задачи описаны в литературе. Известно, как в целях интенсификации процесса коагуляции используется регулируемое механическое перемешивание коагулянта со стоками, перемешивание с помощью воздуха, ввод коагулянта посредством струйных или камерных смесителей. Авторы данной статьи предлагают интегрировать в одном корпусе фильтр осветлительный вертикальный (ФОВ) и камеру перемешивания. Такой подход описан впервые. Исключены недостатки, характерные для эксплуатации обособленных устройств: не нужны дополнительные площади, можно расположить рядом зоны образования агрегатов и их удаления на фильтрах, а также избежать разбивания хлопьев в соединяющих трубопроводах. Эффективность установки ранее подтвердилась экспериментально. Цель данного исследования — разработать научно обоснованную методику расчета комбифильтра, что важно для массового внедрения.
Материалы и методы. Эффективность перемешивания псевдоожиженного слоя определяли по критерию Кэмпа, который характеризует энергию, затрачиваемую на перемешивание. Учитывались публикации, посвященные исследуемой проблеме. Особое внимание уделяется тому, как описана коагуляция. До разработки методики расчета авторы провели эксперименты и создали математическую модель установки. Рассматривается функционирование комбифильтра с камерой перемешивания, которая состоит из чаши интенсивного перемешивания с плавающей загрузкой и чаши успокаивания. Основные исходные данные для методики расчета: максимальный расход стоков, вязкость воды, диаметр фильтра, высота от загрузки до корпуса, интенсивность обратной промывки и объем расширения загрузки при обратной промывке.
Результаты исследования. Показано, как критерий Кэмпа зависит от массы частиц, их площади, времени контакта и вязкости псевдоожиженного слоя. На этой зависимости основан расчет камеры перемешивания комбифильтра. Принимается во внимание регенерация фильтров, связанная с эффективностью обратной промывки. Приводится методика расчета камеры перемешивания. Учитываются факторы снижения эффективности обратной промывки. В качестве компенсации предлагается усилить интенсивность промывки или уменьшить высоту фильтрующего слоя. Показано, как рассчитать габариты элементов камеры перемешивания — диаметр и высоту чаш. В расчете также заложена самопроверка, которая позволит избежать ошибок.
Обсуждение и заключение. Впервые описаны усовершенствованная конструкция комбифильтра и методика его расчета. Предложенный подход позволяет определить габариты камеры перемешивания и обеспечить необходимую эффективность обратной промывки. Новое решение представляет практический интерес для предприятий, которые эксплуатируют очистные сооружения с ФОВ.

Ключевые слова: фильтр осветлительный вертикальный, комбинированный фильтр, расчет комбифильтра, критерий Кэмпа для псевдоожиженного слоя, интенсификация фильтрования

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Introduction. By the end of 2022, polluted wastewater accounted for an average of 33.4% of the total volume of wastewater in Russia[1]. One of the main reasons for this issue is insufficient cleaning of wastewater. Industrial facilities use not only one- or two-stage systems, but also integrated solutions that provide several stages of cleaning. They consist of components such as raking devices, reverse osmosis membranes, and evaporation plants. Despite the variety and complexity of these systems, there are several obstacles to their efficiency:

– high cost of equipment;
– outdated structures;
– deterioration of wastewater quality.

[1] *On the State and Protection of the Environment of the Russian Federation in 2022.* The State Report. Ministry of Natural Resources and Ecology of the Russian Federation. (In Russ.) URL: https://2022.ecology-gosdoklad.ru (accessed: 26.08.2024).

To address these challenges, there are several methods that can be used to improve the performance of wastewater treatment plants. These methods include mixing coagulants with water in different ways:

– controlled mechanical [1];
– with the addition of air and concentrated coagulant [2];
– due to cavitation resonance effects [3];
– using jet [4] or chamber mixers [5].

However, these technical solutions have their drawbacks. Firstly, additional space is required to accommodate equipment such as a flocculator or flocculation chamber. Secondly, the areas where aggregates form and are removed from the filters are located some distance apart. Thirdly, when flocculation and filtration are separated, flakes break up in connecting pipelines.

To address this issue, we need water purification systems that integrate multiple processes into one unit. This would improve the existing systems and save space. We would like to emphasize that it concerns upgrading the existing equipment. To achieve this goal, it is advisable to use combined filters.

The aim of the work is to develop a scientifically sound method of calculation that would allow for the replication of positive effects of a combined filter with other filters.

Materials and Methods. The authors propose a utility model of a combined filter [6]. This is a sand filter with a coagulant mixing chamber built into its body. Earlier, the expediency of this approach was proved by the authors of this article [7]. Combined installations and systems are suitable for solving multiple problems simultaneously. For example, biochar can be used to remove microplastics from water [8], and the hybrid membrane distillation system can produce purified water and generate electricity [9], while reverse osmosis can be powered by a concentrated solar gas engine [10].

According to the authors, the proposed utility model of a combined filter (Fig. 1) represents an effective solution for enhancing filtration in existing industries. The design of the presented filter differs slightly from the original one [6], due to design features identified through computer modeling [7]. These features allowed for an increase in the efficiency of the filter.

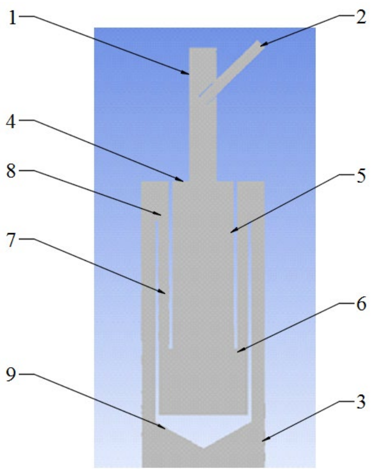

Fig. 1. Design of the combined filter: 1 — source water pipe; 2 — reagent supply pipe; 3 — filter housing; 4 — mixing chamber; 5 — rapid mixing tank with floating load; 6 — lower overflow; 7 — settling tank; 8 — upper overflow; 9 — cone insert

Through pipes 1 and 2, water and coagulant flow into the rapid mixing tank. The coagulant is mixed in the first chamber under the pressure of source water due to the mixing load. After the coagulant treatment, the water is directed through the lower overflow into the settling tank, and then through the upper overflow into the filter housing.

The coagulant helps to neutralize the charge of colloidal particles [11] and form insoluble compounds [12]. The coagulation process includes two stages [13], for each of which specific zones are provided in the mixing chamber.

The first stage, the perikinetic stage, takes place in the mixing chamber. Due to the special loading inside the chamber, the reagents are evenly and quickly distributed, and a high flow velocity gradient is achieved. Contact coagulation will further increase the efficiency of reagent treatment.

The lower overflow is located between the mixing and flocculation chambers and performs the key function of protecting the mixing load from being carried further into the tank and into the filter. It also helps to reduce flow turbulence.

With a mixing intensity of no more than $G = 50 – 60\ C^{–1}$ [14] optimal conditions for the formation of flakes are created in the chambers.

The second stage of the coagulation process is orthokinetic. It takes place in a settling chamber is accompanied by an increase in the size of colloidal particles greater than1 μm [15]. It implements the functionality of a flocculation chamber.

The source water, together with the formed flakes, enters the filter housing through the upper overflow. A conical insert in the lower part of the housing is needed to eliminate swirls that can destroy the flakes.

When developing the calculation methodology, the authors summarized the literature data, conducted laboratory tests, and performed mathematical modeling. The results of the laboratory studies confirming the effectiveness of the proposed solution are given in [7]. To evaluate the criteria for the processes, the Camp criterion was selected, which evaluated the energy spent on mixing. The literature analysis allowed us to find out how the effectiveness of backwashing depended on its intensity and the degree of load expansion. In addition, the value of the gradient for the fluidized bed was known from publications.

Results

1. Fluidized bed mixing intensity. Fluidized bed mixing intensity was used as a criterion of work efficiency. Based on this indicator, it was possible to use a mixing chamber with filters of various sizes and ensure the previously obtained result [7]. According to [16], the intensity of mixing of the reagent with water was characterized by the Camp criterion:

$$Э = G \cdot t, \tag{1}$$

where t — residence time in the mixing chamber, s; G — velocity gradient, 1/s.

Residence time in the mixing chamber:

$$t = \frac{V}{Q}, \tag{2}$$

where V — volume of the mixing tank, m^3; Q — flow rate of source water, m^3/s.

Velocity gradient:

$$G = \sqrt{\frac{\Delta p}{\mu t}}, \tag{3}$$

where Δp — pressure drop in the mixing chamber, Pa; μ — dynamic viscosity of water, Pa·s; t — mixing time, s.

According to [17], the pressure drop for a fluidized bed is determined by the formula:

$$\Delta p = \frac{m_ч g}{S}, \tag{4}$$

where $m_ч$ — mass of all particles, kg; g — acceleration of gravity, m/s^2; S — cross-sectional area of the mixing tank, m^2.

Combining (1)–(4), we obtain the equation of the Camp criterion:

$$Э = \sqrt{\frac{m_ч g}{S \mu t}} \cdot \frac{V}{Q}. \tag{5}$$

Using formula (5) for laboratory bench [7], the Camp criterion was calculated. It was accepted equal to 100 units.

2. Mixing chamber calculating methodology. The following is a method for calculating the mixing chamber and the required initial data for the calculation.

Initial data:

– the Camp criterion, Э;
– maximum flow rate of the treated water, Q, m^3/h;
– dynamic viscosity of water, μ, Pa·s;
– bulk particle density $\rho_{m_ч}$, kg;
– acceleration of gravity, g, m/s^2;
– filter diameter, $d_ф$, m;
– height from loading to housing, H, m;
– backwashing intensity, $ИОП_1$, l/(s c·m^2);
– volume of load expansion during backwashing, V_{exp1}, m^3.

By converting formula (5), system of equations (6) can be obtained, which is used to determine the dimensions of the mixing chamber.

$$\begin{cases} d_{\text{ч.п.}} \cdot H_{\text{ч}} = 2 \cdot Э \cdot Q \sqrt{\dfrac{\mu \cdot t}{\pi \cdot m_{\text{ч}} \cdot g}} \\ t = \dfrac{\pi \cdot d_{\text{ч.п}}^2 \cdot H_{\text{ч}}}{4Q} \\ m_{\text{ч}} = \rho_{m_{\text{ч}}} \cdot \dfrac{\pi \cdot d_{\text{ч.п}}^2 \cdot H_{\text{ч}}}{Q} \end{cases}. \tag{6}$$

Here $d_{\text{ч.п.}}$ — mixing tank diameter, m; $H_{\text{ч}}$ — height of the mixing tank and the settling tank, m.

The flow rate in the settling tank should be equal to the flow rate in the filter housing. To determine the diameter of the settling tank (the entire chamber as a whole), we use the formula:

$$d_{\text{ч.у.}} = \sqrt{\frac{d_{\text{ф}}^2 + d_{\text{ч.п.}}^2}{2}}, \tag{7}$$

where $d_{\text{ч.у.}}$ — settling tank diameter, m.

Let us check whether the chamber fits into the filter housing. To do this, we take into account:

– height of cone insert H_{cone} (1/4 of the diameter of the chamber);

– margin of the distance from the cone to the load with a minimum height of 1/16 of the diameter of the chamber.

$$H - H_{\text{ч}} - \frac{d_{\text{ч.у.}}}{4} - \frac{d_{ч.у.}}{16} \geq 0. \tag{8}$$

Let us check that the camera size is correct:

$$d_{\text{ч.у.}} < d_{\text{ф}}. \tag{9}$$

If conditions (8) or (9) are not met, then it is necessary to return to (6) and adjust the dimensions of the mixing chamber.

Let us calculate the volume occupied by the mixing chamber:

$$V_{chamber} = \frac{\pi \cdot d_{\text{ч.у.}}^2}{4} \cdot \left(H_{\text{ч}} + \frac{d_{\text{ч.у.}}}{12} \right). \tag{10}$$

Let us define the condition for ensuring the necessary load expansion:

$$\frac{\pi \cdot d_{\text{ф}}^2}{4} \cdot H_{\text{ч}} - V_{chamber} \geq V_{exp1}. \tag{11}$$

If the condition is not met, the backwashing efficiency may be reduced. To address this issue, it is important to understand how backwashing effectiveness can be maintained.

1. By increasing the intensity of backwashing, we find new backwashing intensity $ИОП_2$ [18]:

$$ИОП_1 \cdot V_{exp1} = ИОП_2 \cdot \left(\frac{\pi \cdot d_{\text{ф}}^2}{4} \cdot H - V_{chamber} \right). \tag{12}$$

2. By reducing the loading height, we find the height value from the housing to the load H_{new}, which will provide the necessary volume for the load expansion:

$$H_{new} = \frac{V_{exp1} + V_{chamber}}{\dfrac{\pi \cdot d_{\text{ф}}^2}{4}}. \tag{13}$$

Let us calculate how much the load height needs to be reduced:

$$\Delta H_{load} = H - H_{new}. \tag{14}$$

3. For calculations related to changes in the intensity and volume of loading, we use formulas (12) and (13), taking into account the necessary conditions. For example, based on the capabilities of specific wastewater treatment plants, we use (13) to set the permissible value for reducing the loading height, set it to (12) and calculate the desired backwashing intensity.

Let us determine the volume of mixing tank $V_{\text{ч.п.}}$ and settling tank $V_{\text{ч.у.}}$:

$$V_{\text{ч.п.}} = \frac{\pi \cdot d_{\text{ч.п.}}^2}{4} \cdot H_{\text{ч}}, \tag{15}$$

$$V_{\text{ч.у.}} = \frac{\pi \cdot \left(d_{\text{ч.у.}}^2 - d_{\text{ч.п.}}^2 \right)}{4} \cdot H_{\text{ч}}. \tag{16}$$

Let us calculate the required volume of mixing load V_{load}:

$$V_{load} = \frac{1}{3} V_{ч.п.}. \tag{17}$$

Let us calculate water residence time in the mixing and calming tanks:

$$t_{ч.п.} = \frac{3600 \cdot V_{ч.п.}}{Q}, \tag{18}$$

$$t_{ч.у.} = \frac{3600 \cdot V_{ч.у.}}{Q}. \tag{19}$$

Discussion and Conclusion. The scientific research results of presented in the paper suggest that it is reasonable to use the proposed method for calculating the filter's performance. Firstly, this method is based on reliable data from published sources. Secondly, its relative simplicity — consisting of only 19 concise formulas — makes it practical for real-world applications. After completing this research, the authors verified the previously obtained findings. It was crucial to demonstrate that the simulated mixing chamber enhances the filtration process and improves coagulation activity. Therefore, we can use the mixing intensity of a fluidized bed as a measure of efficiency. The method of calculating a mixing chamber allows us to determine its size and ensure the required backwash efficiency. This solution can be applied to vertical clarifying filters of various types and sizes. Therefore, this technique can be applied to any production facility that uses such equipment.

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Refinement of the Ground Forest Fire Model Taking into Account Convective Turbulence

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Abstract

Introduction. The scientific literature is actively discussing the topic of mathematical modeling of forest fires development to predict the speed of spread and area covered. From the perspective of turbulent processes, the height and deflection of fire, smoke, and hot air columns, as well as the spread of combustion particles and rational directions for extinguishing the fire, are evaluated. However, existing models do not provide a clear understanding of how turbulence occurs during the transition of a fire from a near-surface to an unsteady surface layer and higher. In other words, calculating the transition from ground fire to its more intense form remains a challenge. Addressing this gap is an urgent scientific and practical task. The aim of this study is to refine the equations of mathematical models for predicting the spread of forest fires, in order to better control these incidents, which will ultimately help reduce risks and damage from them.

Materials and Methods. To achieve this goal, we studied works covering different approaches, both theoretical and practical, devoted to the problem of predicting the development of fires. The works of D.L. Laikhtman, A.S. Gavrilov, and P.M. Matveev were accepted as the main ones. In addition to analyzing these literary sources, the authors applied statistical methods of information processing and used the possibilities of mathematical modeling.

Results. The generally accepted elliptical shape of the contour of a ground forest fire in the R. Rothermel model has been interpreted. Its disadvantages for predicting spot and intense crown fires have been demonstrated. The introduction of parameters such as relative humidity, terrain slope, surface roughness or viscosity, and features of the burning substance into the equation has been evaluated. The types of convection typical of spot and intense crown fires have been indicated: internal (thermal) and external (mechanical). The decision not to consider near-surface turbulence has been justified. To account for surface air layer turbulence, the authors have relied on the concepts of instability and corresponding physical laws. As a result, the basic formula of the R. Rothermel model was supplemented with a second layer so that it was possible to predict the development of a fire from a ground one to an intense crown fire. The dimensionless parameter of 0.397 was replaced by turbulence coefficient k_z. This indicator was introduced into the corrected R. Rothermel equation and supplemented with the average Richardson number, which showed the relationship between temperature and the diffusion rate in neighboring layers. From these components, an updated formula has been developed. The results of simulations for typical cases of convective turbulence and fires, with and without turbulence, were presented in tables. Based on the summary data, we could conclude that the model developed within the scope of this work was adequate.

Discussion and Conclusion. When refining the semi-empirical R. Rothermel model for an unsteady surface layer, the introduction of a turbulence coefficient is justified. In addition, it is shown that it is necessary to supplement the single-layer model with second-level formulas characterizing the development of a fire in an unsteady surface layer. The adjusted model should more effectively predict the parameters of spot and intense crown fires. Further refinements of equations for semi-empirical forest fire models are promising, and it is advisable to continue research in this area.

Keywords: mathematical modeling of fire, turbulence in fire conditions, transition from ground to crown fire

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Оригинальное теоретическое исследование

Уточнение модели низового лесного пожара с учетом конвективной турбулентности

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Аннотация

Введение. В научной литературе довольно активно обсуждается тема математического моделирования развития лесных пожаров для прогнозов скорости их распространения и площади, которую они охватят. С точки зрения процессов турбулентности оцениваются потенциальная высота и отклонение столбов огня, дыма, горячего воздуха, разброс частиц горения и рациональные направления гашения огня. Однако известные модели не дают четкого представления о том, как срабатывает турбулентность при переходе пожара с приповерхностного слоя на нестационарный приземный и выше. Иными словами, сложно просчитать переход низового пожара в его более опасную интенсивную форму. Восполнение этого недостатка — актуальная научная и прикладная задача. Цель данной работы — уточнить уравнения математических моделей распространения низовых лесных пожаров для лучшего контроля за этими инцидентами, что в итоге будет способствовать уменьшению рисков и сокращению ущерба от них.

Материалы и методы. Для достижения цели исследования были изучены труды, охватывающие разные подходы, как теоретические, так и прикладные, посвященные проблеме прогнозирования развития пожаров. В качестве основных приняты работы Д.Л. Лайхтмана, А.С. Гаврилова, П.М. Матвеева. Кроме анализа этих литературных источников, авторы применяли статистические методы обработки информации и использовали возможности математического моделирования.

Результаты исследования. Интерпретирована общепринятая эллиптическая форма контура низового лесного пожара в модели Р. Ротермела. Показаны ее недостатки для прогнозирования пятнистых и интенсивных верховых пожаров. Оценено введение в уравнение таких параметров, как относительная влажность воздуха, уклон местности, шероховатость или вязкость поверхности, особенности горящего вещества. Обозначены виды конвекций, характерных для пятнистого и интенсивного верхового пожара: внутренняя (термическая) и внешняя (механическая). Обоснован отказ от учета приповерхностной турбулентности. Для рассмотрения турбулентности приземных слоев воздуха авторы руководствовались представлениями о нестационарности и соответствующих физических закономерностях. В итоге базовая формула модели Р. Ротермела была дополнена вторым слоем, чтобы можно было прогнозировать развитие пожара от низового к интенсивному верховому. Безразмерный параметр 0,397 заменен коэффициентом турбулентности k_z, этот показатель внесен в откорректированное равенство Р. Ротермела и дополнен средним числом Ричардсона, которое показывает зависимость между температурой и скоростью диффузии в соседних слоях. Из этих составляющих была сформирована обновленная формула. В виде таблиц представлены результаты моделирования характерных случаев развития конвективной турбулентности и пожаров (с учетом и без учета турбулентности). Сводные данные позволяют говорить об адекватности модели, созданной в рамках представленной работы.

Обсуждение и заключение. При уточнении полуэмпирической модели Р. Ротермела для нестационарного приземного слоя обосновано введение коэффициента турбулентности. Кроме того, показана необходимость дополнения однослойной модели формулами второго уровня, характеризующими развитие пожара в нестационарном приземном слое. Откорректированная модель должна более эффективно прогнозировать параметры пятнистых и интенсивных верховых пожаров. Перспективны дальнейшие уточнения уравнений полуэмпирических моделей лесных пожаров. Целесообразно продолжить исследования в этом направлении.

Ключевые слова: математическое моделирование пожара, турбулентность в условиях пожара, переход пожара из низового в верховой

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Introduction. According to the United Nations, the number of severe forest fires is expected to increase by 50% by the end of the 21st century. In 2003, fires in Siberia, Russia, destroyed approximately 22 million hectares of forest ecosystems. In 2004, 2.6 million hectares of forest were affected in Alaska, USA. In 2010, 1.5 million hectares of forest ecosystems were destroyed in Bolivia. In Canada, 0.7 million hectares were lost in 2011, and 3.4 million hectares in 2014. In 2020, wildfires destroyed more than 16.8 million hectares of forest in Australia. The economic damage amounts to billions of dollars.

The frequency of forest fires and the damage they cause raise questions about how to adequately model the risks of their occurrence. This includes forecasting the development of emergencies and developing measures to minimize losses. The construction of model equations assumes that a fire will occur on a specific area during a certain time period. It is also necessary to estimate the possible duration of the fire, which depends on a number of factors that can be difficult to determine [1].

Semi-empirical models allow for the selection and refinement of parameters for effective fire prediction in forest ecosystems. These models are based on the principles of mass, energy, and momentum conservation, and they assume that the model equations can be written in a simplified form. The corresponding coefficients or empirical parameters are obtained as a result of observations or experiments [2]. These models spread in the middle of the 20th century and were mainly used to predict grass-root fire dynamics. They usually take into account various parameters related to the combustibility of forest materials, including the initial condition of the forest stand and terrain features.

Meteorological conditions, particularly wind, play a significant role in the occurrence and spread of forest fires. The combustibility of forest floor materials and terrain slopes, which are taken into account, for example, in Richard Rothermell's model [1-3], are of secondary importance. The aim of this research is to refine the mathematical model of the spread of forest fires. This will allow for better emergency response and quicker, more effective action. Timely action and appropriate measures can help reduce losses associated with forest fires.

Materials and Methods. The study is based on an analysis of works on the surface layer instability by D.L. Laikhtman, the structure of the boundary layer by A.S. Gavrilov et al. [4, 5], on the detection of forest fires and their likelihood of becoming intense by P.M. Matveev et al.

The authors also used literary, analytical-statistical, and analytical-graphical methods as well as mathematical modeling.

For this study, problems of mathematical modeling in forest fire prediction were analyzed. The almost insurmountable difficulties in calculations for the most dangerous wildfires were noted [6–8], which were caused by unknown physical characteristics of heat redistribution and the amount of air movement, factors that determined fire parameters.

Therefore, it should be noted that mathematical models do not represent the transformation of spot fires into intense crown fires [9]. In the 1970s, P.M. Matveev established that a fire became a spot one if the intensity of convective flows was sufficient to raise and transport burning particles. At the same time, their burning time should be sufficient to set fire to objects far from the hearth: forest floor, ground vegetation, stands of trees, etc.

In 1964, N.P. Kurbatsky proposed the first model of heat and mass transfer. In it, the burnout area was estimated by the surface air velocity, like most fire propagation models. In 2018, a group of authors proposed a modern version of heat and mass transfer model for predicting fire spotting, taking into account the challenges of writing equations and still not fully solving the problem [9].

As shown in [1–3], spotting is characteristic of any crown fire when the wind increases. However, from the point of view of the ground layer physics, a strong ground flow (wind) will contribute to the ignition and spread of fire in its first stage. At the second stage, both types of convection develop:

– internal (generated by fire, own, thermal, with unstable ground layer air);

– external (created by air-mass conditions, the ground flow velocity loses its significance and prevents the transformation of a surface fire into a spot, crown one).

Gavrilov A.S., Mkhanna A.I., Kharchenko E.V. in the article "Verification of the model of atmospheric boundary layer applied to the problem prediction of air pollution from forest fires" emphasized the need to take into account the proportion of turbulent heat influx in an unstable surface layer with developed thermal turbulence [4]. It was found that even with a very insignificant heat flow q = 0.003 W/m^2 in surface conditions, the intensity of the turbulent heat influx increased significantly — in 35 minutes from 0 to +10.2°C.

Thus, the role of convection is obvious, especially an internal thermal one [4–5]. This factor should be taken into account when constructing mathematical models of the transformation of spot forest fires into crown fires.

Results. The R. Rothermel model [1, 6] is based on empirical material and allows us to efficiently calculate the parameters of a surface forest fire (Fig. 1).

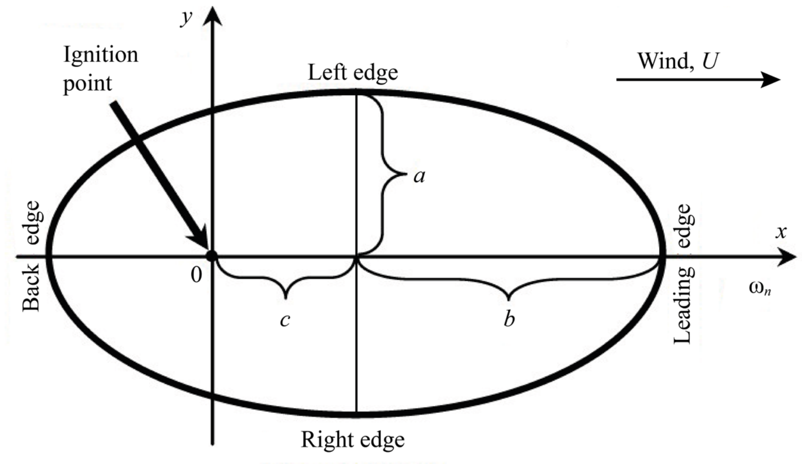

Fig. 1. The generally accepted elliptical shape of the contour of a surface forest fire

To predict the behavior of a forest fire, the ellipse parameters are calculated: *a*, *b* and *c* (formulae 1–3). In this case, the main computational characteristic of the model is the rate of spread of the forest fire, ω_n (m/s), which is determined by (4) [1].

$$a = \frac{b}{LB}, \; b = \frac{\omega_n}{2} + \frac{1+HB}{HB}, \; c = b - \frac{\omega_n}{HB}, \tag{1}$$

$$LB = 0.936\,exp\left(0.2566U\right) + 0.461\,exp\left(-0.1548U\right) - 0.397, \tag{2}$$

$$B = \frac{LB + \sqrt{LB^2 - 1}}{LB - \sqrt{LB^2} - 1}, \tag{3}$$

$$\omega_n = \omega_0\left(1 + k\left(U\right) + k\left(S\right)\right), \tag{4}$$

where a — segment of the ellipse (height); b — segment of the ellipse (the length in the frontal area of the fire); c — segment of the ellipse (the length of the burnt-out area); LB — width of the ellipse segment b; HB — height of the ellipse segment b; U — flow (wind) velocity, m/s; ω_n — speed of forest fire advance, m/min; ω_0 — density of the formation of combustible substances, kg/m^3; $k(U)$ — size of the particles of vegetative burnt matter, m^2; $k(S)$ — rate of complete vegetation burnout, m/min.

The authors believe that this model is not suitable for predicting spot and intense crown fires, as it practically does not take into account meteorological parameters except for the speed of surface flow (wind) [7–8]. In this regard, main predictive equation (2) should be clarified by incorporating additional parameters. Thus, M.A. Sofronov, in 1967, proposed taking into account not only wind speed but also relative humidity, considering its daily fluctuations, and the slope of the terrain and surface roughness or viscosity when assessing the spread rate of surface fires [9–11].

If a crown fire has evolved from a surface one, the rate of fire propagation should be calculated at two levels: near-surface (0–1 m) and surface (1–2 m) [12]. In the near-surface layer, it is more important to take into account the properties of the burning substance, including its density and quantity (see formula 4). In the surface layer (the second level of the model), parameters such as air temperature and humidity, vertical and horizontal flow rates are more significant:

$$\omega_{n_1} = \omega_n \cdot \left|\frac{t_0}{t_1}\right| \cdot \left|\frac{\nu_0}{\nu_g}\right| \cdot \left|\frac{f_0}{f_1}\right|, \tag{5}$$

where ω_{n1} — fire advance rate in the surface layer, m/min; ω_n — fire advance rate in the near-surface layer, m/min, from formula (4); t_0 — air temperature in the near-surface layer, °C; t_1 — air temperature in the surface layer at an altitude of 1–2 m, °C; v_0 — velocity of the air flow in the near-surface layer, m/sec; v_g — horizontal component of the air flow velocity, m/sec; f_0 — relative air humidity in the near-surface air layer, %; f_1 — relative air humidity in the surface layer at a height of 1–2 m.

With the presence of a spot and intense wildfire, both internal (thermal) and external (mechanical) convection occur. Turbulence causes particles to scatter upwards and away from the source, which can significantly alter the parameters *a, b,* and *c*.

The authors note that it is pointless to take turbulence into account in the near-surface layer (0–1 m), since it is extinguished by the surface layer of forest litter or soil. To account for the turbulence of the surface air layers, one should be guided by the concepts of nonstationarity and physical patterns of the surface air layer:

$$\frac{du}{dt} = \frac{d}{dz} k \frac{du}{dz}, \tag{6}$$

$$\frac{d\Theta}{dt} = -\frac{d}{dz} k \frac{d\Theta}{dz}, \tag{7}$$

$$\frac{db}{dt} = k\left(\frac{du}{dt}\right)^2 - k\frac{g}{T}\frac{d\Theta}{dz} - \frac{cb^2}{k} + \alpha_b \frac{d}{dz} k \frac{db}{dz}, \tag{8}$$

$$k = l\sqrt{b}, \tag{9}$$

$$l = -2\kappa C \frac{1}{4} + \frac{\left(\frac{du}{dz}\right)^2 - \frac{g}{T}\frac{d\Theta}{dz}}{\frac{d}{dz}\left[\left(\frac{du}{dz}\right)^2 - \frac{g}{T}\frac{d\Theta}{dz}\right]}, \tag{10}$$

where u — air flow velocity, m/s; t — air temperature, °C; z — height, m; Θ — heat inflow, J/s·m^2·kg; b — energy of turbulence, J/kg; g — acceleration of gravity, m/s^2; l — scale of turbulence, m; k — turbulence coefficient, m/s; c — D.L. Laichtman constant (~0.046); αb — D.L. Laichtman constant calculated by dimensional analysis (0.73); κ — Karman constant calculated to solve this problem (~0.397).

Based on D.L. Laichtman's ideas about the physical laws of an unsteady surface layer of air, we can conclude about the role of turbulent motions in the distribution of heat, energy, and air particles. In the case of diffusion of matter and energy during heating and transformation of the surface soil layer under fire conditions [13–15], modeling is based on the theory of gradient transfer. k is coefficient of turbulent diffusion. k_z is value of diffusion transfer in the vertical plane. Horizontal components of the turbulence coefficient will be negligible due to the surface roughness and the friction force action. To simplify the model equation, we can use the M.I. Budyko equation to calculate vertical diffusion coefficient k_z at a unit level

$$k_z = k_1 p \frac{z}{z_1}\sqrt{1-\overline{Ri}}, \tag{11}$$

where kz — vertical diffusion coefficient, m/s; k_1p — kz value at a unit height of z_1 and under equilibrium conditions, at a height of 1 m, is 0.1–0.2 m/s; $\overline{Ri}$ — average Richardson number with respect to the boundary layer, a dimensionless indicator:

$$\overline{Ri} = \frac{g\frac{dT}{dz}}{T_a\left(\frac{dT}{dz}\right)^2}, \tag{12}$$

where T — air temperature, °C; T_a — temperature in the absolute scale, K; g — acceleration of gravity (9.8 m/s^2).

The authors propose to supplement initial formula (2) of the R. Rothermel model to clarify the development of a fire from a surface one to an intense crown one (second layer of the model), calculating the rate of fire advance ω_{n1} in the surface layer according to formula (5). In this case, equation (2) is supplemented by an expression for calculating turbulence coefficient k_z and replaced by a dimensionless indicator 0.397, because the latter acts as a parameter that reduces the segment width of ellipse a. According to the authors of this work, taking into account intense convection and subsequent turbulence can help to adjust the width of segment a with greater accuracy in relation to real-world conditions. Then formula (2) can be represented by:

$$LB = 0.936\,exp\left(0.2566U\right) + 0.461\,exp\left(-0.1548U\right) - kz. \tag{13}$$

Taking into account expressions (11) and (12), we obtain the final:

$$LB = 0.936\,exp\left(0.2566U\right) + 0.461\,exp\left(-0.1548U\right) - k_1 p \frac{z}{z_1}\sqrt{1 - \frac{g\frac{dT}{dz}}{T_a\left(\frac{dT}{dz}\right)^2}}. \tag{14}$$

Table 1 shows the results of testing equation (14) and modeling typical cases of convective turbulence.

Table 1

Some Results of Modeling Fire Parameters with and Without Turbulence [16] for an Unsteady Surface Layer

No.	Characteristic	*U*, m/s	k_z, m/s	*LB*	*HB*	*a*	*b*	*c*
1	Weak	4.000	–	2.470	22.521	0.521	1.290	1.268
2	Weak	4.000	0.500	2.370	19.640	0.552	1.301	1.276
3	Moderate	8.000	–	7.001	139.001	0.220	1.507	1.500
4	Moderate	8.000	2.000	5.400	107.002	0.281	1.509	1.500
5	Strong	12.000	–	11.610	579.501	0.170	2.001	1.997
6	Strong	12.000	5.000	7.010	199.290	0.290	2.005	1.995

Discussion and Conclusion. The combustion model under conditions of an unsteady surface layer was considered. The values of segment *a* of the elliptical fire edge, taking into account refined expression (14), were compared with the classical R. Rothermel formula [16]. An analysis of the simulation results with the turbulence coefficient (Table 1) revealed the largest deviations of these values. At the same time, no significant differences in the parameters of ellipse *b* and *c* were found, which may confirm the expediency of the proposed refinement.

Adequacy of the obtained values of ellipse segment *a* is determined by the Student's criterion (two-sample *t*-criterion). For this purpose, the calculated values of ellipse segment *a* in the semi-empirical R. Rothermel model and in equation (14) proposed by the authors were compared. Table 2 provides the test results. The calculated value of the Student's t-test is much less than the critical (tabular) value: $0.609 < 2.776$. This proves the statistical convergence of the calculation results in the refined model represented by expression (14).

Table 2

Comparison Results of the Refined Version of the Model Containing the Turbulence Parameter with the Classical Equation of the r. Rothermel Model

No.	Mean value	Variance	Degree of freedom	Combined variance	Value of *t*-criterion	
					calculated	critical*
1	0.374	0.016	4	0.02	0.609	2.776
2	0.304	0.024	4			
**With 95% confidence.*						

Note No. 1 corresponds to calculations using equation (14), which takes turbulence into account. No. 2 corresponds to the classical expression of the Rothermel model, without taking turbulence into consideration.

Thus, the introduction of expression (14) is justified for an unsteady surface layer (the second layer of the model) and makes it possible to significantly adjust the size of ellipse segment *a*, taking into account internal and external vertical convective flows that form turbulence of the surface layer and transform a surface forest fire into an intense crown one.

The adjusted model allows for more efficient calculation of the parameters of spot and intense crown fires within forest ecosystems. Further refinement of the equations for semi-empirical forest fire models is promising. Research in this area should continue.

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Original Empirical Research

Research Results of Heat and Mass Transfer in Conditions of Weak Aerodynamic Coupling with Pulsating Ventilation Mode

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Abstract
Introduction. The issue of heat dissipation in metallurgy is significant due to potential hazards to personnel and the environment. Effective control and management of thermal processes require additional measures and can prevent fires, explosions, and personnel injuries as well as it is a key factor in ensuring the safety and reliability of metallurgical equipment. Metallurgical processes often involve high temperatures, but control over them is necessary for successful steel melting and processing. Current methods of heat transfer control (aeration, general exchange and local ventilation) do not always effectively reduce heat loads to acceptable levels. The choice of a pulsating ventilation mode for increasing the efficiency of heat transfer control is due to two main reasons: low air flow rates in large metallurgical production facilities, and the presence of numerous hard-to-reach areas with heat-generating equipment. The aim of this research is to investigate heat and mass transfer processes in areas with weak aerodynamic coupling with pulsating ventilation mode.
Materials and Methods. To achieve this goal, a method of physical modeling was employed to collect statistical data. Heat and mass transfer were evaluated by measuring temperature changes over time at various points in the model niche under different ventilation conditions (stationary and. pulsating). System analysis was then applied to process the collected data.
Research Results. It was found that pulsating air movement had a positive effect on heat and mass transfer in poorly ventilated spaces inside the laboratory setup. The degree of efficiency of this effect was determined, and it was found that the use of pulsating ventilation slowed down the increase in temperature in the center of the space by 3.8 times compared to the use of general forced ventilation.
Discussion and Conclusion. The data obtained under the simulated conditions of the aforementioned type of production provide a foundation for developing a more specific methodology to counteract the negative effects of heat radiation. This methodology could significantly enhance safety by improving the removal of excess heat in low-aerodynamic areas of mining and metallurgical workshops.

Keywords: experimental results, heat and mass transfer, pulsating ventilation, heat, temperature, weak aerodynamic coupling, air movement

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Оригинальное эмпирическое исследование

Результаты исследования тепломассопереноса в условиях слабой аэродинамической связи при пульсирующем режиме вентиляции

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Аннотация

Введение. Проблема тепловыделения в металлургии актуальна из-за возможных опасностей для персонала и окружающей среды. Действенный контроль за тепловыми процессами и управление ими требуют дополнительных мероприятий и могут предотвратить пожары, взрывы и травматизм в целом. Эффективное управление тепловыми процессами — один из ключевых факторов безопасности и надежности металлургического оборудования. Высокие температуры свойственны металлургии, но контроль за ними необходим для успешного выполнения процессов плавки и обработки стали. Применяемые способы контроля теплопереносом (аэрация, общеобменная и местная вентиляция) не всегда позволяют снизить тепловую нагрузку до требуемого значения. Выбор режима пульсирующей вентиляции для повышения эффективности управления теплопереносом обусловлен двумя основными причинами: низкие скорости движения воздуха, которые свойственны крупным цехам металлургического производства, и большое количество труднодоступных ниш с тепловыделяющим оборудованием в них. Целью данного исследования в связи с этим является изучение процессов тепломассопереноса в зонах со слабой аэродинамической связью при пульсирующем режиме вентиляции.

Материалы и методы. Для получения статистических данных был использован метод физического моделирования. Процесс тепломассопереноса оценивался на основании изменения температуры с течением времени в различных точках модели ниши при разных режимах вентиляции (стационарном и пульсирующем). Для обработки полученных результатов измерений применялся метод системного анализа.

Результаты исследования. Было установлено положительное влияние пульсирующего движения воздуха на тепломассоперенос в плохо проветриваемой импровизированной нише внутри лабораторной установки. Определена степень эффективности влияния пульсирующей вентиляции на тепломассоперенос. Установлено, что при использовании метода пульсирующей вентиляции температура в центральной части ниши повышалась медленнее в 3,8 раза, чем при общеобменной принудительной вентиляции.

Обсуждение и заключение. Данные, полученные в смоделированных условиях вышеуказанного вида производства, позволяют разработать методику борьбы с отрицательным воздействием теплового излучения, что дает возможность повысить безопасность при отводе излишнего тепла в условиях слабой аэродинамики участков цехов горно-металлургических производств.

Ключевые слова: результаты эксперимента, тепломассоперенос, пульсирующая вентиляция, тепло, температура, слабая аэродинамическая связь, движение воздуха

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Introduction. Heat dissipation is an integral part of metallurgical production. Excess heat generation can cause overheating of equipment, which can lead to accidents, damage to production equipment, and injury to workers, resulting in significant financial losses. To control excess heat in the metallurgical process, several methods are used:

1. Direct cooling: cooling of metal in contact with heat sink rods.
2. Water cooling: the use of water to cool metal.
3. Gas cooling: the use of gases to cool metal, which ensures a high level of temperature reduction [1].
4. Cryogenic cooling: the use of supercooled liquid gases for heat treatment of metallic materials [2].
5. Induction cooling: the creation of internal cooling using an alternating magnetic field.

Metallurgical workshops are characterized by a significant amount of heat generated during various stages of metal production, including heating, melting, molding, and casting [3]. In addition, these processes are often accompanied by the emission of dust and gases, leading to an increased concentration of hazardous substances in the air. This can complicate the working conditions for employees and require the use of specialized protective equipment, as well as the compliance with occupational safety and industrial safety requirements [4]. When working in metallurgical workshops, there is also a risk of fires, explosions, and serious thermal injuries [5].

Insufficient cooling of process installations, such as areas with a large number of power cables or local transformer substations, often causes excessive heat generation and heat accumulation, which can lead to equipment failures [6]. Therefore, it is crucial to carefully monitor temperatures at each stage of the process to ensure a stable and safe temperature condition for production facilities and electrical equipment [7]. Regular maintenance and repair of equipment, as well as monitoring of thermal radiation levels in workshops, are necessary to promptly respond to potential problems and develop strategies to address and prevent them [8]. Despite all available cooling methods, emergencies, non-standard situations, and injuries in metallurgical production remain a significant concern, although in the last ten years there has been a downward trend [9].

Analysis of the existing statistical data on accidents and injuries in the mining and metallurgical industry over the past ten years, as well as assessment of the cooling methods used, has shown the need for more effective measures to reduce thermal radiation and ensure the uninterrupted operation of equipment [10]. In this regard, the authors have developed and modeled a process of heat and mass transfer using a method of pulsating air movement, which significantly improves heat transfer with weak aerodynamic coupling [11]. The aim of this research is to study the effect of pulsating airflow on temperature parameters of air environment in conditions of low speeds and difficult aerological permeability with general ventilation in a room. The article presents the results of physical modeling of heat and mass transfer under conditions of weak aerodynamics.

Materials and Methods. The experiments on heat transfer were conducted using a physical model (Fig. 1), which had the following characteristics [12]:

- volume of the ventilated space — 1 m³;
- relative air humidity — from 26 to 28%;
- air temperature — 21–23°C [13].

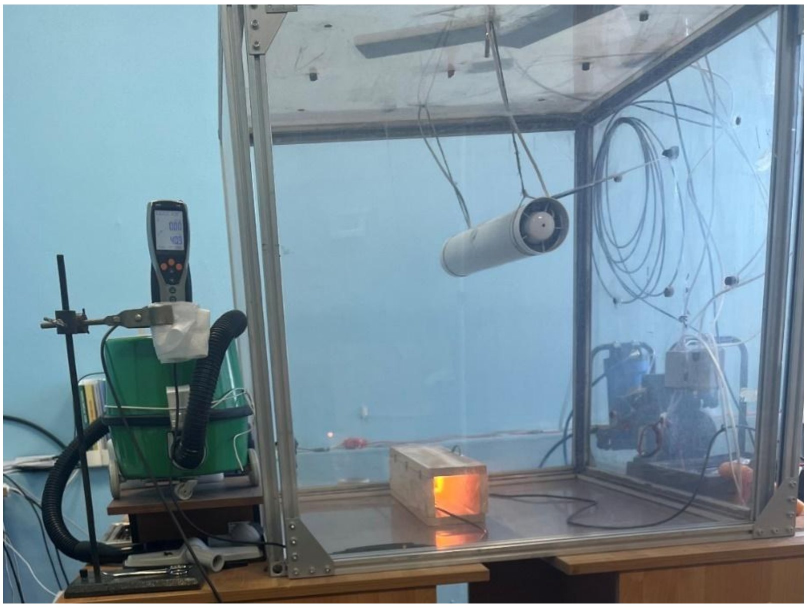


Fig. 1. External view of a laboratory installation for the physical simulation of heat transfer in a pulsating ventilation mode

Figure 1 shows a structure simulating a ventilated room in the form of a cube with sides 1 meter long. The Pulsator device was located in the central part of this volume (Fig. 2 *a*, 5). Its characteristics are shown below:

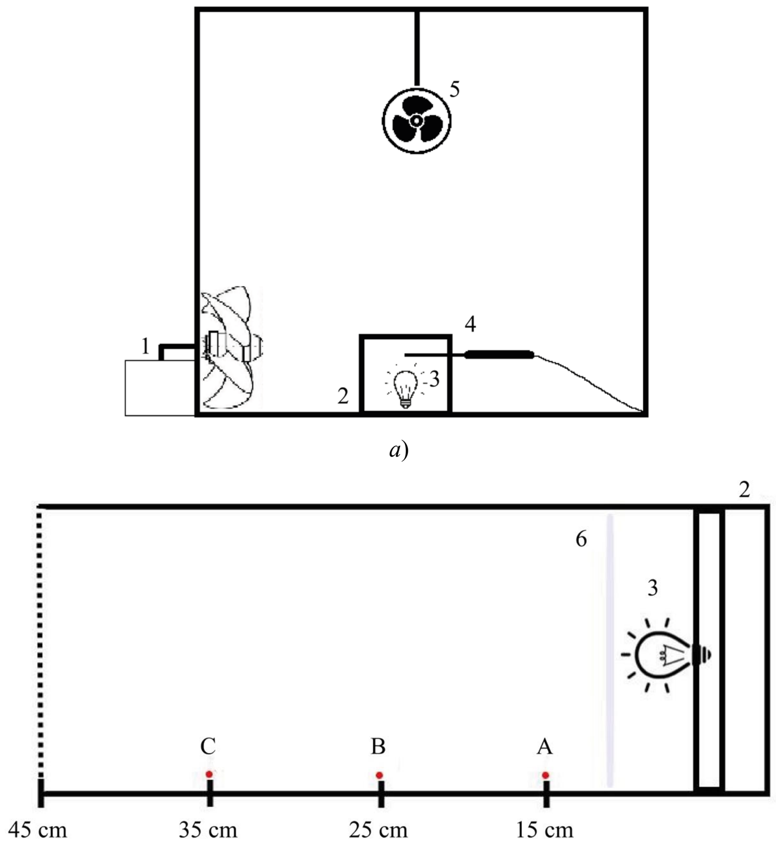
- the Pulsator device length — 0.57 m;
- diameter — 0.1 m;
- fan rotation speed in the Pulsator device — approximately 180 rpm;
- air consumption in the Pulsator device — 0.007 m³/s;
- flow rate of general exchange ventilation — 2.2 m/s [14].

When planning the experiment, minimum and sufficient requirements for its implementation were established [15]. Measurement accuracy:

– time — in minutes;
– temperature — 0.1°C;
– distance — 1 cm;
– pressure pulse — 1 Hz.

Figure 2 provides the diagram of the laboratory installation. The air flow generator (Fig. 2 *a*, 1) for general exchange ventilation, simulating the process of artificial ventilation in a room, was located on the left side at the bottom of the laboratory model (in the middle). The height distance from the base of the laboratory installation was 7 cm. The outlet of the niche (Fig. 2 *a*, 2), simulating a zone of obstructed aerological permeability, was in the base of a laboratory installation in the center. The niche structure itself rested against the back wall of the cube. The dimensions of the niche had the following parameters:

– height — 0.1 m;
– length — 0.5 m;
– opening width — 0.12 m;
– wall thickness — 0.012 m;
– wall material — pine.



a)

b)

Fig. 2. Diagram of the laboratory installation for studying heat and mass transfer processes:
a — general view of the laboratory bench;
b — location of the temperature sensor, indicating the distance from the heat source;
1 — fan; 2 — niche simulating a zone of difficult aerological permeability; 3 —eat source;
4 — temperature and humidity sensor; 5 — the Pulsator device; 6 — the shielding plate

In the part of the niche farthest from the entrance, at a distance of 0.45 m, there was a heat source (Fig. 2 *b*, 3). The heat source was an incandescent lamp with a power of 25 watts. During the experiments, two types of heat transfer were studied: radiative and convective. Figure 2 provides the layout of the equipment during the experiment.

The experiment to study the processes of heat and mass transfer was carried out with the temperature values recorded by a sensor located on the floor of the niche at a distance of 0.15, 0.25 and 0.35 m (Fig. 2 *b*). The letters highlighted in red indicate the position of the temperature sensor during the experiment. The experiment was carried out both with stationary (without the use of a pulsator) air exchange and with the use of a pulsating ventilation mode. On each segment, 70 temperature values were recorded for 60 minutes. In accordance with the experimental program, as mentioned earlier, the niche was located on the basis of a laboratory installation, and the temperature sensor was located at measuring points A, B, and C (Fig. 2 *b*). The measurements were carried out in the lower part of the niche (near the floor).

The second stage of the research to assess the influence of the air movement pulsating mode consisted in the use of a screen that dissipated direct thermal radiation. This screen was located between the heat sources and the temperature measuring points. The screen was installed permanently in one place for all measurements. The screen dimensions were 0.1 x 0.1 m. The screen material was white plastic 0.001 m thick. Periodically, during the heating process, the Pulsator was turned on, for example, at the 18th minute of the experiment. It was noted that the Pulsator operation led to a decrease in the temperature rise in the niche at each measurement point. The measurements were performed using the same methodology.

In general, it was found that at the time of switching on the Pulsator, the temperature increase in the niche was 1.5 times less than when the device was turned off. In the future, similarity criteria would be used to scale the process of turbulent heat transfer in natural conditions.

Results. Based on the conducted experiments, graphs of the dependence of temperature changes on time were constructed. Figure 3 shows the results of these measurements. The absolute and relative errors were 4.45°C and 8%, respectively. The graph with the blue line shows temperature changes when using the screen, and the graph with the green line shows temperature changes (in the range from the 18th to the 30th minute of this stage of the experiment) when the pulsating air movement mode was turned on with the plastic screen installed.

After the experiments, relative temperature increments at each measurement point of stationary (marked in blue on the graph) and pulsating modes were calculated to compare them. After calculating the increments for different modes, the dependencies were obtained. Figure 4 shows a graph of the dependencies of temperature increment coefficient on time using the screen.

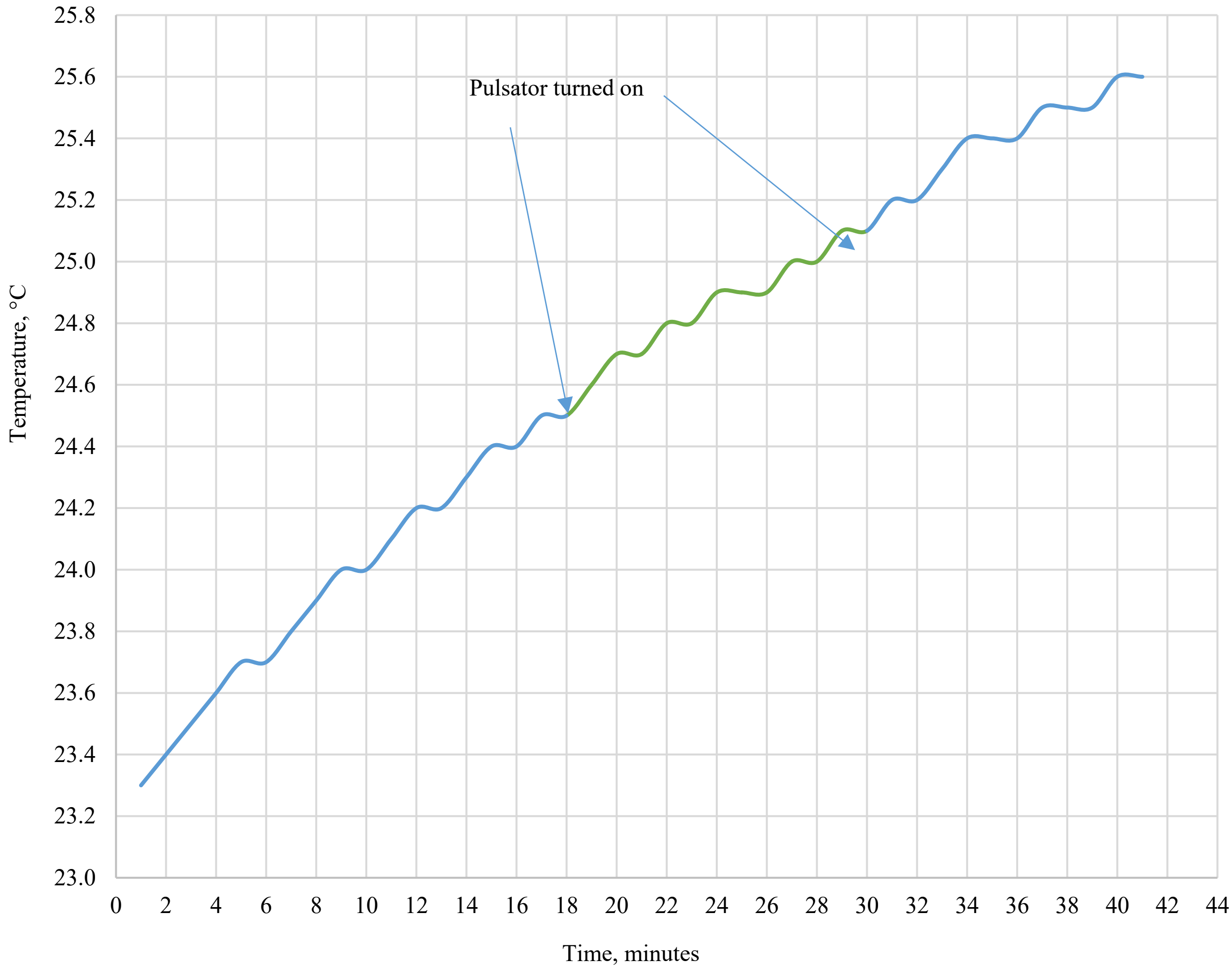


Fig. 3. Dependency graph of temperature on time of thermal radiation at a distance of 35 cm from a radiation source with an installed screen

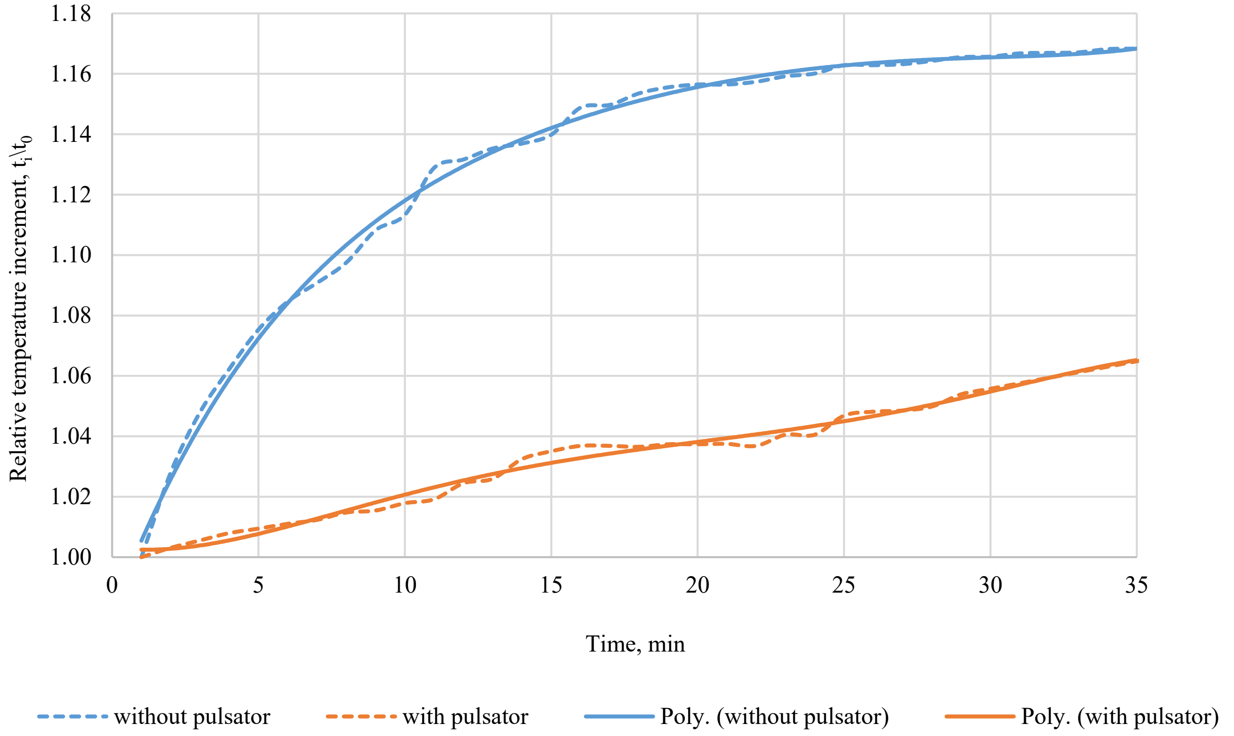


Fig. 4. Dependency graph of relative temperature increment on time at a distance of 35 cm from the radiation source using a screen

Further, these increments were distributed by modes and time ranges. Figure 5 shows dependency graphs of average values of relative temperature increment ($t_i \backslash t_0$) on time in stationary and pulsating modes for the entire volume of the niche.

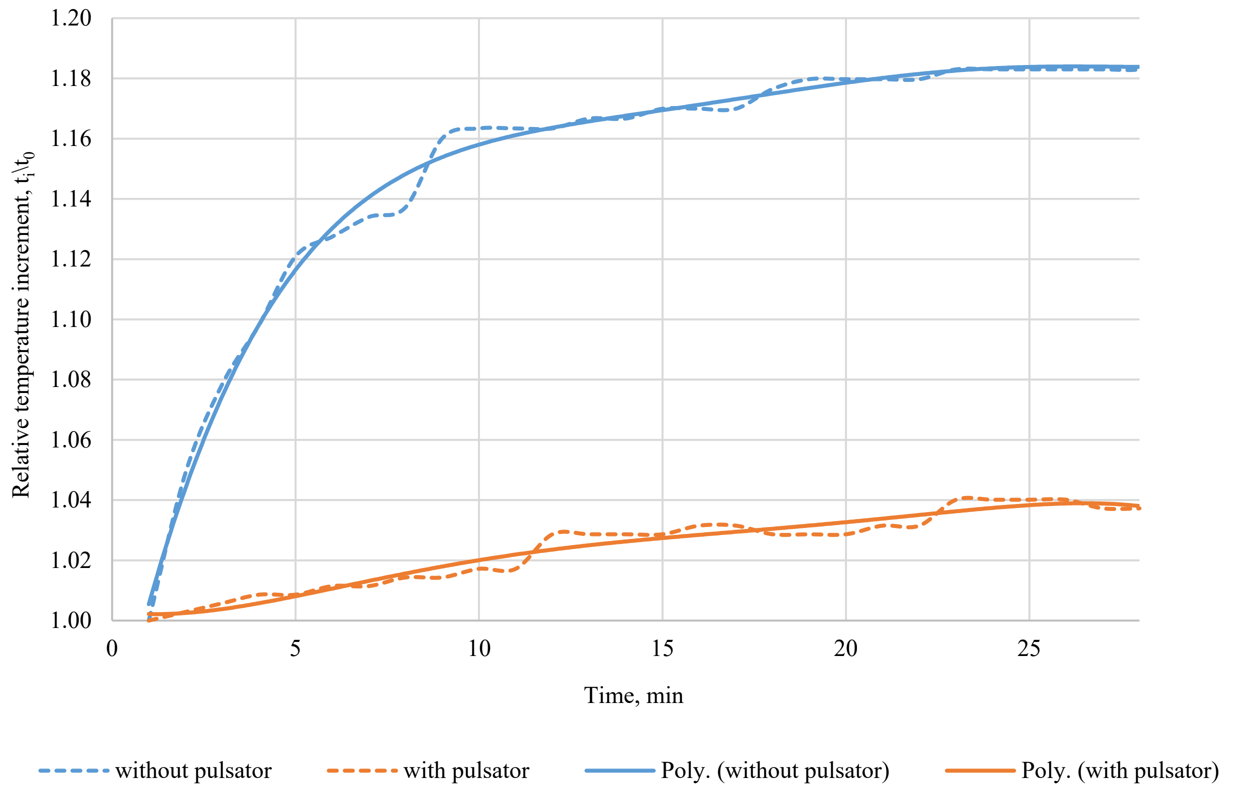


Fig. 5. Dependency graphs of averaged values of relative temperature increment on time in stationary and pulsating modes

According to this graph, during the first 15 minutes of the experiment, the temperature increased at a slower rate using the pulsating ventilation method, and there was a steady, slight increase. Under the conditions of the steady-state regime of the process under study, the maximum rate of temperature increase was observed.

Comparison of temperature changes over the intervals of 1–15 minutes and 16–32 minutes showed that during the first interval, the efficiency of the pulsating mode was less than the temperature increase (Fig. 6). However, the characteristics remained the same during the second interval (Fig. 7).

Figure 8 shows the values of angular coefficients, which indicate the degree of efficiency of the pulsating mode compared to the stationary mode, at different time intervals. In the range from 1st to 15th minute, the angular coefficient was 3.8 times higher in the stationary mode than in the pulsating mode, which indicated a higher intensity of heat and mass transfer. In the next interval (16–32 min.), this effect was not observed.

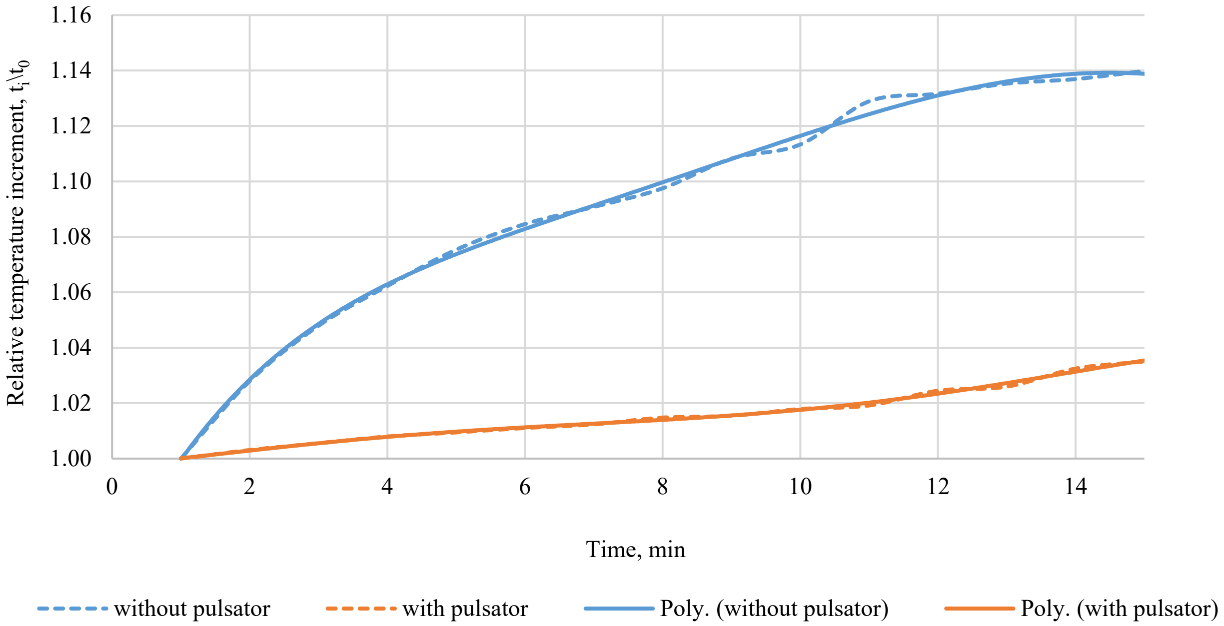


Fig. 6. Dependency graphs of the averaged values of relative temperature increment on time in stationary and pulsating modes (time range — 1–15 min.)

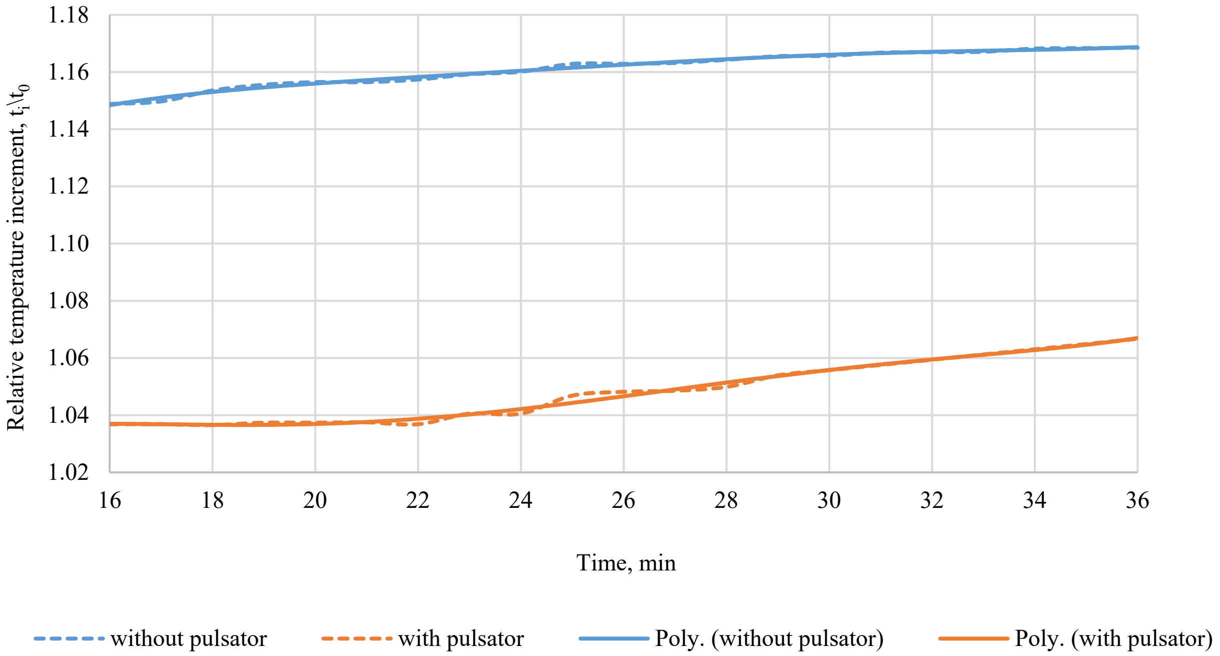


Fig. 7. Dependency graphs of the averaged values of relative temperature increment on time in stationary and pulsating modes (time range — 16–32 min.)

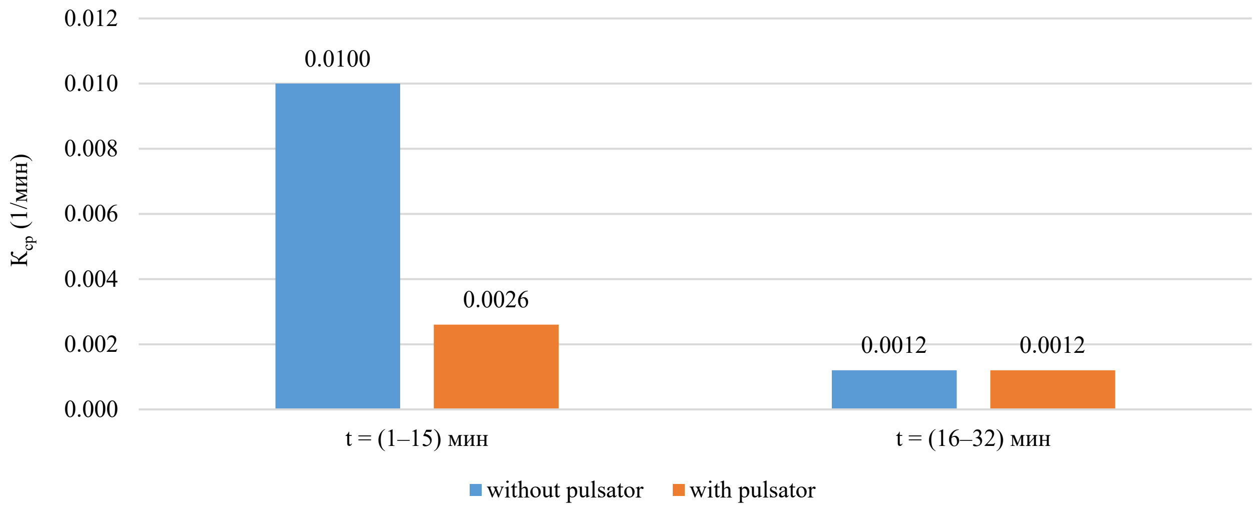


Fig. 8. Angular coefficients values at different time intervals

Discussion and Conclusion. The obtained dependencies of relative temperature increments with and without the pulsator allowed us to visually compare the processes of temperature increase and obtain the angular coefficient values for these two modes. The coefficients showed that the pulsating mode reduced the temperature rise by 3.8 times within the first 15 minutes at all measured points of the niche, proving the effectiveness of the proposed method. During the subsequent time period, temperature indicators stabilized in all cases and temperature in the niche increased slightly, both with and without the pulsator on.

The pulsation efficiency was observed at a distance of at least three diameters (L = 3d) of the niche under these conditions. We found that each time the pulsator was turned on, a steady increase in turbulent heat transfer occurred. Therefore, we can conclude that this method could be used to regulate the thermal load on various pieces of equipment and several technological processes.

The experiments conducted have allowed us to obtain initial information about the effectiveness of the above-mentioned method for heat and mass transfer. Further work will continue, and experiments will aim to obtain and analyze the dimensional and dimensionless characteristics of turbulent heat and mass transfer.

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IS Kolbina: validation of results.

DE Pronina: visualization.

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Д.Э. Пронина: визуализация.

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Original Empirical Research

Use of Underwater Video Surveillance to Monitor a Fish Protection Device at a Thermal Power Plant Water Intake Facility

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Abstract
Introduction. In the near future, the issue of selecting appropriate methods to assess the effectiveness of fish protection devices (FPDs) will continue to be relevant. Previously, the necessary data could only be obtained by ichthyological studies, which involved using specific techniques and equipment. However, the introduction of a new edition of the Code of Rules SP 101.13330.2023 changed the situation and opened up the possibility of using sonar tools to determine the FPDs effectiveness. While there is a lack of public information regarding the specifics and potential of this approach, it is possible that underwater video surveillance may yield similar results to ichthyological (hydroacoustic) methods. This study aims to verify this hypothesis.
Materials and Methods. During ichthyological studies at the Zainskaya power plant, fish were captured using nets with mesh sizes of 10, 18, 20, 22, 30, and 70 mm. A Molchanov GR-18 bathometer was used to take phytoplankton samples. Zooplankton samples were collected by the Apstein network. Zoobenthos samples were collected using an automatic DAK-250 dredger. Underwater video surveillance was conducted using a Praktik Murena camera with a resolution of 720 HD (1,280×720 pixels), which is equipped with built-in infrared illumination and displays information on a surface monitor. The camera has a wide-angle lens with a 130° viewing angle.
Results. A notable advantage of the proposed method, identified in the course of scientific research, concerned the sample size. With video surveillance, it turned out to be 2.25 times larger than with the traditional method. This was because video cameras captured more individuals than the number of fish caught in a net. A larger sample size provided a more statistically significant result. As the amount of data increased, the accuracy of the characteristics of the general population increased, and random error decreased. To determine the FPD efficiency coefficient (EC), the concentration of fish before and after the FPDs, as well as the survival rate of individuals after contact with the FPDs were taken into account. When using the traditional method in 2023, the average EC of the FPDs efficiency at on-shore pumping station No. 3 was 86.9%. Under the same conditions, the new approach proposed by the authors showed a similar average efficiency of 87.3%, with a difference of only 0.46%, which was completely insignificant. The maximum discrepancy was in the spring of 2023, where the indicator of the alternative method was 9.3% higher than the traditional one, while the minimum was noted in autumn at 0.1%.
Discussion and Conclusion. So, it was possible to confirm the hypothesis that the underwater video surveillance method is comparable in results with the ichthyological (hydroacoustic) method. However, the new approach is not yet legally recognized and can only be used as an additional tool. Firstly, video surveillance can help to determine whether ichthyological studies are necessary. Secondly, water intake operators can use the experimental method in between ichthyological surveys to obtain operational data on the effectiveness of FPDs.

Keywords: fish protection device efficiency, hydroacoustic verification of the device, ichthyological verification of fish protection, underwater video surveillance of the fish protection device

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Оригинальное эмпирическое исследование

Применение подводного видеонаблюдения для контроля рыбозащитного устройства на водозаборном сооружении тепловой электростанции

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Аннотация

Введение. В ближайшее время сохранит актуальность проблема выбора средств определения эффективности рыбозащитных устройств (РЗУ). Ранее необходимые данные можно было получить только ихтиологическими исследованиями. Для этого используются специфические методики и оборудование. Ситуацию изменила новая редакция Свода правил СП 101.13330.2023, которая предусматривает возможность применения гидроакустических средств для определения эффективности РЗУ. В открытом доступе нет публикаций об особенностях и перспективах такого подхода. Можно предположить, что метод подводного видеонаблюдения сопоставим по результатам с ихтиологическим (гидроакустическим). Цель работы — подтвердить данную гипотезу.

Материалы и методы. При ихтиологических исследованиях на Заинской электростанции рыб отлавливали сетями с ячеей 10, 18, 20, 22, 30 и 70 мм. Для отбора проб фитопланктона применяли батометр Молчанова ГР-18. Пробы зоопланктона отбирали сетью Апштейна. Зообентос собирали автоматическим дночерпателем ДАК-250. Подводное видеонаблюдение вели с помощью камеры «Практик Мурена» с разрешением 720 HD (1 280×720 пикселей). Это оборудование оснащено встроенной инфракрасной подсветкой. Информация выводится на надводный мониторный блок. Объектив — широкоугольный, с углом обзора 130°.

Результаты исследования. Преимущество предложенного метода, выявленное в ходе научных изысканий, касается объема выборки. При видеонаблюдении она оказалась в 2,25 раза больше, чем при традиционном методе. Очевидно, что видеокамеры фиксируют больше особей в сравнении с количеством рыб, попавших в сети. Широкая выборка обеспечивает статистически более значимый эффект. С ростом объема данных увеличивается точность характеристик генеральной совокупности, сокращается случайная ошибка. Для определения коэффициента эффективности (Кэф) РЗУ учитывали концентрацию рыб до и после РЗУ, а также показатель выживаемости особей после контакта с РЗУ. При использовании традиционного метода в 2023 году средний Кэф рыбозащитной эффективности РЗУ на береговой насосной станции № 3 Заинской электростанции составил 86,9 %. Новый подход, предложенный авторами данной статьи, в тех же условиях показал аналогичную среднюю эффективность — 87,3 %. Разница совершенно несущественна — 0,46 %. Максимальное расхождение фиксировалось весной 2023 года. Тогда показатель альтернативного метода был на 9,3 % больше в сравнении с традиционным. Минимум отметили осенью — 0,1 %.

Обсуждение и заключение. Удалось подтвердить гипотезу, согласно которой метод подводного видеонаблюдения сопоставим по результатам с ихтиологическим (гидроакустическим). Новый подход все еще не признан законодательно, и его можно использовать только как вспомогательный. Во-первых, видеонаблюдение позволит выяснить, нужны ли ихтиологические изыскания. Во-вторых, эксплуатант водозабора может задействовать экспериментальный метод между ихтиологическими исследованиями для получения оперативной информации об эффективности РЗУ.

Ключевые слова: эффективность рыбозащитного устройства, гидроакустическая проверка устройства, ихтиологическая проверка рыбозащиты, подводное видеонаблюдение рыбозащитного устройства

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Introduction. The equipment of thermal power plants requires cooling. For this purpose, water is used. Water is taken from natural and artificial reservoirs by hydraulic structures called water intakes [1]. Two essential operating conditions for these facilities are an uninterrupted supply of water and the presence of a fish protection device (FPD) that prevents fish from entering the equipment [2].

The minimum regulatory FPD efficiency is 70% [3]. Modern FPD designs meet this requirement [1].

The Zainskaya State Regional Power Plant (GRES) water supply system is reversible. The waste water is cooled in the Zainsk reservoir. Three on-shore pumping stations (SPS) supply circulating industrial water. The Zainsk reservoir is a fishing reservoir. Taking into account this circumstance and natural factors, FPDs of WAC (water-air curtain) type were installed on all three SPSs from 2015 to 2018. It should protect the young fish from water intake, and the intake from floating and submerged debris. Industrial and energy water intakes at Iriklinskaya, Kaliningradskaya and Reftinskaya regional power stations were equipped with the same FPDs. The devices have shown high fish protection efficiency [4].

The ascending water-air curtain is formed by a stream of water, which is pumped to the system of bottom modules of an FPD. Air is also supplied there via a parallel pipeline. Passing through the aerating nozzles, it is directed into a perforated pipeline, mixes with water, rises to the surface and thus forms an obstacle for fish and debris (Fig. 1).

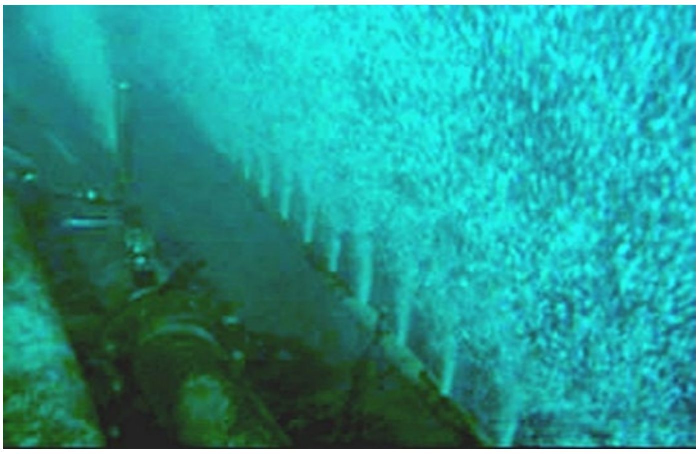

Fig. 1. WAC-type FPD in action

For a WAC-type FPD, a perforated pipeline is laid along the bottom in front of the water intake zone. An air-water mixture is constantly supplied from its openings. Fish consider a "wall" of air bubbles as a physical barrier. In addition, they are deterred by the sonar noise of air currents. At the same time, the fish are not injured. The WAC-type FPD consists of interchangeable modules of the same type. Therefore, it is easier to maintain it than other protective devices. In winter, the air curtain forms an ice-hole. Due to the constant mixing of water, it does not freeze, and the water intake is not clogged with ice.

The use of WAC-type FPD to protect baby fish is based, in particular, on fright. This is how fish react to a wall of upward-moving air bubbles and swim away from it. The high efficiency of the method can be explained by its complex effect on babies. Firstly, for the visual receptors of fish, the water-air curtain is an external stimulus. Secondly, it is perceived as a mechanical barrier (wall). Thirdly, the curtain makes noise. Air bubbles rise from the holes of the perforated pipes. When surfacing, they expand and collapse with a hydrocavitation effect. A micro-explosion occurs, which scares the fish away.

In comparison with an air-bubble curtain, the energy of an air-water curtain is much higher, as it is created not only by air but also by a denser flow of water. In a water-air curtain, fish are able to rise more efficiently to the upper layers and are carried out by the flow from the intake [5]. As a rule, an air curtain is used at large water intakes for energy purposes.

Materials and Methods. Ichthyological studies were conducted to assess the FPD effectiveness of the Zainskaya GRES water intake facilities[2]. The quantitative and qualitative composition of fish caught in the nets in the supply channel were analyzed. Special studies were conducted to calculate the survival rate. A control group of fish was caught before the FPD, and an experimental group was caught in the supply channel after contact with the FPD elements. In both groups, the number of dead and live individuals was calculated. The survivors were observed during the 24 hours [6]. Then the number of dead and survivors was calculated again and thus the survival rate was obtained.

[1] *On the Instructions on the procedure for monitoring the effectiveness of fish protection devices and monitoring fish deaths at water intake facilities.* Order No. 786 of the Federal Agency for Fisheries dated September 1, 2009. (In Russ.) URL: https://base.garant.ru/12171525/ (accessed: 10.12.2024).

[2] *Retaining walls, shipping locks, fish passageways and fish protection structures.* Code of Rules. SP 101.13330.2023. (In Russ.) URL: https://www.minstroyrf.gov.ru/docs/318744/ (accessed: 10.12.2024).

The FPD efficiency coefficient was expressed as a percentage and was calculated by dividing the number of fish that are trapped by the FPD by the total number of fish that enter the intake structure when the FPD was not present. Records were kept continuously throughout the year to ensure accuracy.

An observation post for ichthyological sampling using standard methods was set up at SPS No. 3, equipped with a FPD [7]. The fish species were determined through taxonomic revisions and summaries [8].

Seasonal dynamics of fish entering the water intake facilities of SPS No. 3 at Zainskaya GRES is observed. Before and after the FPD, the highest number of fish was caught in summer, with the lowest numbers in autumn, winter, and early spring (Table 1). This can be explained by the fact that colder water reduces the activity of fish.

Table 1

Quantitative Composition and Species of Fish Recorded in the Water Intake Facilities of SPS No. 3 at Zainskaya GRES Before and After the FPD in 2023, Number.

Types of fish	Winter		Spring		Summer		Autumn	
	Before FPD	After FPD	Before FPD	After FPD	Before FPD	After FPD	Before FPD	After FPD
Bream	–	–	–	–	5	–	–	–
Alburn	45	–	1	1	6	1	–	2
White bream	6	–	7	1	–	–	–	4
Chub	–	–	2	–	–	–	–	–
Roach	–	–	2	1	56	1	2	4
Catfish	–	–	–	–	1	–	–	–
Perch	21	2	36	6	250	115	152	6
Total	72	2	48	9	318	117	154	16

According to round-the-clock observations at SPS No. 3, the highest number of fish got into nets and equipment at dusk and at night (in 21:00, 1:00, 5:00 and 9:00). At this time, the fish saw the obstacles worse, and they were captured by the current near the FPD. First of all, this applied to babies. It was harder for them to resist the flow.

The motion activity of carp fish decreased from 20:00 to 6:00. This was revealed by spectral analysis, which took 34 hours.

Underwater video surveillance was also conducted together with the ichthyological research. A Praktik Murena camera was installed before and after the FPD [9]. It took photos and videos. This equipment output information to the surface monitor and stored the data. The resolution of 1280×720 pixels provided a clear image even in low light conditions. In addition, it was possible to turn on the LED or infrared backlight. They were remotely adjustable, and this was important when working in muddy water or in bad weather. Special sensors measured the water depth and temperature. The optional compass function displayed the camera's direction; it showed which way it was turned.

Due to the powerful built-in lithium-ion battery (10,000 mAh), the camera could work for 6 hours even in cold weather, while the battery indicator showed the battery life.

Figure 2 shows the above-water block. This is a portable five-inch color TFT (thin-film transistor) monitor.

Fig. 2. Underwater Praktik Murena video camera

The high resolution 720 HD (1,280×720 pixels) provided a clear and detailed image even at a depth of 10–15 meters in conditions of average water clarity. A special visor protected the screen from sunlight, and it was possible to install a microSD card with a capacity up to 128 GB. The wide viewing angle was 130 degrees, and powerful illumination from two white LEDs and four infrared LEDs allowed exploration of the underwater world both day and night, even in low-visibility conditions. The video camera had an IP 68 protection rating, making it waterproof and resistant to wear. The waterproof video cable, with a length of 15 meters and a maximum load capacity of 15 kg, could withstand extreme temperatures from –20°C to +60°C.

The complex combined elements with three main functions: a video camera, a power source and an information storage device. Two additions were made to the original design. Firstly, an aluminum case was purchased to carry, store, and protect the device from precipitation (Fig. 3). The case was insulated to extend the battery life during cold seasons. Second, an additional 2 terabyte external hard drive was added to store all footage.

Fig. 3. The case and the surface unit of the Praktik Murena video camera

A special conductor has been developed for installing and fixing the camera underwater (Fig. 4).

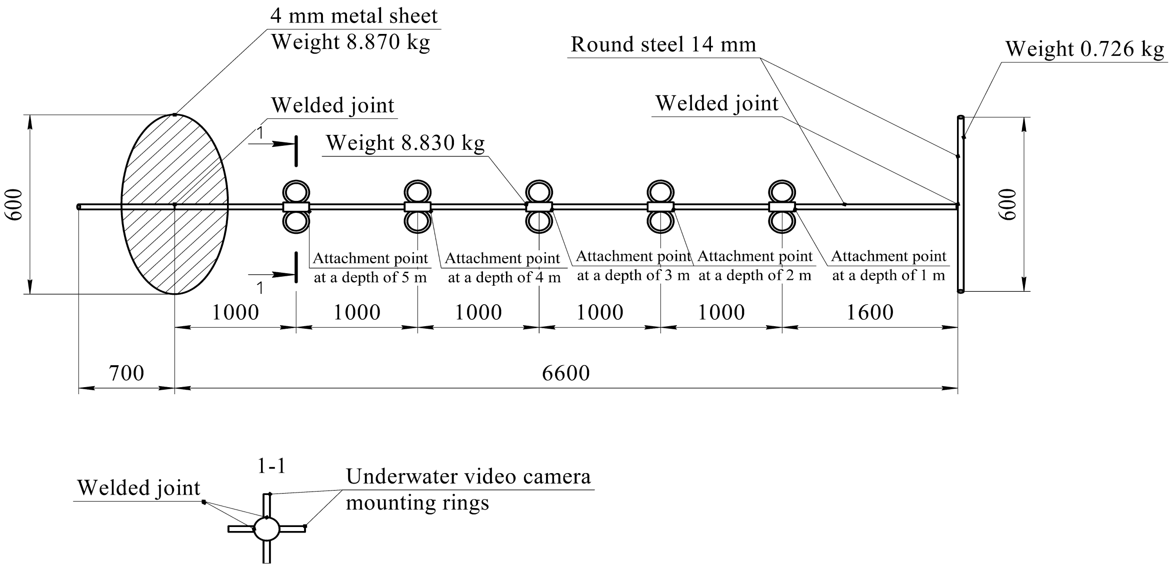

Fig. 4. A conductor for underwater video surveillance

The conductor was made of a steel round bar with a diameter of 14 mm and a length of 7,300 mm. In the upper part, there was a transverse crossbar with a diameter of 14 mm and a length of 600 mm, welded to the main part. The crossbar acted as a handle when the lower end of the conductor was immersed in the bottom soil and when it was rotated to orient the video camera in the desired direction. At a distance of 600 mm from the lower end of the conductor, a round metal sheet with a thickness of 4 mm was fixed with a welded joint. It restricted the penetration of the conductor into the ground and fixed it in an upright position. To attach the underwater camera, metal rings were welded every 90° around the circumference of the metal sheet. The distance between them was 1,000 mm. The total weight of the conductor structure did not exceed 19 kg, so even one researcher could work with it.

Results. The survey before and after the FPD at the SPS No. 3 of the Zainskaya GRES revealed the stability of fish species composition. It did not depend on the season and generally corresponded to the data of ichthyological studies. During the study, 1,654 individuals were recorded. 256 individuals (15.48% of the total number) could not be identified [10]. Therefore, for the sake of objectivity, Figure 5 shows the quantitative composition, and Table 2 contains all the data obtained [11].

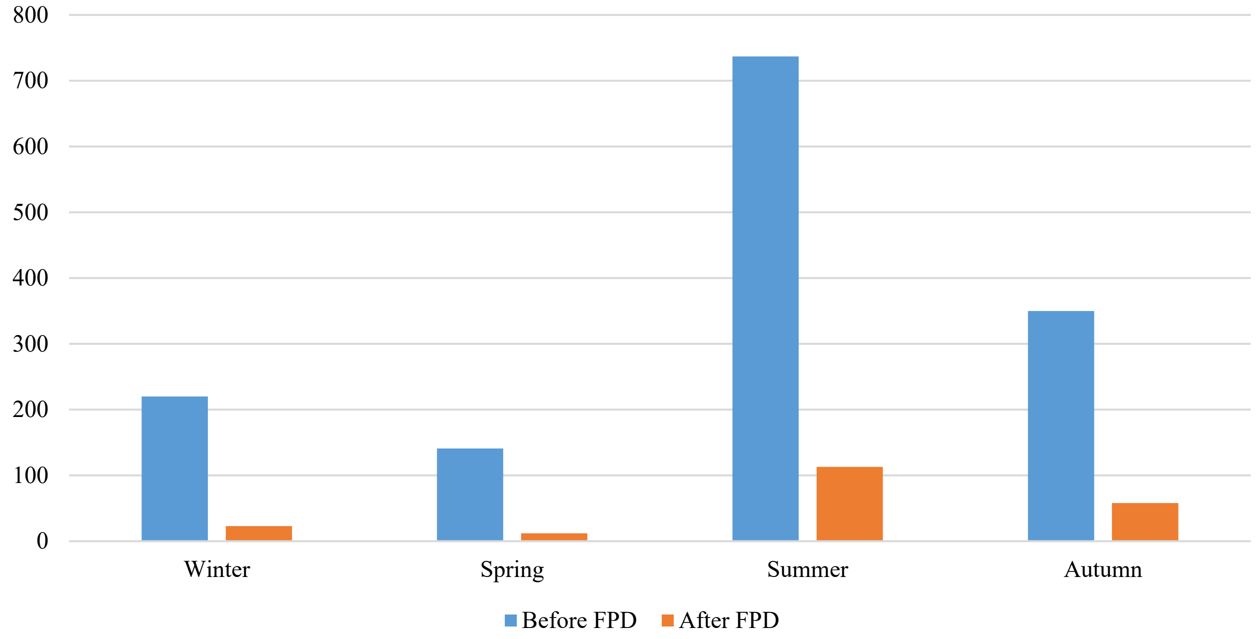

Fig. 5. Number of fish caught by the underwater surveillance camera before and after the FPD at SPS No. 3 in 2023, individuals

Table 2

Number and Types of Fish Recorded by Underwater Surveillance Cameras Before and After the FPD at SPS No. 3 During Different Seasons of 2023, Individuals

Types of fish	Winter		Spring		Summer		Autumn	
	Before FPD	After FPD	Before FPD	After FPD	Before FPD	After FPD	Before FPD	After FPD
Alburn	89	3	63	2	271	15	131	7
White bream, bream *	18	1	12	–	71	8	35	5
Perch	42	6	24	2	143	25	72	15
Chub	22	3	12	3	78	16	35	8
Roach	20	5	14	2	69	14	32	5
Not determined	29	5	16	3	105	35	45	18
Total	220	23	141	12	737	113	350	58

**White bream and bream come together because they can be difficult to distinguish on the screen.*

Table 3 provides the total number of fish recorded in the FPD area by two methods. According to these data, fish were especially active in autumn. Relatively high activity was observed in summer, low — in winter and spring.

Table 3

The Total Number of Fish Recorded in the FPD Area of the Zainskaya GRES During the Period of Research by the Ichthyological (Ich.) Method and the Method of Underwater Video Surveillance (Exp.) in 2023

Season and fixation method	Winter		Spring		Summer		Autumn		Total for a year	
	Ich.	Exp.	Ich.	Exp.	Ich.	Exp.	Ich.	Exp.	Ich.	Exp.
Number	74	243	57	153	170	408	435	850	736	1654

In comparison with the ichthyological observations, the underwater observations recorded 2.25 times more individuals. The larger the sample size, the more likely it was to detect a statistically significant effect. Additionally, a larger amount of data improved the accuracy of estimating parameters for the general population and reduced random error. This was an advantage of the alternative research method.

According to the results of round-the-clock observations, regardless of the season, underwater cameras recorded fish more frequently during daylight hours (Table 4).

Table 4

The Number of Fish Recorded by Underwater Video Surveillance Cameras in 2023 at SPS No. 3 of Zainskaya GRES, Individuals/%

Time	0:00–4:00	4:00–8:00	8:00–12:00	12:00–16:00	16:00–20:00	20:00–0:00	Per season
Winter	4/ 1.65	78/ 32.10	53/ 21.81	36/ 14.81	42/ 17.28	30/ 12.35	243/ 100
Spring	2/ 1.31	51/ 33.33	33/ 21.57	15/ 9.8	33/ 21.57	19/ 12.42	153/ 100
Summer	13/ 1.53	337/ 39.65	185/ 21.76	104/ 12.24	155/ 18.23	56/ 6.59	850/ 100
Autumn	4/ 0.98	162/ 39.71	93/ 22.79	39/ 9.56	77/ 18.87	33/ 8.09	408/ 100
Total for a year	23/ 1.39*	628/ 37.97*	364/ 22.01*	194/ 11.73	307/ 18.56*	138/ 8.34*	1654/ 100
**The indicator is calculated not by the time of day, but by the results of the year. This is a fraction of the total annual number of 1,654.*							

Underwater video surveillance revealed the smallest number of fish at dusk and at night, from 22:00 to 4:00. This was due to the biorhythmicity of most fish. Their motor activity decreased from 20:00 to 6:00 [11]. From 0:00 to 4:00, the underwater surveillance camera recorded only 23 out of 1,654 individuals, or 1.39%. This indicator remained low (from 0.98% to 1.65%) regardless of the season.

From 20:00 to 0:00, a video survey found 138 out of 1,654 individuals, or 8.34%. Particularly low rates were recorded in summer (6.59%) and autumn (8.09%).

From 12:00 to 16:00, 194 out of 1,654 individuals were captured, or 11.37%. Lows were recorded in spring (9.80%) and autumn (9.56%).

For ichthyological studies, the FPD efficiency coefficient (Кэф) was calculated using the formula:

$$K_{эф} = \frac{C_0 - C}{C_0} \cdot B \cdot 100\,\%,$$

where C — fish concentration after the FPD, C_0 — fish concentration before the FPD, B — survival rate of fish after contact with the FPD structural elements.

$K_{эф}$ (in %) of the FPD based on the ichthyological research results in 2023:

– Winter — 97.2;

– Spring — 83.7;

– Summer — 83.4;

– Autumn — 83.3.

In 2023, the average coefficient of fish protection efficiency of the FPD at SPS No. 3 was 86.9% (according to standards — at least 70%).

Together with the ichthyological research, the experiments on fish fixation using an underwater camera were conducted at SPS No. 3. They were also monitored before and after the FPD. FPD Кэф based on video surveillance results in 2023:

– Winter — 89.6%;
– Spring — 91.5%;
– Summer — 84.7%;
– Autumn — 83.4%.

Average FPD Кэф in this case — 87.3%.

Table 5 compares the indicators of the FPD fish protection efficiency obtained by different methods.

Table 5

Comparison of the Effectiveness of Ichthyological and Alternative (Experimental) Methods for Determining Fish Protection Effectiveness of FPD at SPS No. 3 in 2023, %

Season	FPD $К_{эф}$ (ichthyological method)	FPD $К_{эф}$ (experimental method)	Difference (– lower, + higher)
Winter	97.2	89.6	–7.8
Spring	83.7	91.5	+9.3
Summer	83.4	84.7	+1.6
Autumn	83.3	83.4	+0.1
2023	86.9	87.3	+0.46

As it can be seen, the peak difference in efficiency was less than 10%, the minimum was 0.1%, and the average was 0.46%.

Discussion and Conclusion. Underwater video surveillance at a WAC-type FPD at SPS No. 3 of Zainskaya GRES has confirmed the data of traditional ichthyological studies. According to the results, these two methods show slight differences, with an average difference of less than 1% (0.46% to be more precise). This confirms the accuracy of the results and supports the hypothesis that the underwater video surveillance method is informative and promising.

To be more specific, the experimental method has not yet been legally recognized, and therefore it cannot be used as a standalone and sufficient approach. Nevertheless, it would be useful to first determine whether ichthyological research is necessary. Secondly, underwater video surveillance could be used together with traditional studies to obtain additional information on the FPD effectiveness.

Thus, the proposed method provides the water intake operator with the opportunity to quickly monitor the FPD efficiency. This monitoring can be done much more frequently than professional ichthyological (hydroacoustic) monitoring.

Underwater video surveillance is also well-suited for remote detection of fish parameters, such as length. This method allows for the monitoring of fish without the need to remove them from the water or cause any harm to them [12].

Another advantage of the new method compared to the traditional one is the larger sample size. Within the context of the presented scientific study, a difference of 2.25 times was noted in favor of underwater video surveillance. Increasing the sample size allows for greater accuracy in the estimate and reduces the likelihood of errors in calculations.

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Specifics of Green Energy Development in the Russian Federation

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Abstract

Introduction. The issues of sustainable development, environmental protection and transition to a low-carbon economy remain relevant for countries worldwide, including the Russian Federation. In the context of global climate change and depletion of traditional energy sources, the need to develop "green" energy has become increasingly important. However, despite the presence of a certain potential, this sector in Russia is still underdeveloped, which is due to various economic, technological and legislative factors. There are numerous theoretical studies on renewable energy sources in the scientific literature, but many aspects of their functioning and development remain insufficiently explored. This scientific gap makes it difficult to fully understand the mechanisms and strategies for its further development.

In connection with the above, this study aims to analyze the current features and trends in the development of green energy in the Russian Federation. The study will also identify potential obstacles and opportunities for the expansion of green energy, as well as ways to overcome negative aspects of its functioning. The objectives of the authors of the study are focused on analyzing the priorities of public policy in Russia as a signatory to the UN Framework Convention on Climate Change, the Paris Climate Agreement, and the Kyoto Protocol on Reducing Greenhouse Gas Emissions, on determining the impact of public policy, technology and investment on the development of renewable energy sources, as well as on studying factors that can accelerate the country's transition to more sustainable energy models. The results of the study aim not only to fill a current gap in scientific knowledge, but also to provide the basis for developing recommendations that can help optimize energy policy in the country.

Materials and Methods. The authors analyzed legislative materials related to the topic of study. Statistical data on the types of energy capacities in the country over the past decade were used. The study was conducted based on regulatory and legal acts of the Russian Federation. Results from monitoring the implementation of government programs and strategies on the issue were also studied. Content analysis, structural and functional analysis were used as main research methods. The current state of affairs in the energy industry was presented based on the analysis of hierarchies, which was a set of elements, each of which reflected a specific step in achieving the goal.

Results. The clear growth of renewable energy sources (RES) use in the total global energy capacity has been explicated. It has been established that Russia is paying significant attention to the development of renewable energy sources, with a focus on introducing public-private partnerships in this area. Methods and principles of government support aimed at developing this sector, as well as competitive technologies (RES.1 and RES.2) for the commissioning of generating facilities using various forms of renewable energy, have been analyzed. It has been confirmed that the energy development roadmap in Russia corresponds to a proposed hierarchy of strategies based on a hybrid approach. Priorities in reducing greenhouse gas emissions and combating pollution have also been established.

Discussion and Conclusion. The data obtained from the research conducted by the authors indicates that Russia has started to move towards the active implementation of renewable energy sources while not disregarding the use of traditional energy from non-renewable resources, taking steps to minimize associated costs. The development of green energy in the country is still proceeding at a slow rate. Its development is hampered, on the one hand, by the already powerful potential of energy capacities, and on the other hand, by negative factors affecting both the production and use of renewable energy sources. While advocating for a faster transition to green energy, it is important to acknowledge that this process is fraught with challenges that must be predicted and addressed. To do so, a thorough analysis of the impact of different types of renewable energy sources on the environment and human health is necessary. Therefore, the introduction of renewable energy sources should be phased and carefully thought out. In this regard, this topic requires further study.

Keywords: Russian Federation, the country's energy system, renewable energy sources, legislative acts, stages and prospects of development

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Оригинальное теоретическое исследование

Особенности развития зелёной энергетики в Российской Федерации

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Аннотация
Введение. Вопросы устойчивого развития, охраны окружающей среды и перехода к низкоуглеродной экономике не теряют своей актуальности для стран по всему миру, в том числе и для Российской Федерации. В условиях глобальных изменений климата и истощения традиционных источников энергии необходимость в развитии зелёной энергетики приобретает особую значимость. Однако несмотря на наличие определённого потенциала данный сектор в России пока ещё недостаточно развит, что обусловлено различными экономическими, технологическими и законодательными факторами. В научной литературе существует ряд теоретических исследований, посвящённых вопросам возобновляемых источников энергии (ВИЭ). Тем не менее, многие аспекты функционирования и становления зелёной энергетики пока еще мало изучены, этот научный пробел затрудняет полноценное понимание механизмов и стратегий её дальнейшего развития.
В связи с вышеизложенным цель данного исследования заключается в том, чтобы проанализировать существующие особенности и тенденции развития зелёной энергетики в Российской Федерации, выявить потенциальные препятствия и возможности для её расширения, определить пути преодоления негативных аспектов её функционирования. Задачи авторов исследования сосредоточены на анализе приоритетов государственной политики России, подписавшей Рамочную конвенцию ООН об изменении климата, Парижское соглашение по климату и Киотский протокол о сокращении выбросов парниковых газов, на определении влияния государственной политики, технологий и инвестиций на развитие возобновляемых источников энергии, а также на изучении факторов, которые могут способствовать ускорению перехода страны к более устойчивым энергетическим моделям. Результаты исследования призваны не только заполнить текущий пробел в научном знании, но и стать основой для выработки рекомендаций, направленных на оптимизацию политики в сфере развития зелёной энергетики в стране.
Материалы и методы. Авторами проанализированы законодательные материалы, касающиеся исследуемой темы. Были использованы статистические данные по видам энергетических мощностей страны за последнее десятилетие. Исследование проводилось на основе нормативных и правовых актов РФ. Изучены результаты мониторинга реализации государственных программ и стратегий по рассматриваемому вопросу. В качестве основных методов исследования были использованы контент-анализ и структурно-функциональный анализ. Современное положение дел в энергетической отрасли представлено на основе анализа иерархий как совокупности элементов, каждый из которых отражает конкретную ступень в достижении поставленной цели.
Результаты исследования. Эксплицирован явный рост использования возобновляемых источников энергии в общей мировой энергетической мощности. Установлено, что в России уделяется значительное внимание развитию возобновляемых источников энергии, при этом акцент делается на внедрение механизмов государственно-частного партнерства в этой области. Проанализированы методы и принципы государственной поддержки, направленные на развитие данного сегмента, а также технологии конкурсного отбора (ДПМ ВИЭ.1 и ДПМ ВИЭ.2) для ввода в эксплуатацию генерирующих объектов, использующих разнообразные виды возобновляемых источников энергии. Подтверждено, что дорожная карта развития энергетики в России соответствует предложенной иерархии стратегий, разработанной на основе гибридного подхода. Также установлены приоритеты в области сокращения парникового эффекта и борьбы с загрязнением окружающей среды.

Обсуждение и заключение. Данные, полученные в результате проведенного авторами исследования, свидетельствуют о том, что Россия начала движение в направлении активного внедрения возобновляемых источников энергии, не оставляя при этом без внимания и функционирование традиционной энергетики на невозобновляемых источниках, осуществляя мероприятия по минимизации возникающих при этом издержек. Становление зелёной энергетики в стране пока идёт медленными темпами, её развитие тормозят, с одной стороны, уже имеющийся мощный потенциал энергетических мощностей, а с другой стороны, негативные факторы, отрицательно влияющие как на изготовление, так и на применение ВИЭ. Но, ратуя за повсеместное форсирование внедрения зелёной энергетики, нельзя не принимать во внимание тот факт, что процесс перехода к ней таит в себе немало угроз, которые надо уметь прогнозировать и устранять. Для этого должно быть проведено тщательное исследование влияния различных видов возобновляемых источников энергии на окружающую среду и здоровье людей. Поэтому внедрение ВИЭ должно быть поэтапным, тщательно продуманным. В связи с этим данная тема требует дальнейшего изучения.

Ключевые слова: Российская Федерация, энергосистема страны, возобновляемые источники энергии, законодательные акты, этапы и перспективы развития

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Introduction. The urgency of developing green energy in Russia stems from the need to transition to more sustainable and environmentally friendly energy sources due to global climate change and the depletion of traditional resources. Given that the Russian Federation possesses vast hydrocarbon reserves and heavily relies on nuclear energy, the challenge of introducing and promoting renewable energy sources within the country has not been thoroughly explored, particularly with regard to their potential negative impacts on the environment and public health. Significant attention is given to existing energy production capacities and volumes, yet the utilization of alternative energy sources like solar, wind, and hydropower, as well as their integration into the overall energy system, remains underexplored and lacks scientific justification.

The Russian Federation is a country rich in natural energy resources. This makes it a world leader in hydrocarbons and nuclear energy use and export. The adopted Energy Strategy of the Russian Federation for the period up to 2035[1] outlines forecast indicators for the production of various fuels. Figure 1 shows these data for two stages of the Strategy's implementation: for 2024 and for 2035 in accordance with two types of scenarios — the lower and upper. Both scenarios aim to maintain the macroeconomic stability of the state. The scenario corresponding to the upper limit of the range of parameters for the development of the fuel and energy complex assumes the achievement of economic growth rates above the global average. The scenario corresponding to the lower limit indicates the limit of the sustainability of the country's energy sector and ensuring its energy security.

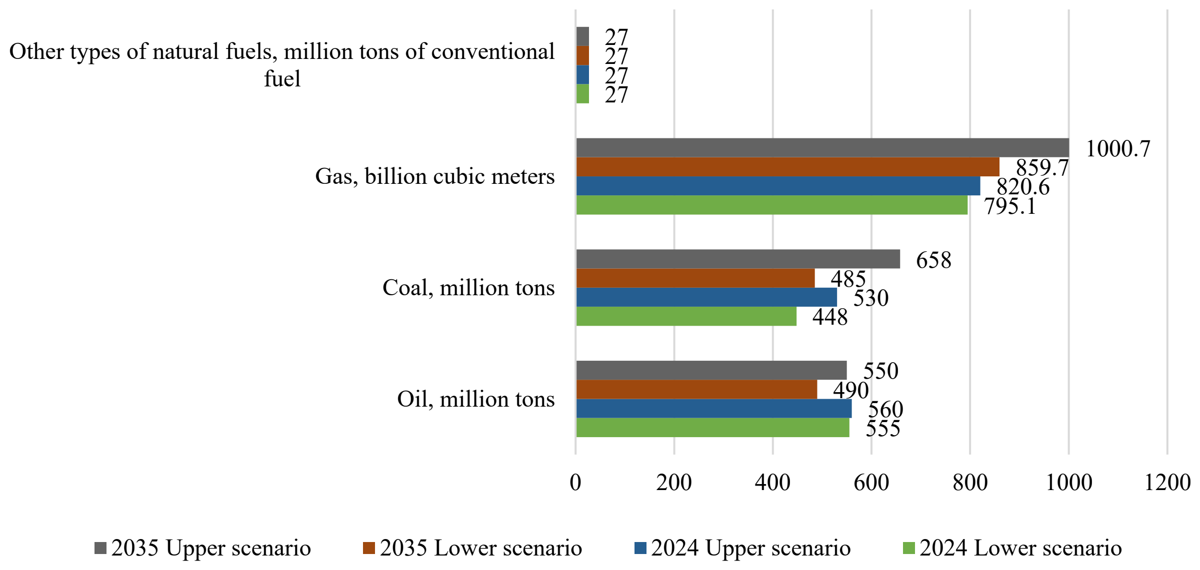

Fig. 1. Forecast of Russia's fuel and energy balance (2024, 2035)

[1] *Energy Strategy of the Russian Federation for the Period up to 2035.* Decree of the Government of the Russian Federation No. 1523–r dated June 9, 2020. (In Russ.) URL: http://static.government.ru/media/files/w4sigFOiDjGVDYT4IgsApssm6mZRb7wx.pdf (accessed: 13.01.2025).

According to the data in Figure 1, the country has no plans to significantly decrease the extraction of natural, non-renewable energy resources until 2035. The Energy Strategy emphasizes that one of the main objectives of energy development is to support the socio-economic growth of the state and encourage the development of other economic sectors, which highlights as priorities of the state energy policy "guaranteed energy security of the country as a whole and at the level of the subjects of the Russian Federation, especially those located in geostrategic territories; primary satisfaction of domestic demand for products and services in the energy sector"[2].

At the same time, the volumes of extraction and production of energy resources from extracted raw materials, fuel and electric energy production in the Russian Federation consistently exceed domestic consumption: for oil — by more than 1.9 times, for gas — by 1.5 times, for coal — by 1.8 times, for diesel fuel — by 2.6 times, for automobile gasoline — by 1.1 times [1]. This makes Russia one of the leading exporters of energy resources in the world. The profits from these exports are planned to be used for various purposes, including developing the industry, accelerating technological and digital evolution, and achieving national goals such as sustainable growth in real incomes for citizens.

The Strategy notes that among the world's largest economies, the fuel and energy balance of the Russian Federation is one of the most environmentally friendly (low-carbon). More than a third of electric energy generation comes from nuclear power, hydropower and other renewable energy sources. About half of the energy comes from natural gas[3], which is in line with global trends in the energy industry. Despite having abundant natural resources, the Russian Federation adheres to the goals of sustainable energy production and consumption, as defined by the United Nations Environment Programme[4].

To date, literary sources have primarily focused on specific aspects of green energy, including legal, economic, and technological aspects. However, a comprehensive analysis of the current state of renewable energy in Russia is lacking. This indicates a gap in scientific knowledge about the interaction between public policy, capital markets, and scientific developments required for the successful promotion and implementation of innovative and sustainable energy technologies in the country's energy sector. Furthermore, empirical data on the actual opportunities and growth potential of this sector of the Russian economy has not been thoroughly explored.

Therefore, the aim of this research was to conduct a comprehensive analysis of the features and trends in the development of green energy in the Russian Federation. This included studying the impact of government policies on the adoption of renewable energy sources, identifying existing barriers and opportunities for growth in this sector, and developing recommendations to improve conditions for further development of green energy in the country.

Materials and Methods. The study used regulatory and legal acts of the Russian Federation: the Energy Strategy of the Russian Federation for the period up to 2035, the State Program of the Russian Federation "Energy Development", the Decree of the President of the Russian Federation "On Reducing Greenhouse Gas Emissions", the Strategy of Socio-Economic Development of the Russian Federation with low greenhouse gas emissions until 2050, Decree of the Government of the Russian Federation "On the Main Directions of State Policy in the Field of Improving the Energy Efficiency of the Electric Power Industry Based on the use of Renewable Energy Sources for the Period up to 2035", Federal Law "On Electric Power Industry".

The data of the Federal State Statistics Service of the Russian Federation, the Association for Renewable Energy Development (ARWE), RES statistics, and information articles on the UNEP (United Nations Environment Program) website were used. The United Nations Environment Programme's assessment reports presented on the IPCC (Intergovernmental Panel on Climate Change) website and materials on the problems of green energy development in the world and Russia presented in scientific works by domestic and foreign authors were also considered. Special attention was paid to the results of the "Renewable Energy in Russia and the World" review presented by Rosenergo[5]. Plans, reports, and results of monitoring the implementation of the State Program "Energy Development"[6] of the Russian Federation were analyzed using content analysis and structural-functional analysis methods.

A mixed research method was employed, which included qualitative and quantitative analysis. Public speeches by government officials, texts in the open press, and regulatory documents were analyzed qualitatively, while secondary information from statistical sources was analyzed quantitatively. The authors applied the methodological approach proposed by [1] as a basis for determining and analyzing the interrelationships of strategies for financing sustainable development in the Russian Federation.

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[2] Id.

[3] *Energy Strategy of the Russian Federation for the Period up to 2035.* Decree of the Government of the Russian Federation No. 1523–r dated June 9, 2020. (In Russ.) URL: http://static.government.ru/media/files/w4sigFOiDjGVDYT4IgsApssm6mZRb7wx.pdf (accessed: 13.01.2025).

[4] *The United Nations Environment Programme.* (In Russ.) URL: https://www.unep.org/ru (accessed: 13.01.2025).

[5] *Renewable Energy in Russia and the World.* The Ministry of Energy of Russia. Moscow: 2022. 105 p. (In Russ.) URL: https://rosenergo.gov.ru/upload/iblock/e04/3xtm87iv99x76b23c6wjul3as5pzz8zj.pdf?ysclid=lxezlwzc66231521884 (accessed: 13.01.2025).

[6] *The State Program of the Russian Federation "Energy Development".* Decree of the Government of the Russian Federation No. 321 dated April 15, 2014. (In Russ.) URL: https://minenergo.gov.ru/activity/government-program?ysclid=m7afzr9it1340468075 (accessed: 13.01.2025).

Results. The analysis of statistical data, scientific research, and government documents conducted by the authors as part of this work suggests that the number of non-renewable energy sources is decreasing year after year, despite their significant reserves. This could lead to the eventual depletion of these resources. The growth of the global population and constant increase in living standards have led to an increase in energy consumption. Since the 1960s, energy consumption has increased by 3.6 times[7]. This is a major reason for the active search for and implementation of alternative energy sources.

Other reasons are outlined in the United Nations Environment Programme. First and foremost, this is climate change on Earth, the need to eliminate its consequences. Greenhouse gas emissions are known to be the main cause of global warming. In 2020, the average surface air temperature exceeded the pre-industrial level of 1850–1900 by 1.1°C. If the current situation is ignored, the climate can warm by more than 2.9°C over the next century. According to the 2021 report of the Intergovernmental Panel on Climate Change, anthropogenic climate change is unprecedented over the last 2,000 years and is increasing in all regions of the world[8]. This can have disastrous consequences for life on Earth. According to the Paris Climate Agreement, which was adopted in 2015, the preferred temperature rise limit is 1.5°C. This requires a significant reduction in greenhouse gas emissions, by 50% by 2030 and by 100% by the end of the 21st century[9]. Review [2] examines in detail the driving forces of climate change, analyzes its consequences, and explains measures to mitigate these effects.

It should be understood that we are living in a time of natural crisis. Therefore, conservation, restoration, and the responsible use of natural resources are the main priorities at the moment. To prove this, UNEP provides specific examples of how human activity has led to the destruction of nature. This proves that "we are using the equivalent of 1.6 Earth to maintain our current lifestyle, and ecosystems are unable to keep up with our demands"[10].

Supporting territories affected by natural disasters, industrial accidents, and anthropogenic crises; combating environmental pollution; minimizing the adverse effects of chemicals — these activities can and should contribute to the restoration of nature and its riches. At the same time, they have a significant impact on states taking all necessary measures to implement them.

Currently, the legal basis for international cooperation on climate change is the United Nations Framework Convention, which was adopted on May 9, 1992 and developed into the Kyoto Protocol on December 11, 1997. To achieve the goals of the Framework Convention, the Paris Climate Agreement[11] was also adopted on December 12, 2015. The Russian Federation is a signatory to the Framework Convention, the Kyoto Protocol and the Paris Agreement. On November 25, 2020, the Russian Federation announced its first nationally determined contribution to the implementation of the Paris Agreement. These data are posted on the official portal of the secretariat of the United Nations Framework Convention on Climate Change[12]. The basis for this statement was the Decree of the President of the Russian Federation "On Reducing Greenhouse Gas Emissions", which tasked the government of the country with ensuring a reduction in greenhouse gas emissions by up to 70% by 2030, relative to 1990 levels. This reduction was to be achieved while taking into account the maximum absorption capacity of forests and other ecosystems, and subject to the sustainable and balanced socio-economic development of the Russian Federation[13], and the Strategy of socio-economic development of the Russian Federation with low greenhouse gas emissions until 2050[14]. The strategy provides for two scenarios of such development: inertial and targeted (intensive). It is the target scenario that is considered as the main one, which assumes the implementation of the commitments undertaken by the Russian Federation under the Paris Agreement and the Framework Convention and the achievement of a balance between anthropogenic greenhouse gas emissions and their absorption by 2060 at the latest. As part of technological development, the Strategy pays special attention to the development of renewable energy sources in the country.

[7] Id.

[8] *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panelon Climate Change. Intergovernmental Panel on Climate Change, Cambridge University Press*. IPCC; 2021. URL: https://www.ipcc.ch/report/ar6/wg1/ (accessed: 13.01.2025).

[9] *The Paris Agreement.* United Nations. URL: https://www.un.org/ru/climatechange/paris-agreement (accessed: 13.01.2025).

[10] *Facts about the nature crisis.* UN environment programme.URL: https://www.unep.org/facts-about-nature-crisis (accessed: 13.01.2025).

[11] *On the Ratification of the UN Framework Convention on Climate Change.* Federal Law. URL: http://www.kremlin.ru/acts/bank/7188. *On the Adoption of the Paris Agreement.* Decree of the Government of the Russian Federation No. 1228 dated September 21, 2019. (In Russ.) URL: http://static.government.ru/media/files/l0US0FqDc05omQ1VgnC8rfL6PbY69AvA.pdf (accessed: 10.02.2025).

[12] *NDC Registry.* United Nations. URL: https://unfccc.int/ru/NDCREG (accessed: 13.01.2025).

[13] *On Reducing Greenhouse Gas Emissions.* Decree of the President of the Russian Federation No. 666 dated November 4, 2020. (In Russ.) URL: www.kremlin.ru/acts/bank/45990 (accessed: 13.01.2025).

[14] *The Strategy of Socio-Economic Development of the Russian Federation with Low Greenhouse Gas Emissions until 2050.* Decree of the Government of the Russian Federation No. 3052-r dated October 29, 2021. (In Russ.) URL: http://static.government.ru/media/files/ADKkCzp3fWO32e2yA0BhtIpyzWfHaiUa.pdf (accessed: 13.01.2025).

The decree of the Government of the Russian Federation "On the main directions of state policy in the field of increasing the energy efficiency of the electric power industry based on the use of renewable energy sources for the period up to 2035"[15] states that the use of renewable energy sources is one of the significant measures "related to the fulfillment of the international obligations of the Russian Federation to limit greenhouse gas emissions".

According to the Federal Law "On Electric Power Industry", there are several types of renewable energy sources (Table 1)[16]:

Table 1

Renewable Energy Sources

Sun energy
Wind energy
Water energy (including wastewater energy), with the exception of cases when such energy is used in pumped storage power plants
Tidal energy
Wave energy of water bodies, including reservoirs, rivers, seas, and oceans
Geothermal energy using natural underground heat carriers
Low-potential thermal energy of earth, air, and water using special heat carriers
Biomass, which includes plants specially grown for energy production, including trees, as well as production and consumption waste, with the exception of waste obtained from the use of hydrocarbon raw materials and fuels
Biogas
Gas released by production and consumption waste in landfills of such waste
Gas produced at coal mines

The global technical potential of all types of renewable energy differs in terms of volume. Thus, the share of solar energy is 62.52%, geothermal energy (at depths up to 10 kilometers) — 32.75%, ocean energy — 4.47%, wind energy — 0.23%[17].

There is a steady increase in the use of renewable energy sources in the total global energy capacity (Fig. 2) [3].

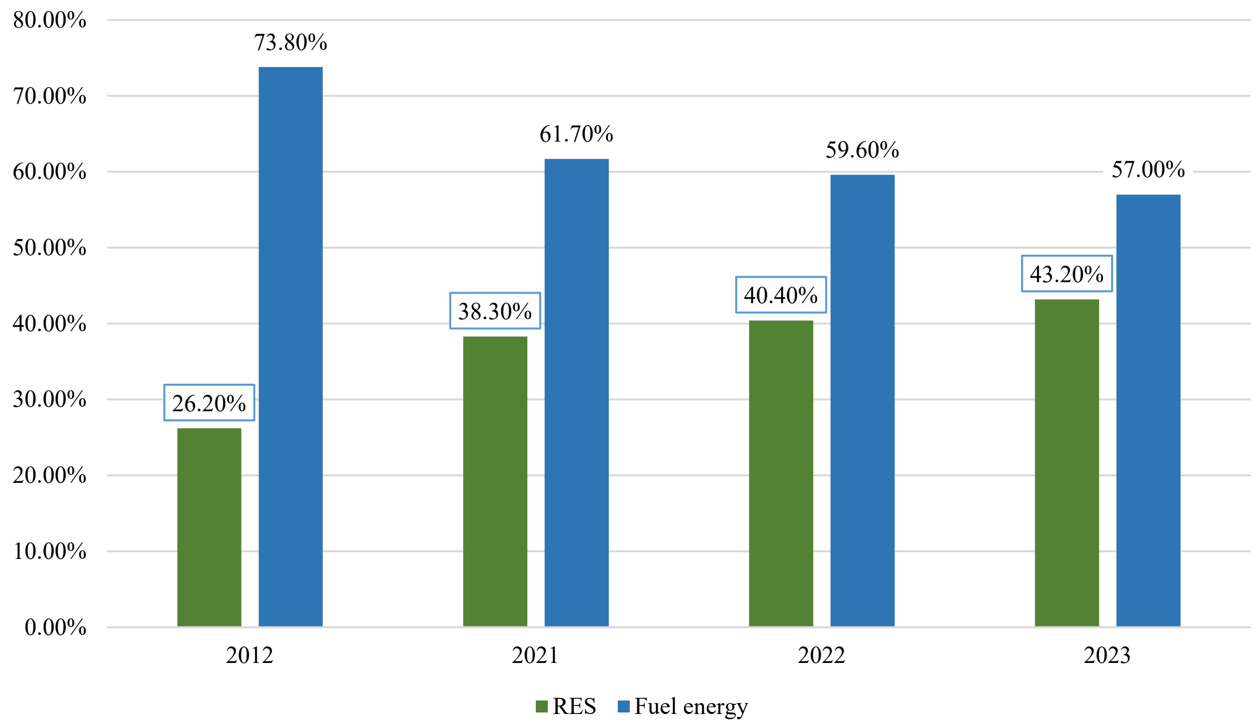

Fig. 2. Growth in the use of renewable energy sources

[15] *On the Main Directions of State Policy in the Field of Increasing the Energy Efficiency of the Electric Power Industry Based on the Use of Renewable Energy Sources for the Period up to 2035.* Decree of the Government of the Russian Federation No. 1-r dated January 8, 2009 (as amended by Decree of the Government of the Russian Federation No. 1446-r dated June 1, 2021). (In Russ.) URL: http://government.ru/docs/all/66930/ (accessed: 13.01.2025).

[16] *On the Electric Power Industry.* Federal Law No. 35-FZ dated March 26, 2003. The official website of the President of Russia. (In Russ.) URL: www.kremlin.ru/acts/bank/19336 (accessed: 13.01.2025).

[17] Id.

The largest volume of electricity generated from solar (SES) and wind power plants (WPP) is produced in China, followed by the United States, India, Germany, Brazil. Due to a large number of hydroelectric power plants, Russia is considered to have access to renewable energy sources to some extent, but it still lags behind in most other forms presented in Table 1. This has led to the need for further development of renewable energy sources in the country, which are given sufficient attention at the state level. The main focus is on the implementation of public-private partnerships in this area. In particular, the government decree[18] provides for competitive selection with the establishment of targets for the commissioning of renewable energy generating facilities, as well as basic limits for capital expenditures per kilowatt of installed capacity for each type of facility. It also sets basic limits for efficiency indicators, etc.

Government support and financial incentives for the development of renewable energy between 2013 and 2021 produced results that are significantly different from the occasional cases of previous years.

Meanwhile, the total capacity of renewable energy sources in the Russian energy system is still small, and the main contribution to the country's energy sector is still made by traditional fuel. Renewable energy accounts for only 2.41% of the country's unified energy system. As of April 1, 2024, the total capacity of renewable energy facilities in Russia was 6.11 GW, with wind and solar power plants leading the way (Fig. 3).

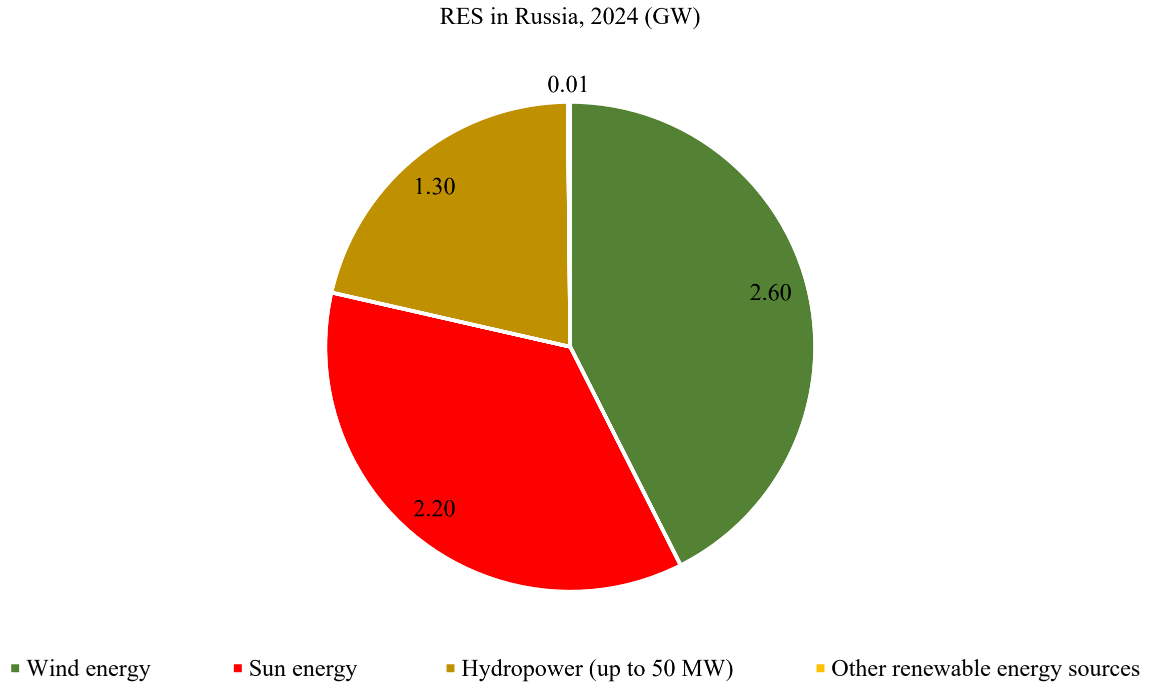

Fig. 3. Renewable energy sources in Russia in 2024

From 2013 to 2024, the country implemented a Capacity Delivery Agreement RES 1.0. The program was aimed at supporting the introduction of renewable energy sources financially. A competitive selection process was conducted among applicants, with the condition for signing contracts for the provision of renewable energy capacity for 15 years. Andrey Maksimov, Deputy Director of the Energy Development Department at the Ministry of Energy of the Russian Federation, emphasized that "investors receive a guarantee of returns on their investments through fixed income payments for capacity" [4].

It is important to note the constant increase in the commissioning of new renewable energy capacities during this period. From 2014 to 2023, the capacity increased from 1.66 to 6.11 GW. The highest peak occurred in 2020 and 2021. After that, due to sanctions imposed by states unfriendly to Russia, there was a noticeable decrease in the commissioning of new capacities (Fig. 4)[19].

[18] *On the Main Directions of State Policy in the Field of Increasing the Energy Efficiency of the Electric Power Industry Based on the Use of Renewable Energy Sources for the Period up to 2035.* Decree of the Government of the Russian Federation No. 1-r dated January 8, 2009 (as amended by Decree of the Government of the Russian Federation No. 1446-r dated June 1, 2021). URL: http://government.ru/docs/all/66930/ (In Russ.) (accessed: 13.01.2025).

[19] *RES statistics.* RREDA. (In Russ.) URL: https://rreda.ru/industry/statistics/?ysclid=lxxa7d8w6b624652409#graph2 (accessed: 13.01.2025).

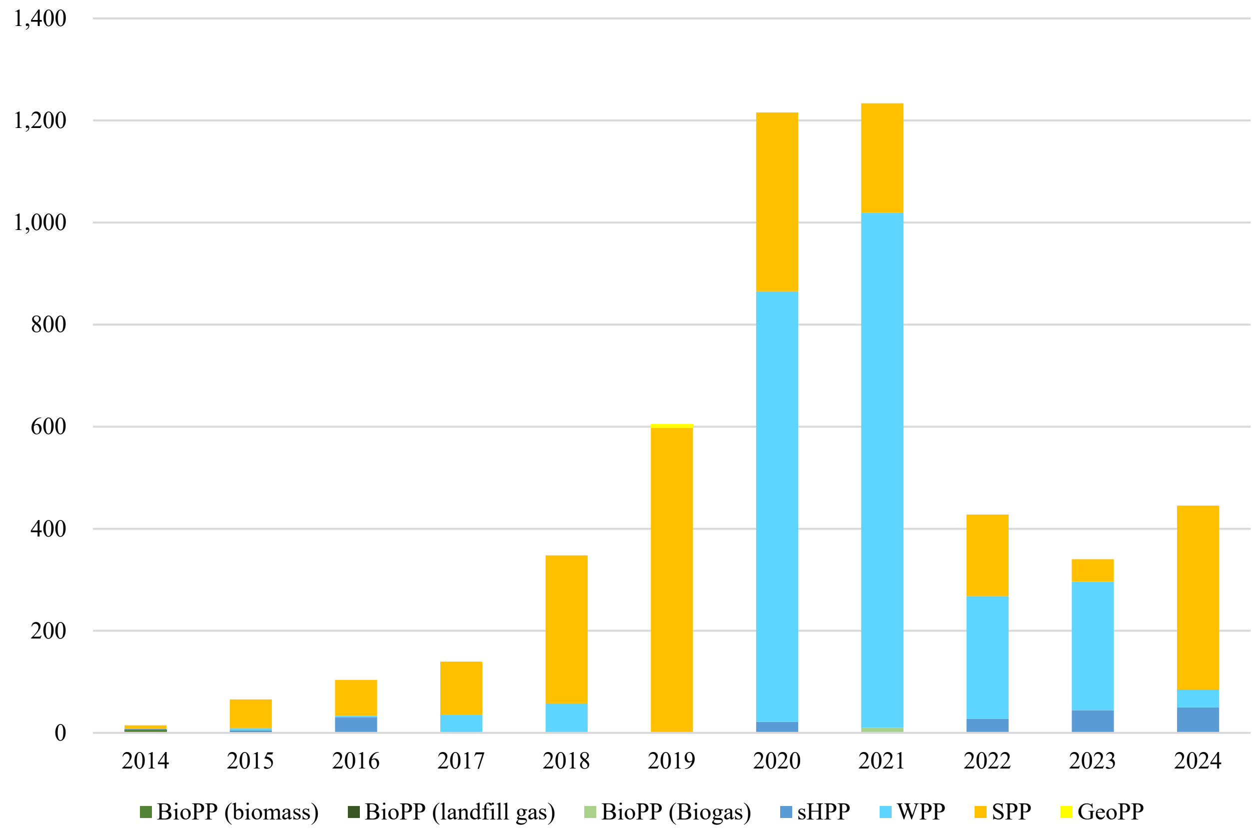

Fig. 4. Dynamics of commissioning of renewable energy power plants in Russia

The dependence on foreign components and materials for the production of domestic renewable energy equipment has led to delays in several investment projects[20]. At the same time, all previously announced investment projects continued their work. The government has taken measures aimed at specifying the timing of competitive selections for the construction of renewable energy generating facilities in the wholesale and retail electricity markets, and amendments have been made to the policy documents regulating this industry[21].

The CDA RES 1.0 program contributed to the creation of a production base of equipment for the commissioning of green energy capacities, which did not exist in the country in sufficient quantity. It determined the dependence of this industry on imported goods. As A. Maksimov noted, "the result of the first program was the introduction of new renewable energy facilities and the creation of a scientific basis for the production of necessary equipment" [4]. Since 2024, there is the CDA RES 2.0 program. It is designed to last until 2035. It aims to improve on the achievements of the first program. In the second program, the competitive selection process for projects has been adjusted. In the first program, projects were selected based on the level of capital expenditure. Now, the projects that demonstrate a higher efficiency in the facilities being commissioned are considered for nomination. The first competitive selection under the second program was held in 2021. The total capacity of the supported projects was 2.7 GW. The new approach has led to an increase in efficiency and a decrease in the cost of renewable energy facilities by approximately 85%.

[20] *Renewable Energy Market of the Russian Federation: Current Status and Development Prospects.* Plumbing, Heating, Air Conditioning. (In Russ.) URL: https://www.c-o-k.ru/articles/rynok-vozobnovlyaemoy-energetiki-rf-tekuschiy-status-i-perspektivy-razvitiya-chast-1 (accessed: 13.01.2025).

[21] *On Amendments to Certain Acts of the Government of the Russian Federation Regarding the Postponement in 2022 of the Competitive Selection of Investment Projects for the Construction of Generating Facilities Based on the Use of Renewable Energy Sources in the Wholesale Electricity and Capacity Market and the Competitive Selection of Projects for the Construction of Generating Facilities Based on the Use of Renewable Energy Sources in the Retail Markets Electrical Energy.* Decree of the Government of the Russian Federation No. 338 dated March 10, 2022. (In Russ.) URL: https://normativ.kontur.ru/document?moduleId=1&documentId=460412 (accessed: 13.01.2025).

On Amendments to Certain Acts of the Government of the Russian Federation on the Issues of Conducting Competitive Selections of Investment Projects for the Construction of Generating Facilities Operating on the Basis of Renewable Energy Sources in the Wholesale and Retail Electric Energy Markets and on the Establishment of Certain Features of State Regulation of Prices (Tariffs) in the Electric Power Industry in 2022 and 2023. Decree of the Government of the Russian Federation No. 999 dated June 01, 2012. (In Russ.) URL: http://publication.pravo.gov.ru/Document/View/0001202206010030?ysclid=lxxgus4o9z227009000 (accessed: 13.01.2025).

On Amendments to the Decree of the Government of the Russian Federation No. 1172 dated December 27, 2010. Decree of the Government of the Russian Federation No. 2389 dated December 29, 2023. (In Russ.) URL: https://base.garant.ru/408323687/?ysclid=lxxha7ty7t736108420 (accessed: 13.01.2025).

In [1], a roadmap is presented that outlines strategies for promoting green development through a hybrid approach. The authors identify 12 strategies, indicating that lower-level strategies are more significant than higher-level ones (Fig. 5). Based on this hierarchy, the researchers analyzed the extent to which Russia's energy development meets these criteria.

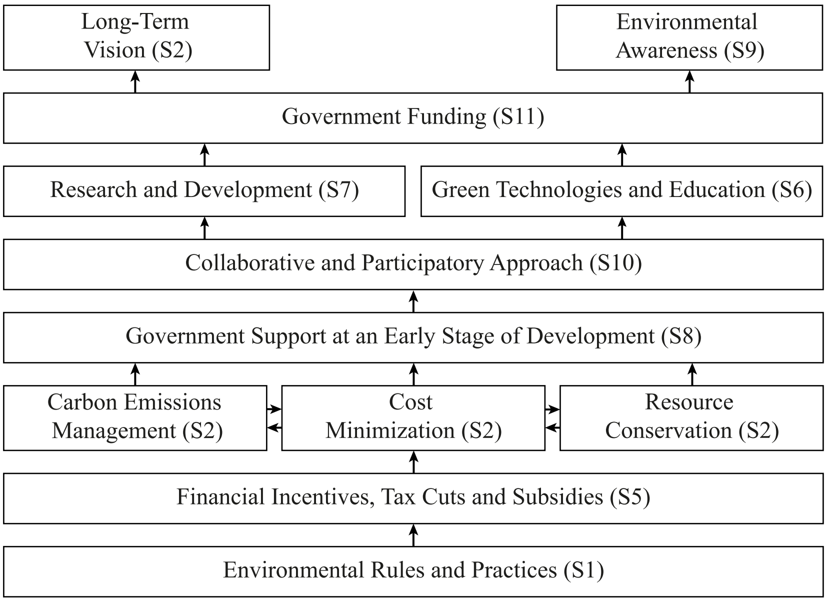

Fig. 5. Hierarchical structure of green innovation strategies [1]

The authors note that the fundamental basis of this structure is S1 “Environmental Rules and Practices” criterion. As mentioned above, Russia is a party to the Framework Convention, the Kyoto Protocol, and the Paris Agreement, having adopted all environmental rules and practices at the state level, as evidenced by the country's array of regulatory documents.

The next step in the proposed hierarchy is S5 “Financial Incentives, Tax Cuts and Subsidies”. The Russian Federation is the driving force behind the green transition, based on a public-private partnership. The Government of the Russian Federation[22] has defined measures of state support to achieve real competitiveness of renewable energy technologies against fossil fuel-based energy production. These measures include preferential tariffs for the sale of electricity generated from renewable energy sources, tax credits, preferential loans, and the introduction of a green tariff in Russia to attract additional investments[23]. From 2013 to 2021, the mechanism for supporting and stimulating the development of renewable energy sources has supported the commissioning of 121 power plants in Russia, including 83 SES, 27 WPP, and 11 sHPP. An important aspect here is the legal framework for the proportion of renewable energy sources in a country's overall energy mix.

As can be seen in Figure 5, the next most significant level is determined by three factors: S3 “Resource Conservation”, S4 “Cost Minimization” and S12 “Carbon Management”. Regarding S12, the Strategy[24] emphasizes that emissions management focuses primarily on their absorption by forests and swamps. Russia has a large number of forests and swamps, and there is a hypothesis that the absorption of greenhouse gases prevails over their release. The country has established a Unified national monitoring system for climatically active substances, and based on it, a National Cadastre has been created with information in a standardized international format for detailed verification of this hypothesis[25]. By government decree, it was given the status of an innovative project of national importance[26].

[22] *The Main Directions of the State Policy in the Field of Increasing Energy Efficiency of the Electric Power Industry Based on the Use of Renewable Energy Sources for the Period up to 2035* . Decree of the Government of the Russian Federation No. 1-r dated January 08, 2009. *On Amendments to the Decree of the Government of the Russian Federation dated January 08, 2009. N 1-R.* Decree of the Government of the Russian Federation No. 1446-r dated June 01, 2021 Legalact — laws, codes, and regulatory legal acts of the Russian Federation. (In Russ.) URL: https://legalacts.ru/doc/rasporjazhenie-pravitelstva-rf-ot-01062021-n-1446-r-o-vnesenii/?ysclid=m7bgc5ly4u984542445 (accessed: 13.01.2025).

[23] *On Amendments to Certain Acts of the Government of the Russian Federation Regarding the Definition of the Specifics of Legal Regulation of Relations of Microgeneration Facilities Functioning.* Decree of the Government of the Russian Federation No. 299 dated March 02, 2021. Official publication of legal acts. (In Russ.) URL: http://publication.pravo.gov.ru/Document/View/0001202103060015?ysclid=m7bgl0kdif79000694 (accessed: 13.01.2025).

[24] *On the Strategy of Socio-Economic Development of the Russian Federation with Low Greenhouse Gas Emissions until 2050.* Decree of the Government of the Russian Federation No. 3052-r dated October 29, 2021. Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/726639341?ysclid=m7bgpyga7q176688002 (accessed: 13.01.2025). (In Russ.)

[25] *In Europe, Everything was Cut Down. Russia has Become the Lungs of the Planet.* RIA News. (In Russ.) URL: https://ria.ru/20231011/poligon-1901702366.html?ysclid=ly5mwnjkql692557096 (accessed: 13.01.2025).

[26] *On Approval of the Most Important Innovation Project of National Importance “Unified National Monitoring System for Climatically Active Substances” and the Action Plan (Roadmap) for the Implementation of the First Stage (2022-2024) of the Most Important Innovation Project of National Importance “Unified National Monitoring System for Climatically Active Substances”.* Decree of the Government of the Russian Federation No. 3240-r dated October 29, 2022. Official publication of legal acts. (In Russ.) URL: http://publication.pravo.gov.ru/Document/View/0001202211010041?ysclid=ly5ob08110614670035 (accessed: 13.01.2025).

Along with the measures commonly used in other countries, the Strategy also includes measures to restore previously drained wetlands, improve fire safety in wetlands and forests, develop forest infrastructure, expand afforestation areas, and more. Research into carbon sequestration using new integrated technologies for improving rural health is ongoing in various countries [5–14].

S8 level of "State Support at an Early Stage of Development" is proved by all the previous content of the article. In Figure 5, S11 "State Financing" level is located penultimate when moving up, that is, as a less significant strategy. However, the authors believe that it should be placed at the same level as S8, especially since S6 and S7 strategies are provided to a greater extent by S11, as indicated in the "Priority-2030"[27].

S6 "Green Technologies and Education" and S7 "Research and Development" strategies emphasize the importance of cooperation between higher education institutions and industry. Here we should mention the Priority 2030 program, implemented by the Ministry of Science and Higher Education of the Russian Federation since 2016. This program brought together 142 universities across the country to ensure their integrative contribution to achieving Russia's national development goals, including the development of technologies that will help eliminate the negative effects of anthropogenic impact. The implementation of this program is supported by the Association of Green Universities in Russia, which unites 214 university volunteer teams and clubs that are actively involved in environmental protection activities. The interregional environmental public organization EKA is actively implementing the program "Green Universities of Russia" for 2021–2026 in educational institutions in order to enhance the ecological culture of Russian society[28]. While the emergence of sustainable environmental trends in Russian universities is encouraging, the country's lack of development in renewable energy sources has also led to a lack of educational programs for training specialists in alternative energy technologies. The training of highly professional engineers in the field of renewable energy, as rightly noted in the hierarchy in Figure 5, is possible only if S6 and S7 are included in S10 "Collaborative and Participatory Approach". In this regard, it is worth mentioning the inclusion of the "Advanced Engineering Schools" initiative in the list of initiatives for socio-economic development of the Russian Federation until 2030[29]. This initiative is part of larger programs such as "Low-Carbon Development Policy" and "Clean Energy (Hydrogen and Renewable Energy)". The federal project "Advanced Engineering Schools" is aimed at training specialists for high-performance sectors of the economy. They are created on a common basis by universities and technology companies for the formation of platforms for joint scientific research and project training of students in accordance with the profile of partners. One of the thematic areas is electric and thermal power engineering. The work includes 50 universities across the country and 150 companies. An obligatory part of the project is to attract extra-budgetary funds. According to the Ministry of Education and Science, in 2022, the financing of all schools from the federal budget amounted to 2.5 billion rubles, and the partner companies of the schools confirmed co-financing for another 3.8 billion. In 2023, the total financing amounted to about 10 billion rubles, and in 2024 it was planned to allocate about 18 billion rubles[30]. It is hoped that in the future, a platform will be selected to solve scientific and technical problems in the field of renewable energy and educational programs will be developed for training engineering personnel in this area [15, 16].

As for S2 "Long-Term Vision" and S9 "Environmental Awareness" strategies, we agree with the authors [1] that environmental awareness programs expand knowledge and understanding of sustainable development issues. The long-term vision provides a strategic framework for governments, financial institutions, and businesses to integrate sustainable development into planning.

Having gone through all the steps of the roadmap, we can make conclusions about the effectiveness of the proposed navigation by the authors [1], and the priority of factors by using the example of the Russian Federation. We can also identify the level of implementation of these strategies in Russia's movement towards sustainable development.

Discussion and Conclusion. In the Russian Federation, due to the abundance of natural resources and the development of nuclear power compared to many other countries, interest in the use of renewable energy for industrial purposes came later than in other countries. This delay in the introduction of renewable energy sources into the country's energy system is due to a number of reasons:

1) large natural reserves of fuel and energy resources;
2) significant reserves of combined power systems capacity;
3) operation of large hydroelectric power plants built in the USSR;
4) advanced nuclear power industry;
5) low prices and tariffs for electric and thermal energy.

[27] *The "Priority 2030" Program.* Sociocenter. (In Russ.) URL: https://www.garant.ru/products/ipo/prime/doc/405491263/ (accessed: 13.01.2025).
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[29] *A List of Initiatives for the Socio-Economic Development of the Russian Federation until 2030.* Decree of the Government of the Russian Federation No. 2816-r dated October 06, 2021. (In Russ.) URL: http://static.government.ru/media/files/jwsYsyJKWGQQAaCSMGrd7q82RQ5xECo3.pdf (accessed: 13.01.2025).
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However, according to Russian experts, the potential of renewable energy sources in Russia is also quite high. They estimate that it is 178 times higher than the current level of energy consumption in the country. This fact determines the priority of developing renewable energy. Government policy today aims to eliminate the gap between the Russian Federation and other countries in terms of the number of solar and wind renewable energy sources. It also aims to create competitive advantages for green energy over fossil fuels. A legislative definition of the timing of the introduction of renewable energy shares into the country's energy mix could be of great importance.

The country has begun to make a transition to more active use of renewable energy sources. At the same time, we should not forget that progress in one segment inevitably leads to regression in another. This is actually proved by the previous development of the fuel and energy sector. Therefore, it is important to continue studying the entire process of switching to green energy. While the introduction of alternative energy sources does require the use of fossil fuels for production and transportation, the production and maintenance of renewable components can lead to an increased demand for rare earth minerals. This can affect the issue of exhausting natural resources. Large-scale energy production, especially for solar energy, requires large areas of land. The production of solar panels can also lead to greenhouse gas emissions. Renewable energy sources create toxic waste, for example, at Solar Energy, compared to nuclear power plants, there are hundreds of times more of them. There is a risk of solar panels catching fire. Their harmful effects on the environment and wildlife are also possible. They have a low efficiency, as well as a relatively short service life, and are expensive. Renewable energy sources have a high degree of dependence on natural conditions, and there are serious risks in ensuring the sustainability of their operation.

The negative aspects of the introduction and operation of renewable energy sources and the environmental danger they pose are widely discussed by scientists [17–20]. Scientific research is underway to determine the impact of renewable energy on the environment, and experts are looking for technologies to eliminate related negative factors and increase the capacity of power plants. Russian President Vladimir Putin[31] also drew attention to the need for a phased and thoughtful movement towards green energy, noting, in particular, that green energy was actively developing, but it would not be able to cover all the needs of the global economy for a long time. The processes related to the introduction and stable functioning of green energy will take a lot of time, as they take place in stages, including the scientific justification of the explication of threats that arise from the use of renewable energy, and the identification of ways to eliminate them. Therefore, at the present time, while non-renewable energy sources continue to be used, it is essential to reduce greenhouse gas emissions, combat environmental pollution, preserve, restore and use nature carefully, and increase the ecological culture of production and the population.

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Original Empirical Research

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Digital Safety Monitoring System for Auto Repair Company

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Abstract

Introduction. The scientific literature discusses the potential of artificial intelligence (AI) for ensuring industrial safety. Risk control methods are considered and recommendations for incident prevention are given. The relationship between the competencies of lifting crane operators and the probability of accidents has been studied. Examples of using neural networks for determining the reliability of removable lifting devices are presented. Remote monitoring of operational safety is described. However, the use of AI to manage risks in a car repair station has not been sufficiently studied. This research aims to address this gap. The aim of this work is to demonstrate the potential of neural networks in creating a safety monitoring system for an automobile repair facility.

Materials and Methods. The design materials of the service station at the equipment repair and maintenance center served as basic information. This enterprise was created by specialists of the Department of Operation of Transport Systems and Logistics at the Don State Technical University (DSTU). Risks were classified according to GOST ISO 12 100[1] and GOST R 58 771[2]. Neural networks were trained using open-source libraries for the Python programming language. The digital monitoring system model with visualization was implemented using the AnyLogic simulation system.

Results. The authors of this work trained 20 neural networks and selected five with the lowest error function values (from 74% to 78%). Out of five networks that worked most correctly, one was chosen that predicted the output parameter more accurately — 74%. The neural network with the best performance was a multilayer perceptron with 30 neurons in the input layer, 15 in the hidden layer, and 3 in the output layer. It was used to create a digital twin that warned in real time about potentially dangerous events: the movement of a car, a crane, and the opening of an inspection pit. Additionally, it identified workers without personal protective equipment or access to the work area.

Discussion and Conclusion. The use of a digital safety monitoring system model will make it possible to identify high-risk work areas in advance, and reduce accidents and industrial injuries. The introduction of this model in auto repair facilities involves the installation of sensors and warning systems. In the future, we plan to explore the possibility of integrating algorithms with the risk monitoring system to help personnel repair specific types of machines.

Keywords: auto repair shop safety, risk assessment tool, body repair shop safety, digital twin for safety assessment

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Оригинальное эмпирическое исследование

Система цифрового мониторинга безопасности для авторемонтного предприятия

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Аннотация
Введение. В научной литературе описываются возможности искусственного интеллекта (ИИ) для обеспечения производственной безопасности. Рассматриваются методы контроля рисков, даются рекомендации по предотвращению инцидентов. Изучена связь между компетенциями машинистов грузоподъемных кранов и вероятностью аварий. Есть примеры использования нейросетей для определения надежности съемных грузозахватных приспособлений. Описан дистанционный мониторинг эксплуатационной безопасности. При этом недостаточно проработаны вопросы применения ИИ для контроля рисков в автосервисе. Представленное исследование призвано закрыть данный пробел. Цель работы — показать возможности использования нейросетей для формирования системы мониторинга безопасности на авторемонтном предприятии.
Материалы и методы. В качестве базовой информации использовали проектные материалы станции технического обслуживания при Центре по ремонту и обслуживанию техники. Это предприятие создали специалисты кафедры «Эксплуатация транспортных систем и логистика» (ЭТСиЛ) Донского государственного технического университета (ДГТУ). Риски классифицировали по ГОСТ ISO 12 100 и ГОСТ Р 58 771. Нейронные сети обучали по открытым библиотекам для языка «Питон» (Python). Модель системы цифрового мониторинга с визуализацией реализовали в системе имитационного моделирования «Эни лоджик» (AnyLogic).
Результаты исследования. Авторы представленной работы обучили 20 нейросетей и отметили пять с наименьшими значениями функций ошибок (от 74 % до 78 %). Из пяти наиболее корректно сработавших нейросетей выбрали ту, которая точнее предсказала выходной параметр — 74 %. Наилучшая нейронная сеть, определяющая уровень риска для зоны кузовного ремонта, — это многослойный персептрон с 30 нейронами во входном слое, 15 нейронами в скрытом слое и 3 нейронами в выходном слое. Ее задействовали для создания цифрового двойника, который в режиме реального времени предупреждает о потенциально опасных событиях: движении автомобиля, крана, открытии осмотровой канавы. Кроме того, обнаруживаются работники без средств индивидуальной защиты и лица без допуска в зону работ.
Обсуждение и заключение. Применение модели цифровой системы мониторинга безопасности позволит заранее обнаруживать зоны с повышенным риском проведения работ, сокращать аварийность и производственный травматизм. Внедрение этой модели в центрах по ремонту автотранспортных средств предполагает установку датчиков и систем оповещения. В перспективе планируется исследовать возможность дополнения системы мониторинга риска алгоритмами, которые помогут персоналу в ремонте конкретных видов машин.

Ключевые слова: безопасность авторемонтного предприятия, инструмент оценки риска, безопасность зоны кузовного ремонта, цифровой двойник для оценки безопасности

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Introduction. In the near future, machine learning methods will be increasingly used to ensure safety and assess production risks at transport repair facilities. This trend is supported by the rapid development of artificial intelligence and the transport sector. As a result, theoretical and practical research on this subject is becoming increasingly important.

New, more complex machines and equipment are being introduced. Car service companies are increasingly utilizing information and communication technologies. Production algorithms and work processes are changing. These developments can lead to harmful effects on people and equipment, and many of these potentially dangerous situations are difficult to predict. In this case, an integrated approach involves following the rules listed below.

1. It is important to monitor staff behavior and to ensure the compliance with safety requirements. It is necessary to focus on issues such as work performance and the use of personal protective equipment (PPE).
2. Regular updates on the characteristics and conditions of complex technological equipment are necessary.
3. Employees should be aware of the fire extinguishing equipment available at the workplace and know how to use them.
4. All employees should familiarize themselves with the evacuation procedures and first aid measures.

Let us note that the quality of such a complex, multifactorial system cannot be determined by the quality of its components. General safety in this case will be a higher-order concept, and artificial intelligence has the best tools to ensure it. Given the obvious inconsistency of the elements discussed above, we should note the importance of self-learning neural networks, which should be used to solve the problems of the presented scientific work.

The production process is exposed to external risks and also generates some of its own. While it is impossible to completely eliminate all potential dangers, there are known methods to reduce and limit them. One such method is the use of protective and monitoring devices, known as collective protective equipment[3]. The aim of such solutions is to reduce the likelihood of harm or its severity.

In [1], the issues of applying various methods of industrial risk control are discussed in detail, and recommendations are given for the formation and support of a safety system. Paper [2] provides examples of the use of neural networks to ensure the reliability control of lifting accessories. There are studies on the influence of the lifting crane operators' competencies on the likelihood of emergencies [3].

Patent work is underway in the same direction. For example, patent RU 2 682 020 C1 describes a method for remote safety monitoring during the operation of an object [4]. The solution is based on digital information technology systems. The location of safety control objects is recorded by geo-points, and the data about their parameters is transmitted to the neural network system. Video cameras are used for remote monitoring. The complex combines a server and a mobile software. Patent RU 2 534 371 C1 establishes a method for remote monitoring of hazardous production facilities. To achieve this goal, they will utilize:

– an information technology system;
– means of radio frequency identification;
– a set of devices for implementing the method.

It is proposed to equip safety control facilities with radio frequency identification (RFID). These devices are designed to transmit and receive data through remote devices, which are called readers in the patent. This is how safety parameters of the monitored facilities are fixed and their remote adjustment is ensured. At the same time, an unlimited number of authorized users get Internet access to the database.

Using the example of healthcare, the authors [5] explore the potential of using blockchain and the Internet of Things to create integrated monitoring systems.

In [6], it is proposed to install hazard monitoring sensors at the facility. For this purpose, three situations are modeled:

– it is possible to unlock barriers and open access to the facility;
– it is impossible to unlock barriers and open access to the facility;
– it is necessary to stop the operation of industrial equipment.

In the latter case, the shutdown will occur when the light and sound warning signals are triggered.

Machine learning methods were considered for monitoring the safety of bridges and roads. The author [7] focuses on the detection of damage. In this case, a neural network uses an array of data collected on an object without flaws to train it. This information is compared:

– with new data on intact and damaged objects;
– with forecasts from the vicinity of the output signal of the neural network.

Special attention should be paid to the work of Colombian scientists devoted to the use of neural networks to improve the safety of movement of visually impaired people [8]. The authors created artificial neural networks from a cooperative coevolutionary genetic algorithm. It is responsible for structuring, modifying, and training neural networks. The developed program has formed several neural networks. After the training, they chose those that better prevented collisions, that is, they would be useful to visually impaired people.

[3] *The Labor Code of the Russian Federation.* As amended on December 26, 2024. Part 1. Chapter 1. Article 4. (In Russ.) URL: https://www.consultant.ru/document/cons_doc_LAW_34683/ (accessed: 29.12.2024).

An analysis of scientific papers on safety in various fields has revealed common trends:

– verification of existing risks in the system, as well as methods for their reduction, is based on ISO 12100 and ISO 14121;

– machine learning of neural networks is actively used;

– sensors, systems for accumulating and processing information about the state of control objects are widely used;

– sensors and tags should be used to equip both equipment and personnel.

However, we should note that the issues of using artificial intelligence to control and reduce production risks in the field of automotive services are not well-developed. The presented scientific research aims to address this gap. The aim of the work is to demonstrate the potential of using neural networks to form a safety monitoring system at car repair enterprises.

Materials and Methods. The source materials for our scientific research were open data on incidents at the service station. We considered:

– accidents and injuries to personnel;

– the causes for such events.

The research involved the development and training of neural networks to assess the level of production risk at car service stations. This research could become the basis for a future unified safety monitoring system based on digital technologies. Figure 1 shows a schematic representation of this system. The neural network was represented as a separate tool for risk assessment.

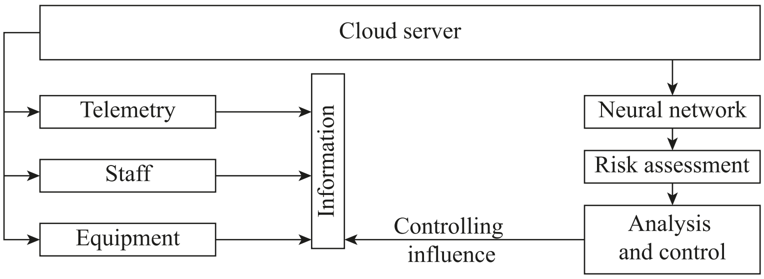

Fig. 1. The operation scheme of safety monitoring system of a car service company

The cloud server automatically collected information from sensors about telemetry, personnel, personal protective equipment (PPE) usage, and equipment. A neural network then analyzed this information to identify potential risks and provided guidance for control measures.

Thus, a particular task of the presented scientific work was the formation of an artificial neural network. To create it, we needed to select the tools, as well as the input and output parameters.

The authors reviewed ready-made platforms from various companies, including, TensorFlow, PyTorch, Keras, Ex-G Boost, and Statistica.

The first four platforms required writing software code, and when working with “Statistics” this was not necessary. All the necessary functionality was provided in the graphical interface. In addition, Statistica had extensive data processing and presentation tools.

To create a neural network, we used input data on car repairs at a service station. This facility was a division of the Equipment Repair and Maintenance Center, which was created by specialists from the Department of Operation of Transport Systems and Logistics at the Don State Technical University.

Let us consider the creation of a neural network for risk assessment in a body repair area. We should name the safety indicators that were constantly changing [9].

1. The remaining lifetime (or service life) of technological equipment. We assign the code A to the indicator.

2. The remaining lifetime (or service life) until scheduled maintenance or inspection. We assign the code B to the indicator.

3. The time remaining until the planned advanced training of specialists allowed performing the work. We assign the code D to the indicator.

4. The time remaining until the next verification of fire extinguishing equipment (mainly fire extinguishers). We assign the code E to the indicator.

Let us list the indicators that were determined by only two conditions: safe and dangerous.

1. Completeness of the issue and the correct use of workwear and PPE (issued or not issued, correctly or incorrectly). We assign the code G to the indicator.

2. Execution of work by authorized specialists (yes or no). We assign the code H to the indicator.

3. Illumination of the work area (meets or does not meet the standards). We assign the code I to the indicator.

4. Air temperature in the work area (meets or does not meet the standards). We assign the code J to the indicator.

5. Content of controlled harmful substances in the work area (meets or does not meet the standards). We assign the code K to the indicator.

If necessary, the set of indicators can be expanded.

A special class of variables should also be distinguished — linguistic qualitative indicators, that is, verbal descriptions of equipment parameters. For example, the technical condition of the equipment can be "very good", "good", "satisfactory", "poor", and "very poor". Such information was obtained by interviewing the personnel who worked with the equipment. We assign the code C to this indicator. Linguistic estimates can be represented numerically using the Harrington desirability function [10].

Thus, the letter designations for safety indicators codes are shown above. They are needed for convenience in entering information into the neural network. Table 1 shows some indicators related to the equipment in the body repair area.

Table 1

Some Safety Indicators of Technological Equipment in the Body Repair Area

No.	Equipment	Indicator code		
		Remaining lifetime (or service life)		Technical condition
		before scheduled maintenance or inspection	after scheduled maintenance or inspection	
1	Electric manual scissors IZ-5403	A1	B1	C1
2	Installation of gas welding and cutting	A2	B2	C2
3	Spot welding machine MT-601	A3	B3	C3
4	Combined electric welding machine	A4	B4	C4

The creation and training of neural networks requires large data samples, so the quantitative and qualitative input parameters for the body repair area have resulted in a unified view using the Harrington desirability function. This allowed us to determine a generalized risk assessment indicator [10].

In order to classify the output parameter of a neural network, we used the graph presented in ISO 14121 (Fig. 2).

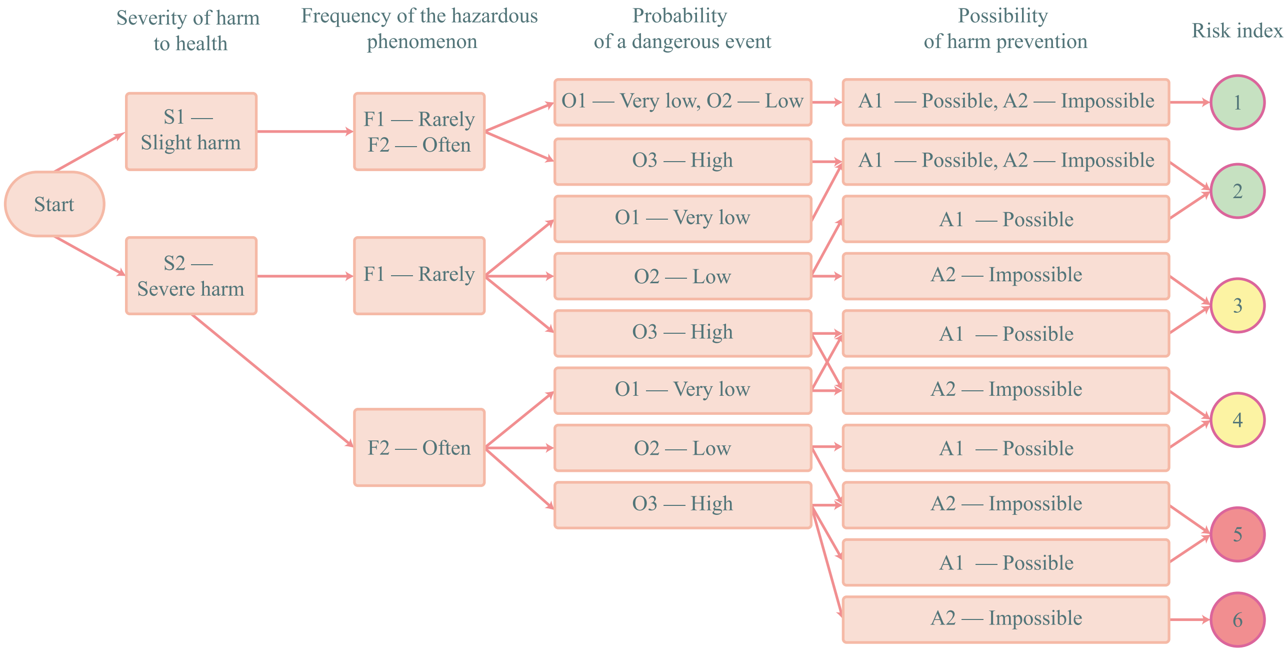

Fig. 2. Risk assessment graph according to ISO 14121 [10]

Letter designations were taken from the standard. They were not related to the codes in Table 1. It should also be noted that this graph was only a methodological guideline for assessing the level of risk, it did not allow taking into account all the variety of influencing factors. This was exactly what a neural network was trained for.

To assess each dangerous situation, the following conditions were taken into account at the output of the graph:

– risk index equal to 1 or 2 corresponded to the lowest priority of actions (priority 3);
– risk index 3 or 4 corresponded to the average priority of actions (priority 2);
– risk index 5 or 6 corresponded to the highest priority of actions (priority 1).

Thus, it was possible to identify risks that corresponded to the green (lowest), yellow (medium) and red (high) danger levels. In other words, the output parameter of the neural network was a generalized risk assessment indicator defined as green, yellow or red.

To train neural networks in Excel spreadsheets, we generated input parameters for 1,000 variants of body repair area indicators. With fewer options, neural networks could not qualitatively detect all patterns and relationships. Based on the calculated value of the generalized risk assessment desirability function [11], the risk level was determined for each data variant on a three-color scale. Figure 3 provides a fragment of the neural network training data. This was a part of the codes not included in Table 1.

1	A6	A7	A8	A	SAFETY
2	0.44	0.74	0.19		GREEN
3	0.97	0.22	0.65		YELLOW
4	0.79	0.73	0.17		GREEN
5	0.57	0.01	0.06		YELLOW
6	0.68	0.69	0.23		GREEN
7	0.67	0.61	0.08		RED
972	0.18	0.26	0.44		YELLOW
973	0.34	0.64	0.12		YELLOW
974	0.26	0.32	0.82		GREEN
975	0.01	0.20	0.24		RED
976	0.66	0.65	0.14		YELLOW
977	0.86	0.56	0.79		RED
978	0.22	0.02	0.27		RED
979	0.34	0.90	0.11		YELLOW

Fig. 3. A fragment of data for neural network training

The source information was imported into a data table created in the Statistica workbook.

The “Neural networks” module of the Statistica environment solved problems of five types:

– regression;
– classification;
– time series (regression);
– time series (classification);
– cluster analysis.

In the developed neural network model, the output parameter was the risk level (green, yellow, red), so this problem was solved as a classification problem.

Next, one needed to select the type of artificial neural network. Within the framework of this work, we considered:

– multilayered perceptron, MLP;
– radial basis function.

The system offered, and the authors used:

– the number of neurons of the hidden layer;
– the number of trained and returned networks;
– activation functions of the hidden and output layers of the network.

Results. The system split the input data into training, test, and validation samples. Their ratio was left at the default. The sum of squared deviations and cross-entropy were chosen as error functions, which Statistica used to evaluate the quality of neural network training.

As a result, 20 neural networks were trained and five neural networks with the lowest error functions were selected (Fig. 4). The system automatically chose the type of error function for each neural network. In the used version of Statistica, the window with trained neural networks did not move vertically, so only three of the five networks were shown in Figure 4. Here, the error function values ranged from 76.7% to 78%. Neural networks 1 and 2, hidden in Figure 4, had error function values of 77.2% and 74%, respectively.

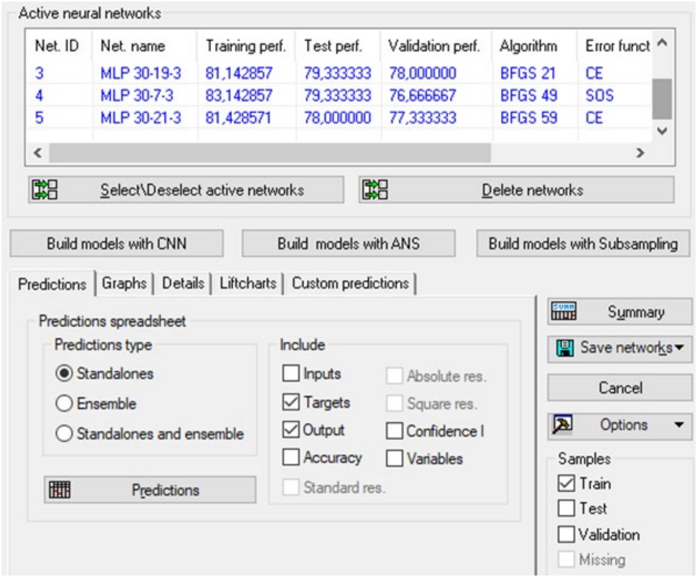

Fig. 4. The learning process of MLP architecture neural networks

The error of the neural network was estimated using cross-entropy [12]. The system chose a hyperbolic tangential function as the activation function of the hidden layer of neurons, and a multidimensional logistic function for the output layer of neurons.

After saving the resulting neural network in xml format, it could be downloaded and used for calculations in the Statistica environment. Here, one could also save a neural network as code in several programming languages for later use in software development.

Of the five trained neural networks that best corresponded to the validation and test data samples, we determined the one with the highest accuracy in predicting the output parameter — 74%. This indicator was expressed as a percentage of convergence with the output parameters of the samples (Fig. 5).

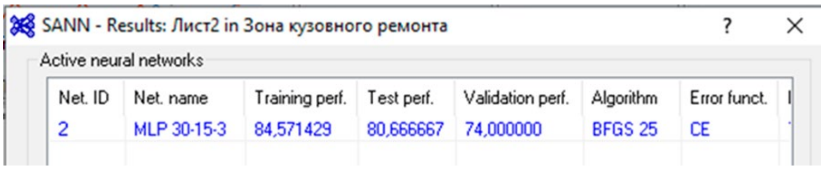

Fig. 5. The result of neural network training

The best neural network that determined the risk level for the body repair area had the MLP 30-15-3 structure, that is, a multilayer perceptron with 30 neurons in the input layer, 15 neurons in the hidden layer and 3 neurons in the output layer. The input layer of 30 neurons was determined by the number of incoming indicators for a given work area. There are 10 groups of indicators described in the “Materials and Methods” section, but due to the limited length of this article, it is not possible to list them all. If needed, the number of indicators could be increased.

The resulting neural network was translated into the Java programming language. The code (Fig. 6) was implemented into the digital twin program [13] and the artificial intelligence system [14] of the car service company safety assessment platform developed on AnyLogic.

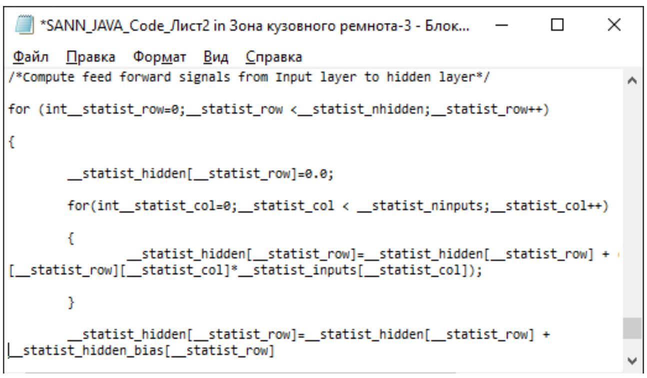

Fig. 6. A fragment of the neural network code in Java

Machine Building

Figure 7 provides the digital twin of the car service company safety assessment platform, developed at AnyLogic.

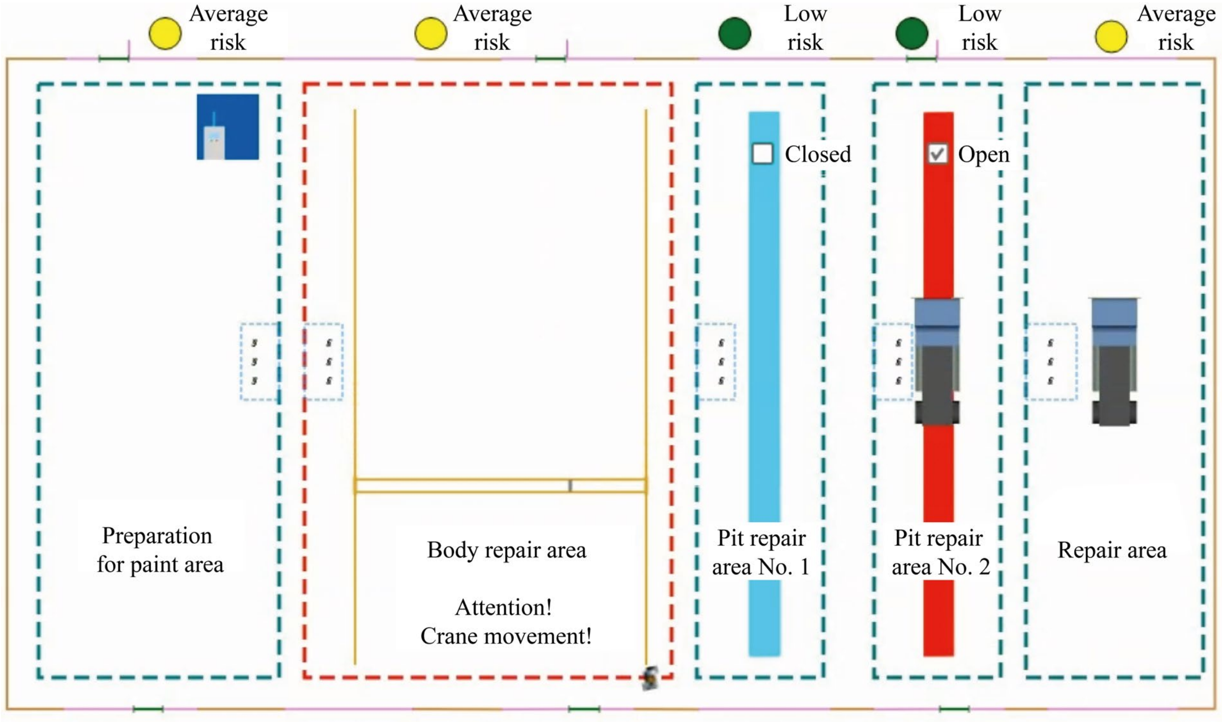

Fig. 7. Digital twin of the safety assessment platform

The digital twin in real time [15] displayed the risk levels at each site in the production workshop and alerted users to potentially dangerous events:

– movement of the crane;

– entry and exit of the car;

– opening of the inspection pit.

Employees without personal protective equipment and persons who did not have access to the hazardous work area were identified.

As a result, the dangerous factors of the car service company's production process were detected in a timely manner. Their comprehensive assessment was presented as a certain level of risk. At the same time, two factors could hinder the development of an unfavorable scenario:

– staff received timely information about the danger in graphic (color) and sound form;

– risk factors were eliminated, i.e. measures were taken to prevent accidents and industrial injuries.

Discussion and Conclusion. The results of the presented study close one of the gaps in risk management. Its scientific novelty is due to the specific nature of car service companies' activities, which have not been previously considered from this perspective. The first and most likely area of practical application of the proposed model of a digital safety monitoring system is car repair shops. However, it should be noted that its practical implementation involves mandatory installation of sensors and warning systems at the facility. The use of a digital safety monitoring system model will allow for the detection of high-risk work areas in advance and reduce occupational injuries. Thus, the digital twin of the car service company's safety assessment platform generated and transmitted the following information necessary for monitoring and management decisions:

– in the area of preparation for painting, — average risk level;

– in the body repair area — average risk level, a moving crane requires special attention;

– in the 1st pit repair zone — low risk level when the pit is open;

– in the 2nd pit repair zone — low risk level when the pit is closed;

– in the repair area — average risk level.

Further research plans include the development of a risk monitoring system at a car service station. This system can be supplemented with features that will assist staff in maintaining specific models of vehicles. Combining the assistance and monitoring systems can help avoid errors and increase safety in the workplace. This is especially important when servicing vehicles with unique design features, such as military vehicles. We plan to use augmented reality technology to display visual cues on specialized screens.

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VV Egelsky: formal analysis.
NN Nikolaev: methodology development.
EV Egelskaya: writing, reviewing and editing an article.
EA Panfilova: validation of results.

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Volumetric Changes and Structural Stresses after Quenching in a Magnetic Field

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Abstract

Introduction. As is well known, the process of steel hardening is accompanied by volumetric changes due to the difference in specific volumes of transforming phases. These volume changes result in structural stresses within the steel. The presence of these stresses in a hardened product negatively affects its resistance to brittle fracture, leading, for example, to decreased safety during operation of steel structures. In this regard, it is essential to improve heat treatment (HT) methods that reduce quenching stresses. One promising method involves applying a permanent magnetic field during phase transformation, which affects the kinetics of transition and resulting transformation products. However, there is a lack of data on volumetric changes during quenching for this method. The aim of this work is to investigate the effects of permanent magnetic fields on volumetric changes and structural stresses during steel hardening.

Materials and Methods. The research was conducted on technical iron and carbon steel 35, 45, U8, U10, U12. Magnetic fields with strengths of 1.4 and 1.6 MA/m were generated in an interpolar gap of the FL-1 electromagnet, designed by Moscow State University. Volumetric changes after conventional and magnetic quenching were quantitatively assessed by measuring the specific volumes using hydrostatic weighing method.

Results. Concentration dependencies of changes in specific volumes of carbon steels during quenching in a magnetic field at temperatures of 800 and 1 000°C were obtained. There were no changes in the volume effect of martensitic transformation in iron and U10 steel when quenching at temperatures higher than 800°C. Different changes in the volume effect were observed in steels with carbon content: from 0 to 1% — reduction in specific volume; from 1.0% to 1.2% — increase in specific volume. Calculation data showed that after quenching without a field, the level of structural stresses increased with an increase in the carbon content in austenite and an increase in the heating temperature for quenching. The influence of the magnetic field was reduced to a decrease in structural stresses in low- and medium-carbon steels and their increase in high-carbon steels. At low tempering temperatures, the level of structural stresses after quenching in a magnetic field was lower for medium-carbon 45 steel, and higher for U12 steel, than after quenching without a field.

Discussion and Conclusion. The data obtained for low- and medium-carbon steels can be explained by the increased degree of martensite decomposition "in statu nascendi" upon cooling in a magnetic field and an increase in the amount of martensite phase in high-carbon iron alloys. The change in the volume effect caused by the increase in the amount of martensite phase under the influence of a magnetic field prevailed over the change in the volume effect caused by its decomposition during the quenching cooling process. The magnitude and sign of the observed effects were determined by the carbon content in the original austenite, and there was a narrow range of concentrations for which magnetic hardening had virtually no effect on the level of structural stresses. The effect of a magnetic field during tempering somewhat slowed down the reduction of residual stresses in the temperature range of martensite decomposition. Structural stresses after heat treatment in a magnetic field, without taking into account the temperature gradient across the cross-section, were mainly determined by the effects obtained during quenching in a magnetic field. The intensification of the phenomena of martensite decomposition caused a decrease, and an increase in the completeness of the martensite transformation, an increase in the level of structural stresses.

Keywords: hardening, steel, volumetric changes, structural stresses, magnetic field, tempering

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Оригинальное эмпирическое исследование

Объёмные изменения и структурные напряжения в стали после закалки в магнитном поле

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Аннотация

Введение. Как известно, закалка стали сопровождается объёмными изменениями, вызванными разностью удельных объёмов превращающихся фаз. Возникающие объёмные изменения приводят к структурным напряжениям в стали. Присутствие напряжений в закаленном изделии сказывается отрицательно на сопротивлении хрупкому разрушению, что обуславливает, например, снижение безопасности при эксплуатации стальных конструкций. В связи с этим важным является совершенствование методов термической обработки (ТО) стали, которые позволяют снизить закалочные напряжения. Наложение постоянного магнитного поля в процессе фазового превращения оказывает влияние на кинетику перехода и образующиеся продукты превращения. Для этого перспективного метода ТО недостаточно данных об объёмных изменениях при закалке. Цель работы — исследование особенностей влияния постоянного магнитного поля на объёмные изменения и структурные напряжения при закалке стали.

Материалы и методы. Исследования проводились на техническом железе и углеродистых сталях 35, 45, У8, У10, У12. Магнитные поля напряженностью 1,4 и 1,6 МА/м создавались в межполюсном зазоре электромагнита ФЛ-1 конструкции МГУ. Количественная оценка объёмных изменений после обычной и магнитной закалки выполнялась путём измерения удельных объёмов методом гидростатического взвешивания.

Результаты исследования. Получены концентрационные зависимости изменения удельных объёмов углеродистых сталей при закалке в магнитном поле от температур 800 и 1 000 °C, на которых отмечалось отсутствие изменений объёмного эффекта мартенситного превращения в техническом железе и стали У10 при закалке от 800 °C, а также наличие разных по знаку изменений объёмного эффекта в сталях с содержанием углерода: от 0 до 1 % — уменьшение удельного объёма, от 1,0 до 1,2 % — увеличение удельного объёма. Расчётные данные показывают, что после закалки без поля уровень структурных напряжений возрастает с увеличением содержания углерода в аустените и повышением температуры нагрева под закалку. Влияние магнитного поля сводится к уменьшению структурных напряжений в низко- и среднеуглеродистых сталях и к их увеличению — в высокоуглеродистых. При низких температурах отпуска уровень структурных напряжений после закалки в магнитном поле для среднеуглеродистой стали 45 ниже, а для стали У12 — выше, чем после закалки без поля.

Обсуждение и заключение. Полученные данные для низко- и среднеуглеродистых сталей объясняются большей степенью распада мартенсита in statu nascendi при охлаждении в магнитном поле и увеличением количества мартенситной фазы в высокоуглеродистых сплавах железа. Изменение объёмного эффекта, вызванное приростом под действием магнитного поля количества мартенситной фазы, превалирует над изменением объёмного эффекта, обусловленного ее распадом в процессе закалочного охлаждения. Величина и знак наблюдаемых эффектов определяются содержанием углерода в исходном аустените, причем существует узкий диапазон концентраций, для которых магнитная закалка не оказывает практически никакого воздействия на уровень структурных напряжений. Действие магнитного поля во время отпуска несколько замедляет снижение остаточных напряжений в температурном интервале распада мартенсита. Структурные напряжения после термической обработки в магнитном поле без учёта температурного градиента по сечению в основном определяются эффектами, полученными при закалке в магнитном поле. Усиление явлений распада мартенсита вызывает снижение, а увеличение полноты мартенситного превращения — повышение уровня структурных напряжений.

Ключевые слова: закалка, сталь, объёмные изменения, структурные напряжения, магнитное поле, отпуск

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Introduction. It is known that steel hardening is accompanied by volumetric changes [1] caused by the difference in specific volumes of converting phases. The resulting volumetric changes [2] lead to structural stresses in steel [3]. The presence of stresses in a hardened product [4] has a negative effect on the resistance to brittle fracture, which, for example, leads to a decrease in safety during operation of steel structures [5].

The application of a permanent magnetic field during phase transformation affects the transition kinetics and the resulting transformation products. In [6, 7], the results of studies of changes in the fine structure and phase composition of steels during quenching in a magnetic field are presented. It has been shown that when exposed to a magnetic field, multiplicative nucleation of martensite crystals occurs and the rate of transformation increases, as well as the temperature of $M_н$ to $M_д$ increases with the formation of stress martensite in the range of superplasticity of the transformation [8, 9]. This leads to an increase in the volume fraction of ϰ-martensite due to the early activation of the tempering stage of the freshly formed α-phase, and a decrease in the volume fraction of $A_{ост}$. in tool steels, significant thinning in the multiplet profile of the X-ray reflection {211}. The combination of these circumstances leads to changes in phase composition of steels, as well as in structure and properties of transformation products after quenching in a magnetic field.

The development of heat treatment methods that reduce quenching stresses is relevant. The above data on a promising maintenance technology involving an external magnetic field indicate that structural changes occurring under the influence of a magnetic field during quenching can affect the bulk and stress state of steel. However, a detailed research of the effect of the magnetic field on changes in the stress state of hardened steels has not been conducted before. Therefore, the aim of this study is to investigate the volumetric changes and structural stresses that occur due to the application of a permanent magnetic field during the hardening process of steel.

Materials and Methods. The research was conducted on ingot iron and 35, 45, U8, U10, U12 carbon steels. Magnetic fields with strengths $H = 1.4$ and 1.6 MA/m were created in the interpolar gap of an FL-1 electromagnet designed by Moscow State University.

Volumetric changes after conventional quenching and with the application of a magnetic field were quantified by measuring the specific volume by hydrostatic weighing. At the first stage, the samples were weighed in air ($P_В$). Next, the samples, suspended on a thin nylon thread 8Ø ÷ $18_{μm}$ were weighed in distilled water ($P_Ж$). The value of the specific volume, taking into account the density of distilled water $δ_Ж$ and air $δ_В$, was determined by the following expression:

$$\upsilon_0 = \frac{P_В - P_Ж}{P_В\left(\delta_Ж - \delta_В\right)} + \frac{1}{\delta_В}. \quad (1)$$

Results. The graph shown in Figure 1 demonstrates the effect of the magnetic field on volumetric changes during martensitic transformation in carbon steels, while the value of the specific volume occurring during conventional quenching was assumed to be zero. It can be noted that the sign of the change in specific volume and its magnitude were correlated with the temperature of heating for quenching and the carbon content in the steel.

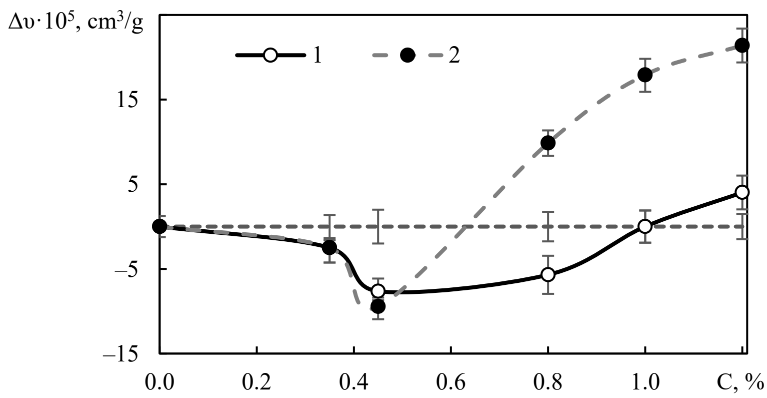

Fig. 1. Relative changes in specific volumes of steels during quenching in an external magnetic field $H = 1.6$ MA/m: 1 — from 800°C; 2 — from 1,000°C

Chemical Technologies, Materials Sciences, Metallurgy

In Figure 1, which shows the dependence of the change in specific volume on the carbon content, the following distinctive features can be observed. First, there is no volumetric conversion effect in pure iron and U10 steel when quenched at a temperature higher than 800°C. Additionally, there were differences in the sign in the volumetric effects change in steels with a carbon content of 0 ÷ 1.0 and 1.0 ÷ 1.2%.When quenching with a magnetic field, there was a decrease in specific volume for steels with 0 ÷ 1.0 % C and an increase for steels with 1.0 ÷ 1.2% C. The largest changes in specific volume occurred at 0.5 and 1.2% carbon. As the quenching temperature increased, the magnitude of the field effect changed and the point with no volume change shifted to lower carbon steel

The occurrence of structural stresses in the alloy was facilitated by volumetric changes during phase transformation, as well as their heterogeneous distribution across micro-volumes [10, 11]. Structural stresses could be calculated using the calculation method presented in [12], which made it possible to determine tangential, axial, and radial stresses in a fully cylinder, assuming that there was no temperature gradient in the analyzed section. The impact of the magnetic field on structural stresses during quenching could be estimated using an expression for calculating the tangential component of stresses on the surface:

$$\sigma_\tau = -\frac{E \cdot l}{2(1-\mu)}, \quad (2)$$

where l — relative value of the structural deformation at the transformation stage; E — modulus of elasticity; μ — Poisson's ratio.

When estimating l, volumetric characteristics of the phases and measurement data of specific volumes of samples of such a small size were used, that the temperature difference between the core and the surface could be ignored. The data in Table 1 show that for the case of conventional quenching, structural stresses increased with the carbon concentration in the initial phase and with the quenching temperature.

Table 1

Structural Stresses (σ_τ) under Various Quenching Conditions

Steel	σ_τ, MPa, at the quenching temperature, °C*		Steel	σ_τ, MPa, at the quenching temperature, °C*	
	800	1,000		800	1,000
45	–600.9 / –549.6	–621.2 / –564.5	U10	–795.4 / –795.4	–923.2 / –1028.7
U8	–774.9 / –766.6	–903.8 / –939.4	U12	–798,6 / –819,7	–888.3 / –1007.0

**Numerator — quenching without a magnetic field; denominator — in H = 1.6 MA/m.*

Table 2 provides the calculation results of the structural stresses caused by transformations during hourly tempering of carbon steels hardened at a temperature higher than 1,000°C.

Table 2

Structural Stresses after Quenching and Tempering

Steel	Magnetic field strength,* MA/m	σ_τ, MPa, at the tempering temperature, ºC (taking into account the austenite yield strength)					
		20	100	150	200	250	300
45	0/0	–421.1	–254.1	–205.3	–163.7	–140.8	–122.2
	0/1.4	–421.2	–273.0	–215.4	–162.9	–140.7	–122.2
	1.6/0	–364.5	–226.1	–196.7	–164.8	–141.1	–122.1
	1.6/1.4	–364.5	–234.4	–200.4	–165.4	–141.7	–122.1
U12	0/0	–688.3	–527.8	–490.7	–536.4	–527.0	–484.2
	0/1.4	–688.3	–584.6	–536.5	–573.7	–531.4	–484.2
	1.6/0	–807.0	–691.7	–634.6	–627.8	–530.7	–484.1
	1.6/1.4	–807.0	–741.6	–670.1	–671.3	–532.7	–484.1

** Numerator — for quenching, denominator — for tempering.*

Discussion and Conclusion. The effects observed in Figure 1 for steels with low and medium carbon content are due to tempering processes occurring directly during quenching cooling in a magnetic field. For steels with high carbon content, the increase in volume fraction of the α-phase is responsible for these effects. An analysis of theoretical calculations [1] shows that for steel 45, after quenching in a magnetic field, a change of $\Delta \upsilon = -9 \cdot 10^{-5}$ cm^3/g is caused by a decrease of 0.04 ÷ 0.05% C in martensite. The observed change in $\Delta \upsilon = 22 \cdot 10^{-5}$ cm^3/g for steel with a carbon content of 1.2% is due to an increase in the volume fraction of the α-phase by 4–5%, assuming that the carbon content in martensite does not change during quenching in a magnetic field compared to conventional quenching.

The comparison of the graph data in Figure 1 with the results of the study on the fine structure of conventional and magnetic quenched martensite [6, 7] allows us to conclude that the change in the volumetric effect caused by an increase in the martensite phase under the influence of a magnetic field prevails over the change in the volumetric effect caused by its decay during quenching cooling.

The effect of the field is manifested in a decrease in structural stresses in steels with low and medium carbon content and their increase in steels with high carbon concentration (see data in Table 1). For example, after quenching 0.45% and 1.2% C steels in a magnetic field with a temperature higher than 1,000°C, the level of structural stresses in the first case decreases by 10%, and in the second case increases by 13%. Comparing the obtained results with the data of X-ray diffraction studies [6, 7], it can be noted that the sign and magnitude of the effects are determined by the concentration of carbon in the initial γ-phase. It is characteristic that for certain concentrations, quenching in a magnetic field has a slight effect on the values of structural stress. These effects of the magnetic field can be explained by the strengthening of tempering processes during the formation of martensite during quenching for steels with low and medium carbon content, and by increasing the volume fraction of martensite for steels with a high carbon content.

The formation of residual stresses during the quenching of steel [13, 14] begins, as is known, at $T_{упр}$ — temperature of the transition of the material from a plastic state to an elastic one. Therefore, the structural stresses that occur during quenching [15, 16] are composed of stresses caused by a change in the specific volume of the alloy during cooling from a temperature of $T_{упр}$ to $M_{н}$. The calculation of the latter by formula (2) shows that when the alloy is cooled to $M_{н}$ temperature, tensile stresses occur on the surface of a continuous cylinder that exceed the yield strength of austenite (200 MPa) for all the alloys studied. In this regard, after quenching, the stresses on the surface of the solid cylinder will be less than those shown in Table 1 by the value of the yield strength of austenite.

According to Table 2, it can be seen that at low tempering temperatures, the level of structural stresses after quenching in a magnetic field is lower for medium-carbon steel 45, and higher for U12 steel than after quenching without a field. The effect of the magnetic field during tempering slows down the reduction of residual stresses in the temperature range of martensite decomposition.

Thus, the magnitude of structural stresses after heat treatment in a magnetic field in the absence of a temperature gradient across the cross-section is largely determined by the effects obtained during quenching in a magnetic field. An increase in the phenomena of martensite decomposition causes a decrease, and an increase in the completeness of the martensite transformation causes an increase in the level of structural stresses.

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Original Empirical Research

The Use of Straw, Coal and Foam to Improve Thermal and Mechanical Properties of Polyurethane

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Abstract

Introduction. Polyurethane, a material composed of polyol and isocyanate, has been recognized as one of the most efficient thermal insulation materials. However, its insulating properties can be further enhanced by incorporating additives such as straw, coal, or foam. Nevertheless, there is a concern regarding the potential for reduced adhesion. The literature describes the introduction of additives into polyurethane as strengthening components. The limited volumes of fillers are justified by the need to maintain the uniformity of the samples. It should be noted that most additives did not significantly impact the thermal properties of the material. The aim of this research is to investigate the possibility of improving thermal and mechanical characteristics of polyurethane by adding fillers.

Materials and Methods. Samples of polyurethane from the company "Daumerk" (Turkey), with various additives, were experimentally studied. In the first stage, four samples were prepared without fillers, and in the second stage, six more samples were created with 5% and 10% additions of coal, straw, and foam. Thermal conductivity was assessed using a hot plate method, while compression testing was conducted using a device that could apply loads up to 5,000 N. Acoustic properties were measured with an instrument that evaluated the sound absorption coefficient.

Results. The sample containing 63% isocyanate and 37% polyol had the lowest density of 33 kg/m³. This was due to the absence of fillers and the homogeneous structure of the material. Adding 5% fillers did not significantly affect the density of the sample because the densities of straw and foam were close to the density of polyurethane without additives. Low water absorption was found in samples without additives (50% isocyanate and 50% polyol) and with 5% addition of foam (62% isocyanate and 33% polyol). As the proportion of isocyanate increased, water absorption increased. Samples with higher density and no fillers had better sound absorption. With a low additive content (5%), sound absorption increased due to the homogeneity of the structure. However, with a higher additive volume (10%), sound absorption decreased due to weaker bonds in the material. Adding 10% foam provided maximum resistance to water.

Discussion and Conclusion. The optimal filler content improves thermal, mechanical, and acoustic properties of polyurethane, opening up new possibilities for its application. However, a large volume of fillers can have a negative effect on the material's properties. For example, a high straw content can significantly increase water absorption. Therefore, it is recommended to use 5% straw content in combination with 62% isocyanate and 33% polyol, resulting in a thermal conductivity of 0.023 W/m·K, a density of 37 kg/m³, and a compressive strength of 358 kN/m². These results confirm the feasibility and possibility of using fillers, such as coal and straw, in the production of polyurethane materials. A modified composition with these fillers would be cheaper and possess better physical properties than the original material. Further research could focus on studying other types of fillers for polyurethane.

Keywords: thermal insulation properties of polyurethane, polyurethane with the addition of coal, polyurethane with the addition of straw

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Оригинальное эмпирическое исследование

Использование соломы, угля и пенопласта для улучшения ермических и механических характеристик полиуретана

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Аннотация

Введение. Полиуретан, состоящий из полиола и изоцианата, считается одним из самых эффективных теплоизоляционных материалов. Вероятно, его изоляционные качества можно усилить, если добавить такие наполнители, как солома, уголь и пенопласт. При этом есть риск ухудшения сцепления. В литературе описано введение добавок в полиуретан как укрепляющих компонентов. Незначительные объемы наполнителей объясняются необходимостью сохранить однородность образцов. Отметим, что большинство добавок не оказали значительного влияния на термические свойства. Цель данного исследования — изучить возможность повышения термических и механических характеристик полиуретана добавлением наполнителей.

Материалы и методы. Изучались образцы полиуретана компании «Даумерк» (Daumerk, Турция) с различными добавками: четыре образца без наполнителей и шесть с добавлением 5 % и 10 % угля, соломы и пенопласта. Теплопроводность оценивали методом горячей пластины. Для испытания на сжатие задействовали устройство, обеспечивающее нагрузку до 5 000 Н. Акустические свойства измеряли прибором для оценки звукопоглощения.

Результаты исследования. Образец, содержащий 63 % изоцианата и 37 % полиола, обладает наименьшей плотностью (33 кг/м³). Причины: отсутствие наполнителей и однородная структура материала. Добавление 5 % наполнителей не оказало значительного влияния на плотность образца, потому что плотности соломы и пенопласта близки к плотности полиуретана без добавок. Низкое водопоглощение — у образцов без добавок (50 % изоцианата и 50 % полиола) и с добавкой пенопласта 5% (62 % изоцианата и 33 % полиола). При увеличении доли изоцианата водопоглощение растет. Образцы с более высокой плотностью и без наполнителей демонстрируют лучшие показатели звукопоглощения. При низком содержании добавок (5 %) звукопоглощение увеличивается благодаря однородности структуры. При более высоком объеме добавок (10 %) звукопоглощение снижается из-за недостаточно прочных связей в материале. Добавка 10 % пенопласта обеспечивает максимальную устойчивость к воде.

Обсуждение и заключение. Оптимальное содержание наполнителей улучшает термические, механические и акустические характеристики полиуретана, открывая новые возможности для его применения. Большой объем наполнителей негативно сказывается на свойствах материала. Так, высокое содержание соломы заметно повышается водопоглощение. Рекомендуется использовать 5 % соломы с 62 % изоцианата и 33 % полиола. Теплопроводность этого состава — 0,023 Вт/м·K, плотность — 37 кг/м³, прочность на сжатие — 358 кН/м². Результаты исследования подтверждают возможность и целесообразность использования наполнителей (особенно угля и соломы) в производстве полиуретановых материалов. Модифицированный состав будет дешевле и с лучшими физическими характеристиками. Задачей дальнейших исследований может быть изучение других видов наполнителей для полиуретана.

Ключевые слова: теплоизоляционные свойства полиуретана, полиуретан с добавлением угля, полиуретан с добавлением соломы

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Introduction. The global energy agenda has led to active research on thermal insulation materials. The effectiveness of these materials is studied in relation to their characteristics and composition [1]. Polyurethane, hardened foam made of polyol and isocyanate, is considered one of the best insulating materials [2]. Natural fillers can be added to the composition to improve its performance, but only in small amounts, as excessive use can lead to decreased adhesion [3].

The scientific literature provides evidence that the addition of straw and coal can improve thermal, mechanical and acoustic properties of polyurethane [4].

The authors [5] obtained a set of samples by mixing purified soil heated to a temperature of 105°C with polyurethane components. Some samples were shaped, others were taken after free foaming. Compression, flexibility, fluidity, and freezing tests were performed. The results were compared with experimental data on marble, ceramic, and basalt samples. It was found that the mixture with purified soil has the best impact strength. However, it is necessary to take into account the lower specific gravity of polyurethane samples.

The researchers [6] integrated recycled and pure polyurethane in various ratios (maximum — 10%). The samples with increased amount of recycled polyurethane foamed faster and had better tensile and compressive characteristics.

In [7], walnut and hazelnut shells are considered as filler for polyurethane. It has been proven that these additives combine well with polyurethane components. Even their small amount increases the mechanical properties and thermal stability of samples.

The possibility of using silica gel as a reinforcing additive for polyurethane was shown in [8]. Four samples containing 0%, 1%, 3% and 5% silica gel were studied. The tests showed that at 5%, thermal conductivity decreased to 0.0268 (W/m·K) compared to a material without a filler of 0.0314 (W/m·K). Stress and compressive strengths increased by 18% with the addition of 3% silica gel, but decreased if the filler volume exceeded 3%.

The author [9] added grain hulls and rubber from recycled tires to polyurethane. The optimal proportion of additives has been established: 5% of grain hulls and 15% of rubber. This ratio ensures the maximum mechanical strength of the material.

The aim of the scientific research described in this article is to study the possibility of improving the properties of polyurethane using additives: straw, coal and foam. It is assumed that the proposed solution will reduce thermal conductivity while maintaining good mechanical, acoustic and physical characteristics. In this case, it will be possible to talk about the economic feasibility of using modified material to increase the energy efficiency of facilities. Moreover, the composition itself should be more affordable, since polyurethane components are partially replaced by cheap fillers.

Materials and Methods. During thermal, physical, mechanical, and acoustic testing, samples of Daumerk polyurethane (Turkey) with and without additives were examined.

Sample preparation. At the first stage of the experiments, four samples of polyurethane were prepared. The main ingredients were mixed without any fillers and then poured into a mold (Fig. 1).

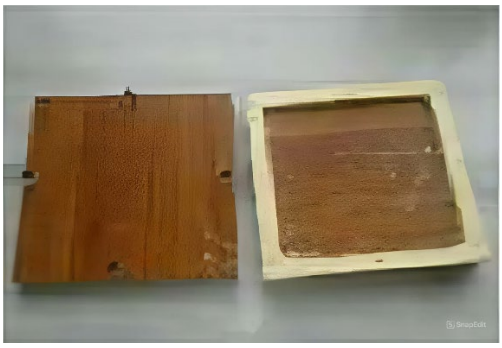

Fig. 1. Wooden sample mold

The dimensions of the wooden mold: 150×150×10 mm. Transparent glue was applied to the bottom and inner surface of the lid to prevent the mixture from sticking to the mold. After pouring the mixture, the lid was attached with four screws.

Table 1 shows samples with different ratios of polyurethane components.

Table 1

Polyurethane Components in the Samples, %

Component	Sample No.			
	1	2	3	4
Isocyanate	50	60	63	65
Polyol	50	40	37	35

At the second stage, the optimal ratios of isocyanate and polyol were selected and six new samples were made. 5% and 10% of coke coal, straw and foam were added to them (Table 2).

Table 2

Composition of Samples with Fillers, %

Sample No.	5	6	7	8	9	10
Isocyanate	62	60	62	60	62	60
Polyol	33	30	33	30	33	30
Additive	Foam — 5	Foam —10	Straw — 5	Straw —10	Coal — 5	Coal — 10

Thermal Testing. We used an HTC device (Highlight Tech Corp, China), which allowed us to determine thermal conductivity using the hot plate method in accordance with the American standard ASTM C177[1] (Fig. 2).

Fig. 2. Device for determining the coefficient of thermal conductivity

The device took into account the current and the applied voltage, and therefore measured heat flux Q between different sides of the sample, as well as temperature difference ΔT between its upper and lower surfaces. Knowing the dimensions of the sample (area A and thickness l), it was possible to determine coefficient of thermal conductivity $\boldsymbol{\lambda}$:

$$Q = A \cdot \lambda \cdot \frac{\Delta T}{l} \rightarrow \lambda = Q \cdot \frac{1}{A \cdot \Delta T}. \quad (1)$$

To ensure accuracy of the results, the device was pre-calibrated using three reference samples made of polystyrene, polyethylene and foam with known thermal conductivity [10]. After that, a calibration graph was constructed (Fig. 3).

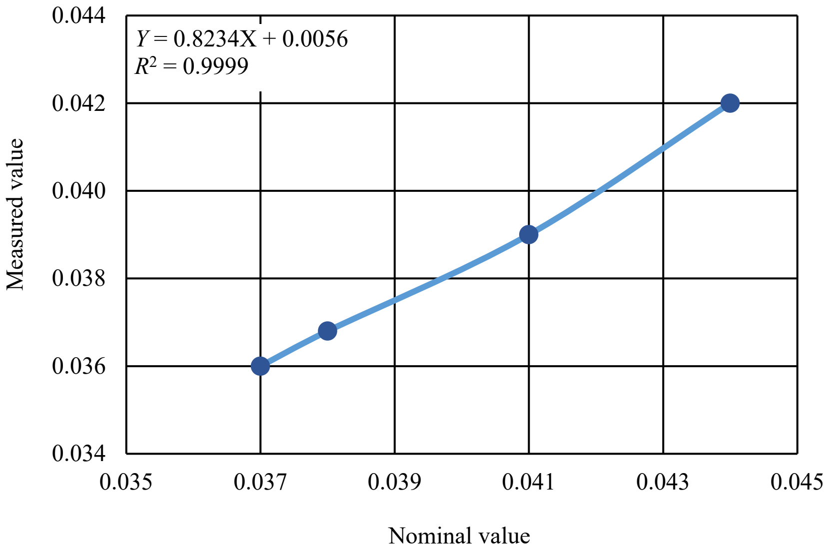

Fig. 3. Calibration graph of the device for measuring thermal conductivity:
R^2 — coefficient of determination; Y — variable value

The total error in measuring the coefficient was 5–7%.

[1] ASTM C177–19. *Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus.* URL: https://www.astm.org/c0177-19.html (accessed: 05.12.2024).

Compression Test. The compression test was performed in accordance with ISO 844[2]. A device was used (Fig. 4), which allowed applying a compression load of up to 5,000 N to the surface of the sample at a given speed. A load at a rate of 1 mm/min was applied to the samples with sides of 10×10 mm until deformation appeared. The results were recorded by a computer connected to the device with special software.

Fig. 4. Compressive strength testing device

Density Determination. To determine the samples density in accordance with ASTM C1622[3] standard, the weight and volume ratios were calculated. To do this, we used:

– scales with an accuracy of ±0.001 g (Fig. 5 *a*),

– vernier calipers with an accuracy of ±0.01 mm (Fig. 5 *b*).

a)

b)

Fig. 5. Devices for determining density:
a — scales; *b* — vernier calipers

[2] ISO 844:2021. *Standard Practice for Verification of Testing Frame and Specimen Alignment under Compressive Axial Force Application.* URL: https://cdn.standards.iteh.ai/samples/73560/24ff667df32b4981b29aa870b385bba2/ISO-844-2021.pdf (accessed: 05.12.2024).

[3] ASTM-C1622:2005-Standard. *Test Method for Apparent Density of Rigid Cellure Plastics.* URL: https://pdfstandards.shop/product/publishers/astm/astm-c1622-4/ (accessed: 05.12.2024).

Thus, the volume was calculated with an accuracy of ±0.01 mm³, and then the sample density was determined using the formula:

$$\rho = \frac{m}{v}, \tag{2}$$

where m — mass of the sample, kg; v — volume of the sample, mm.

Water Absorption Determination. To determine water absorption of the samples, they were immersed in water for a certain period of time. It was done in accordance with ASTM D2842[4] standard. The percentage of water absorption was calculated by taking the difference in weight between the sample before and after being immersed, and dividing it by the initial weight of the sample.

Sound Absorption Determination. To measure the sound absorption coefficient, a device was used that operated on the "transmitter —receiver" principle in accordance with ISO 10534-1[5] (Fig. 6).

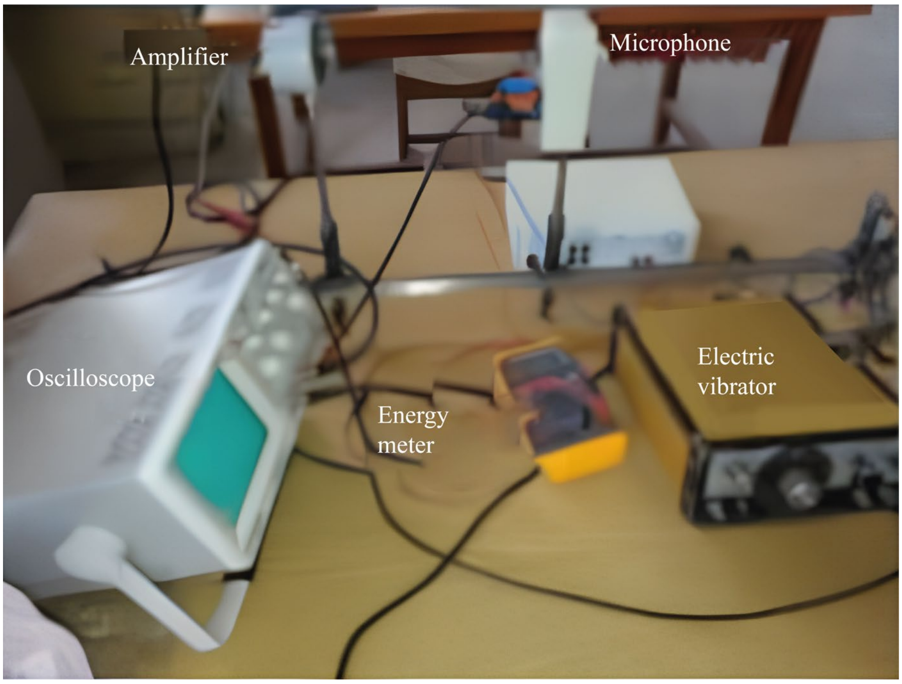

Fig. 6. A device for measuring the sound absorption coefficient

The sample was placed between a sound transmitter and a receiver, and a sound wave with certain energy was sent. The wave's energy was then measured, the frequency range was scanned and analyzed, and the sound absorption coefficient was determined.

Equipment set:
- dual electronic oscilloscope;
- vibrator with a frequency range (1–10 kHz);
- carbon amplifier for transmitting sound waves;
- microphone for receiving sound waves;
- metal bases for mounting the amplifier and microphone;
- bridge on which the amplifier and microphone slide;
- energy meter.

Knowing the wave energy before and after sample installation, it was possible to calculate the sound absorption coefficient:

$$\alpha = \frac{E}{E_0}, \tag{3}$$

where α — sound absorption coefficient; E — wave energy after sample installation (volts); E_0 — wave energy before sample installation (volts).

[4] ASTM D2842–19. *Standard Test Method for Water Absorption of Rigid Cellular Plastics.* URL: https://www.astm.org/d2842-19.html (accessed: 05.12.2024).
[5] ISO 10534–1:1996. *Acoustics — Determination of sound absorption coefficient and impedance in impedance tubes.* URL: https://cdn.standards.iteh.ai/samples/18603/3bfc0004b5024b2f9d8e3f19879aaf61/ISO-10534-1-1996.pdf (accessed: 05.12.2024).

Results

Density. Figure 7 shows the results of determining the density of the tested samples.

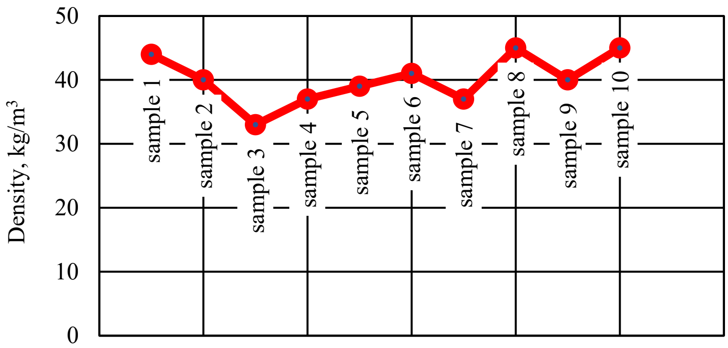

Fig. 7. Comparison of samples by density

The lowest density of sample 3 (33 kg/m³) was explained by the absence of fillers and the uniformity of its structure. The addition of fillers, especially in a volume of 5%, did not significantly affect the density. This was due, firstly, to the insignificant proportion of the additive. Secondly, the density of additives (especially straw and foam) was close to the density of polyurethane without additives.

Water Absorption. The results of water absorption tests are shown in Figure 8.

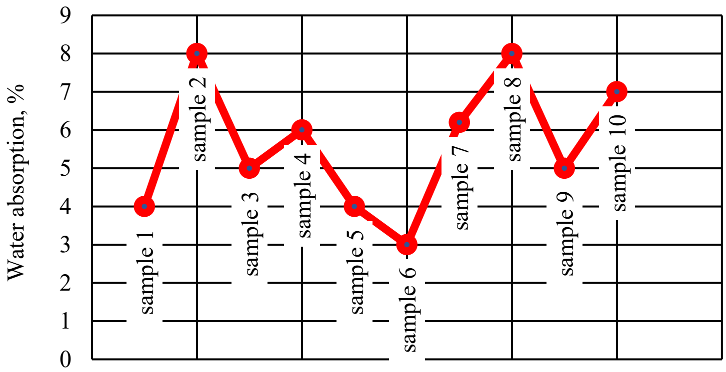

Fig. 8. Comparison of samples by water absorption

A low level of water absorption was recorded in samples without additives (50% isocyanate and 50% polyol) and with the addition of 5% foam (62% isocyanate and 33% polyol). With an increase in the proportion of isocyanate, the water absorption level increased, especially in samples 8 and 10 with 10% straw and coal. This was consistent with the results obtained by other researchers [11]. Sample 2 deviated from the general rule, which may be related to the specifics of its preparation. It is known that straw actively absorbs water. Accordingly, the water absorption is higher for samples with straw. When foam granules were added, on the contrary, water absorption decreased due to the high resistance of this material to water. For this reason, the minimum water absorption was observed for sample 6.

Thermal Properties. Figure 9 provides the results of thermal tests of the samples.

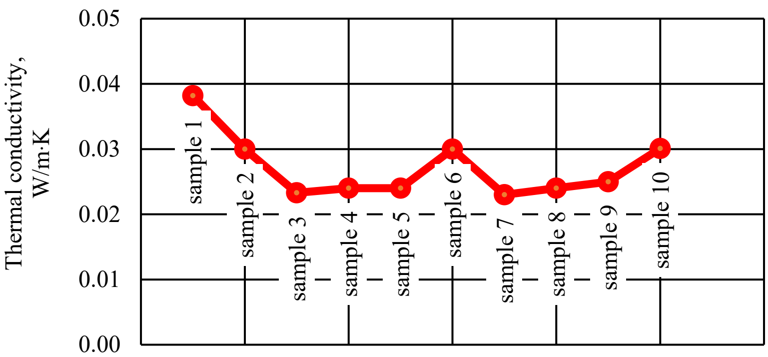

Fig. 9. Comparison of samples by thermal conductivity

The coefficient of thermal conductivity of samples without additives increased with an increase in the proportion of polyol. With high polyol content, the contact between the components improved, the cell sizes decreased, and the density increased. Dense materials provided more efficient heat transfer, i.e. they had higher thermal conductivity [12]. The addition of foam and coal in high concentrations also increased density and significantly increased thermal conductivity [13]. Adding fillers in small quantities, on the contrary, could improve thermal conductivity. For example, when adding foam and straw in the amount of 5%, it was possible to reduce the values of thermal conductivity to 0.023 W/m·K. The author of [14] obtained almost the same result of 0.024 W/m·K.

Compressive Strength. Figure 10 shows the results of determining the compressive strength.

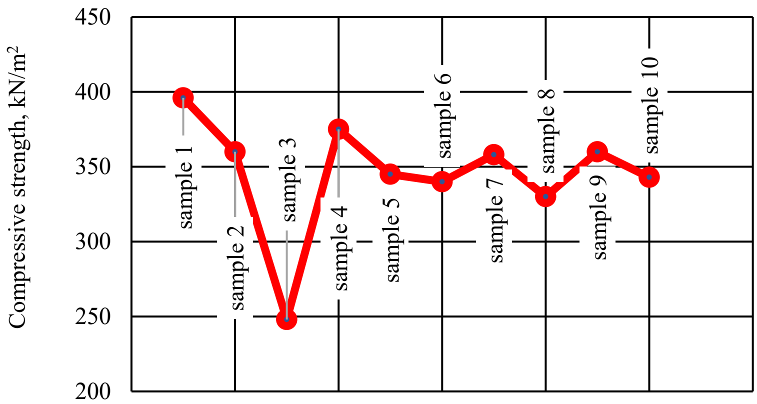

Fig. 10. Comparison of samples by compressive strength

Compressive strength was proportional to density of the material; therefore, in samples without additives, it increased with increasing polyol content. With the addition of 5% straw and coal, the compressive strength was high due to the uniformity of the cellular structure. With the addition of 10% filler, the mechanical strength decreased due to a decrease in the internal binding force of the sample.

Acoustic Characteristics. Figure 11 shows the results of sound absorption tests.

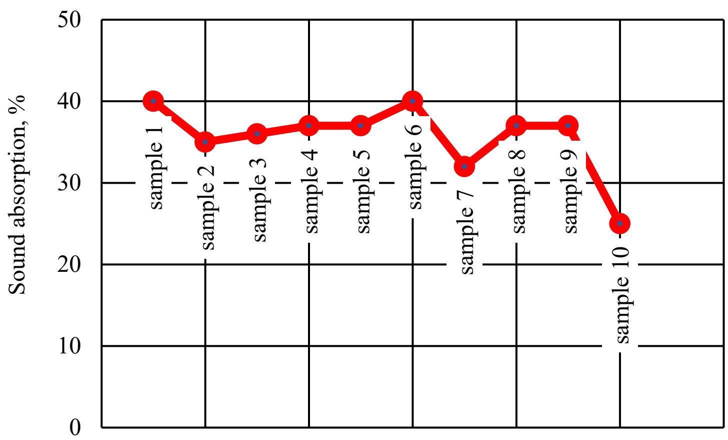

Fig. 11. Comparison of samples by sound absorption

Among the samples without fillers, the densest one had the best score — 1. With a low additive content (5%), sound absorption increased due to the homogeneous cellular structure. With a higher level of additives (10%), it decreased due to insufficiently strong bonds in the sample material.

Discussion and Conclusion. The results of the research allow us to draw the following conclusions.

1. The addition of fillers in a certain amount can improve thermal, mechanical and acoustic properties of polyurethane.

2. An increase in the proportion of additives generally worsens the studied properties and may increase water absorption. This happens when adding straw.

3. To achieve optimal results, it is recommended to add 5% straw to polyurethane, consisting of 62% isocyanate and 33% polyol. Thermal conductivity of this sample (number 7) was 0.023 W/m·K with a density of 37 kg/m^3 and a compressive strength of 358 kN/m^2.

4. The values of thermal conductivity and mechanical strength of sample 7 are better by 2% and 4%, respectively, compared with the sample without additives (number 3).

5. The advantages of sample 7 should also include its lower cost. Straw is cheaper than the main components of polyurethane.

In the future, it is planned to study other fillers in terms of their effect on the properties of polyurethane.

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