Vol. 8, no. 1, 2024
eISSN 2541-9129
PEER-REVIEWED SCIENTIFIC AND PRACTICAL JOURNAL

Safety of Technogenic and Natural Systems

Technosphere Safety

Machine Building

Chemical Technologies, Materials Sciences, Metallurgy

www.bps-journal.ru
DOI 10.23947/2541-9129

Safety of Technogenic and Natural Systems

Peer-reviewed scientific and practical journal (published since 2017)

eISSN 2541-9129
DOI: 10.23947/2541-9129

Vol. 8, no. 1, 2024

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Indexing and archiving:	RISC, CyberLeninka, CrossRef, DOAJ, Index Copernicus, Internet Archive
Name of the body that registered the publication	Mass media registration certificate ЭЛ № ФС 77 – 66531 dated Jule, 21, 2016, issued by the Federal Service for Supervision of Communications, Information Technology and Mass Media
Founder and publisher	Federal State Budgetary Educational Institution of Higher Education Don State Technical University (DSTU)
Periodicity	Quarterly (4 issues per year)
Address of the founder and publisher	Gagarin Sq. 1, Rostov-on-Don, 344003, Russian Federation
E-mail	vestnik@donstu.ru
Telephone	+7 (863) 2–738–372
Website	https://bps-journal.ru
Date of publication	28.02.2024

Безопасность техногенных и природных систем

Рецензируемый научно-практический журнал (издается с 2017 года)

eISSN 2541-9129
DOI: 10.23947/2541-9129

Том 8, № 1, 2024

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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Индексация и архивация:	РИНЦ, CyberLeninka, CrossRef, DOAJ, Index Copernicus, Internet Archive
Наименование органа, зарегистрировавшего издание	Свидетельство о регистрации средства массовой информации ЭЛ № ФС 77 – 66531 от 21 июля 2016 г., выдано Федеральной службой по надзору в сфере связи, информационных технологий и массовых коммуникаций
Учредитель и издатель	Федеральное государственное бюджетное образовательное учреждение высшего образования «Донской государственный технический университет» (ДГТУ)
Периодичность	4 выпуска в год
Адрес учредителя и издателя	344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1
E-mail	vestnik@donstu.ru
Телефон	+7 (863) 2–738–372
Сайт	https://bps-journal.ru
Дата выхода в свет	28.02.2024

Contents

Содержание

ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ

МАШИНОСТРОЕНИЕ

ХИМИЧЕСКИЕ ТЕХНОЛОГИИ, НАУКИ О МАТЕРИАЛАХ, МЕТАЛЛУРГИЯ

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UDC 331.44:612.821.1:519.876.5

https://doi.org/10.23947/2541-9129-2024-8-1-7-19

Original article

EDN: TGMDUK

Methodology for Determining the Parameters of a Mathematical Model of the Dynamics of the Psychophysiological State of a Metallurgical Equipment Operator

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Abstract

Introduction. Mathematical modelling is effective in the analysis of industrial safety at metallurgical plants, in particular for tracking problems of the man — machine system. To introduce the time factor, recurrence relations (in a discrete model) and differential relations (in a continuous model) are used. However, it is also necessary to solve the problem of linking the model parameters to the real conditions of the production environment and to the human factor. The aim of this study is to create a method for determining the parameters of simulation mathematical models of the dynamics of the operator's psychophysiological indicators affecting the work.

Materials and Methods. The operator's psychophysiological state (PPS) was assessed by performance, fatigue levels, and error rate. The data were collected by the Digital Correction Task (DCT) test. Based on the obtained results, the experimental values of the operator's PPS indicators, which were reduced to the normalized scale [0, 1], were calculated. These indicators for a particular respondent, the mathematical model and the developed algorithm were used to determine the numerical values of the model parameters. In order to interpret the indicators of performance, fatigue and error rate, we introduced scales with five gradations.

Results. The use of the authors' modified version of the mathematical model showed a significant improvement in its prognostic properties. Out of 10 participants the best result was shown by respondent no. 7, the worst result was shown by respondent no. 8. During the first working hour (from 9.00 to 10.00) their performance increased almost equally, from 0.5–0.55 to almost 0.6. Then the score of respondent no. 7 increased and remained well above the "good" level until the end of the day. The score of respondent no. 8 dropped and was below average from 14.00 to 15.00. The difference was largely determined by the operators' chronotypes. Their chronophysiological characteristics also affected fatigue and error rate. The model's quality varied for different participants in the experiments. In one case it was excellent (mean relative error ≤5%), in three cases it was good (≤10%) and in four it was satisfactory (≤15%).

Discussion and Conclusion. The proposed approach allows us to obtain the dynamic profiles of psychophysiological characteristics for every individual, to assess their interrelationships and to perform a prediction on the basis of a modified mathematical model. However, in order to extend the functionality of the models to the real working conditions of the metallurgical plant operator, it is necessary to increase the sample size, reduce the discrete time step and conduct studies for different working conditions, considering technological, climatic, environmental, psychological and other factors.

Keywords: safety at metallurgical enterprises, man — machine system, psychophysiological state of the operator, operator chronotype, operator performance

Acknowledgements. The authors express their gratitude to the employees of the Donbass State Technical University for their interest in the topic under discussion and conscientious answers and interviews and thank the editorial board of the journal and the reviewer for their attentive attitude to the article and for the specified comments that improved the quality of the article.

Funding information. The researches were carried out at the expense of the federal budget (theme code: FRRU-2023-0005 in the Unified state information system for accounting the research, experimental and technical works).

For citation. Vishnevsky DA, Podlipenskaya LE, Denisova NA, Bondar NA. Methodology for Determining the Parameters of a Mathematical Model of the Dynamics of the Psychophysiological State of a Metallurgical Equipment Operator. *Safety of Technogenic and Natural Systems.* 2024;8(1):7–19. https://doi.org/10.23947/2541-9129-2024-8-1-7-19

Научная статья

Методика определения параметров математической модели динамики психофизиологического состояния оператора металлургического оборудования

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Аннотация

Введение. Математическое моделирование эффективно при анализе промышленной безопасности на металлургических предприятиях, в частности для отслеживания проблем системы «человек — машина». Чтобы ввести в рассмотрение фактор времени, задействуют рекуррентные соотношения (в дискретной модели) и дифференциальные (в непрерывной). Однако необходимо также решить проблему привязки параметров модели к реальным условиям производственной среды и к человеческому фактору. Цель данного исследования — создание метода определения параметров имитационных математических моделей динамики психофизиологических показателей оператора, влияющих на его работу.

Материалы и методы. Психофизиологическое состояние (ПФС) оператора оценивали по работоспособности, утомляемости и ошибаемости. Данные собрали по тесту цифровой корректурной пробы (ЦКП). На основании полученных результатов вычислили экспериментальные значения показателей ПФС оператора, которые привели к нормированной шкале [0, 1]. Эти показатели для конкретного респондента, математическую модель и разработанный алгоритм задействовали при определении числовых значений параметров модели. Для интерпретации показателей работоспособности, утомляемости и ошибаемости ввели шкалы с пятью градациями.

Результаты исследования. Использование модифицированного авторами варианта математической модели показало значительное улучшение ее прогностических свойств. Из 10 участников наилучший результат оказался у респондента № 7, худший — у респондента № 8. В течение 1-го часа работы (с 9.00 до 10.00) их работоспособность выросла примерно одинаково, с 0,5–0,55 почти до 0,6. Затем показатель респондента № 7 активно увеличивался и до конца рабочего дня оставался существенно выше уровня «хороший». Показатель респондента № 8 падал и с 14.00 до 15.00 оказался ниже среднего. Разницу во многом определили хронотипы операторов. Их хронофизиологические особенности сказались также на утомляемости и ошибаемости. Для разных участников экспериментов варьировалось качество модели. В одном случае оно оказалось отличным (средняя относительная ошибка ≤5 %), в трех случаях — хорошим (≤10 %), в четырех — удовлетворительным (≤15 %).

Обсуждение и заключение. Предлагаемый подход дает возможность получить для каждого индивидуума динамические профили его психофизиологических характеристик, оценить их взаимосвязи и выполнить прогноз на основе модифицированной математической модели. Однако для расширения функциональных возможностей моделей в реальных условиях работы оператора металлургического оборудования требуется увеличить объем выборки, уменьшить шаг дискретного времени и выполнить исследования для различных условий работы с учетом технологических, климатических, экологических, психологических и прочих факторов.

Ключевые слова: безопасность на металлургических предприятиях, система «человек — машина», психофизиологическое состояние оператора, хронотип оператора, работоспособность оператора

Благодарности. Авторы выражают признательность сотрудникам Донбасского государственного технического университета за проявленный интерес к обсуждаемой теме, добросовестное прохождение анкетирования и интервьюирования, благодарят редакционную коллегию журнала и рецензента за профессиональный анализ и рекомендации для корректировки статьи.

Финансирование. Исследования выполнены за счет средств федерального бюджета (код темы: FRRU-2023-0005 в ЕГИСУ НИОКРТР).

Для цитирования. Вишневский Д.А., Подлипенская Л.Е., Денисова Н.А., Бондарь Н.А. Методика определения параметров математической модели динамики психофизиологического состояния оператора металлургического оборудования. *Безопасность техногенных и природных систем.* 2024;8(1):7–19. https://doi.org/10.23947/2541-9129-2024-8-1-7-19

Introduction. According to the Federal Service for Environmental, Technological and Nuclear Supervision of the Russian Federation, by the beginning of 2022, 1,280 hazardous production facilities were registered at metallurgical and coke-chemical plants, 19 of which belonged to the first hazard class, 325 belonged to the second class, and 922 belonged to the third class[1]. According to the "Industrial Pages" journal[2], in 2022, fires and explosions were the most frequent incidents at Russian metallurgical enterprises. These incidents were caused by technical reasons and by violations of industrial safety rules. For example, in January 2022, three employees of the Novolipetsk Metallurgical Plant conducted a routine check of the interdepartment gas main without mandatory gas protection equipment. The workers died as a result of poisoning by toxic fumes and gas.

In [1], technical, sanitary-hygienic, organizational and psychophysiological groups of accident and injury factors at metallurgical and coke-chemical plants are identified. The latter two groups are closely related to the person involved in the production process. From an industrial safety perspective, operators of high-technology units at metallurgical plants are assigned special responsibility. In engineering psychology, they are commonly referred to as "human operators". In the context of this work, the term "operator" will be used to refer to these individuals. On occasion, they prevent the potential for a danger turning into an incident or accident at work.

GOST 12.0.003–2015[3] identifies dangerous and hazardous production factors of psychophysiological effects on humans in an independent block. The operator experiences neuropsychiatric overloads associated with the intensity of the work process[3]. These include:

– mental overstrain;
– overstrain of analyzers;
– monotony of work;
– lack of confidence in actions due to the lack of education and experience.

Emotional overloads lead to overwork, poor health, stress, etc. [1].

The reliability of a person as an element of a complex technical system depends on internal and external conditions that change over time. Another variable is the person themselves. Work is performed by people with different personal qualities, health, experience, etc.

In [2], data on accidents (AC) in the forging and pressing production (FPP) for 1985, 1987 and 1989 were analyzed. Some patterns in the distribution of hours from start of work to incident were noted. These trends can be attributed to the human element, more specifically, the daily work schedule (Fig. 1).

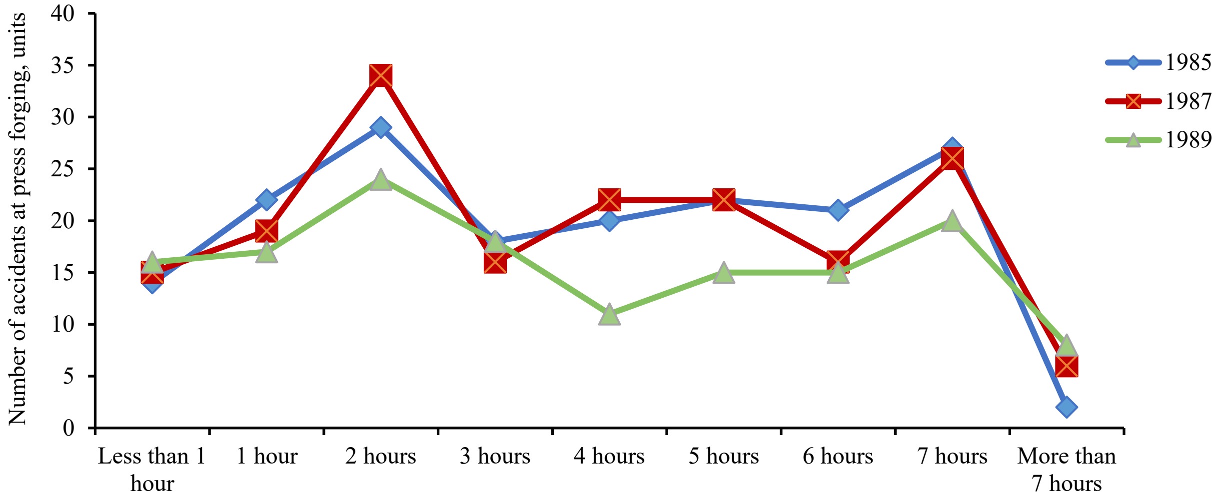

Fig. 1. Distribution of AC in forging and pressing production according to the number of hours since start of work to AC [2]

[1] Annual report on the activities of the Federal Service for Environmental, Technological and Nuclear Supervision in 2021. Moscow: 2022. P. 407. URL:https://www.gosnadzor.ru/public/annual_reports/Годовой%20отчет%20за%202021%20г.pdf (accessed: 22.11.2023). (In Russ.).

[2] Opasnaya tendentsiya: avarii i ChS na metallurgicheskikh proizvodstvakh v 2022–2023 godakh. *Promyshlennye stranitsy.* URL: https://indpages.ru/safe/avareeee-na-myetallurgeechyeskeeh-proeezvodstvah/?ysclid=lnshtjh0z2208396380 (accessed: 22.11.2023). (In Russ.).

[3] GOST 12.0.03–2015. Occupational safety standards system. Dangerous and harmful working factors. Classification. *Elektronnyi fond pravovykh i normativno-tekhnicheskikh dokumentov.* URL: https://docs.cntd.ru/document/1200136071 (accessed: 21.11.2023). (In Russ.).

The graphs in Figure 1 show a fairly pronounced synchronicity of peaks, as well a minimal number of accidents during the last hours of operation. This suggests that the operator's working time is a significant factor in the occurrence of industrial accidents.

In [3], the need to take into account the operator's chronotype when determining professionally important qualities was established experimentally.

For metallurgical industry enterprises, mathematical modeling methods are effective in analyzing situations that:

– are related to industrial safety;

– may occur in a complex technical man — machine system;

– are formed and develop in various conditions of the internal and external environment.

Mathematical models describing the operator's psychophysiological state have been developed in various mathematical formulations. Tools for measuring primary indicators have also been used. V.G. Abashin has found out how the use of biometric technologies is associated with the psychophysiological state of the operator of automatic workplaces, its efficiency, a decrease in the number of defects and accidents of the technological process caused by human error [4]. The operator's performance is modeled by keyboard handwriting. For this purpose, fuzzy sets are used as the basis of adaptive models, both biometric and multibiometric [5].

The authors [6] use biometric features in a mathematical model (voice, keyboard handwriting and the manner in which they work with a computer mouse). This allows them to judge the operator's psychophysiological state: norm, fatigue, intoxication, excitement, relaxation (falling asleep). The models are based on the Bayes strategy, as well as the neural network approach, and allow you to assess the level of the operator's psychophysiological state and predict their ability to perform their current tasks.

In [7], simulation mathematical models of the interrelation of factors of the operator's psychophysiological state were developed. The authors used recurrent relations in a discrete model and systems of differential equations in a continuous model, which allowed them to introduce the time factor into consideration. In this case, the parameters of the model were determined by:

– the results of testing a particular employee;

– their ability to a certain type of activity;

– the results of experimental studies on the workplace and the operator's functional actions.

This part of the simulation is less formalized than others and has the greatest impact on the possibility of using the model to correct the real actions of the operator. The problem has not been solved at the moment. Thus, the issues of determining the parameters of mathematical models that can correctly describe the interrelationships of various factors of the operator's psychophysiological state remain relevant. The aim of this article is to develop a methodology for determining the parameters of such models. Scientific research in this area will help to determine indicators of the condition of the metallurgical equipment operator, which affect their functional performance and can cause serious errors with negative consequences.

Materials and Methods. To assess the operator's psychophysiological state, the following indicators were selected:

– efficiency (the ability to purposefully perform work of a specific quantity and quality for a specified time);

– fatigue (decreased performance with impaired coordination of movements, decreased concentration and accuracy of decisions [8]);

– error rate (estimated by the number of erroneous actions).

Fatigue can be determined by subjective and objective measures [9]. Subjective levels of fatigue were determined using the fatigue assessment scale[4] (FAS) [10]. It was developed by a group of Dutch scientists led by H.J. Michielsen. This scale consists of 10 questions related to the respondent's overall well-being on a daily basis.

Digital correction test (DCT)[5] was used as a source of objective parameters in this work. According to its results, the experimental values of the indicators of the operator's psychophysiological state were calculated. Numerical values for model parameters were determined for a specific respondent by a combination of the named indicators and the model used.

The task of determining the parameters of a mathematical model that described the interrelationship between various psychophysiological factors of an operator was divided into two stages.

The first stage was the experiment. Participants were tested and data was collected on the working conditions of the operator and their personal qualities, which may affect the studied parameters of work activity.

The second stage was calculation. The database collected at the first stage was used. Taking into account the chosen mathematical model, its parameters were estimated for each individual employee. With a sufficient amount of statistical

[4] Fatigue Assessment Scale (FAS). URL: https://wasog.org/dynamic/media/78/documents/Questionairres/fas_rus_anon.html (accessed: 21.11.2023). (In Russ.).

[5] Tsifrovaya korrekturnaya proba.URL: https://metodorf.ru/tests/korrekt/korrektchis.php (accessed: 18.08.2023). (In Russ.).

data in a wide range of variable parameters, averaged models were built that could be used to predict changes in the operator's psychophysiological performance in various conditions and taking into account the time factor.

In this study, a program presented by the online resource "Interactive Portal — book of self-development and success techniques"[6] was used for electronic testing.

When performing the DCT, the participant looked through the numerical array generated by the program line by line and then crossed out the numbers specified in the task. They were given three minutes to complete the test. The program then generated the results described below.

1. The main primary indicators:

– test execution time t;

– total number of digits viewed up to the last selected digit N;

– total number of viewed up lines C;

– total number of digits to be crossed out n;

– total number of crossed-out digits M;

– number of correct answers S;

– number of missed digits P;

– number of wrongly selected digits O.

2. Calculated indicators that characterize:

– speed (productivity) of attention A;

– accuracy of work T (in three variants);

– mental productivity E;

– mental performance A_u;

– concentration of attention K;

– stability of concentration of attention K_u;

– volume of visual information V;

– speed of information processing Q.

To solve this problem, the indicators were selected, on the basis of which efficiency X, fatigue Y and error rate Z of the operator were evaluated according to formulas (1–4).

1. Mental efficiency A_u (according to the digital correction test[7], the unit of measurement is signs per second):

$$A_u = (N/t) \times ((M - (O + P))/n). \quad (1)$$

To bring the indicator to a normalized scale [0, 1] in dimensionless units, the authors proposed formula (2). The result will be the *i-th* value of the efficiency indicator X (corresponds to discrete conditional time i):

$$x_i = A_{ui} / \max\{A_u\}, \quad (2)$$

where $max\{A_u\}$ — maximum possible value of mental efficiency for this type of test, regardless of the employee being tested.

Let us consider a standard DCT test with 1600 digits. We suppose the respondent completed the test correctly in 180 seconds. In this case, value $max\{A_u\}$ would be 8.889 characters per second. If the respondent completed the test in less than 180 seconds, value X in the calculation using formula (2) would be greater than 1. Then value 1 was taken for X.

2. Fatigue Y was estimated by indicator K (concentration of attention):

$$Y = (1 - K/100), \quad (3)$$

where $K = (M–0)\ n\ 100$ — coefficient characterizing concentration of attention, %.

This indicator Y took dimensionless values in the range [0, 1].

3. Error rate Z was proposed to be estimated by the formula:

$$Z = (O + P)/(M + P). \quad (4)$$

This indicator also took values in the range [0, 1].

In the future, we will characterize X, Y and Z as unified quantitative indicators of the operator's psychophysiological state associated with their main production activity. To interpret indicators X, Y and Z, a scale has been developed, presented in Table 1.

[6] Interaktivnyi portal — kniga metodik samorazvitiya i dostizheniya uspekha. URL: https://metodorf.ru/ (accessed: 18.10.2023). (In Russ.).
[7] Tsifrovaya korrekturnaya proba. URL: https://metodorf.ru/tests/korrekt/korrektchis.php (accessed: 18.10.2023). (In Russ.).

Table 1

Interpretation of the values of indicators in a qualitative form

Indicator	Ranges of indicator values / qualitative characteristics				
Efficiency X	[0–0.20] low	[0.20–0.40] below average	[0.40–0.60] average	[0.60–0.80] good	[0.80–1.00] high
Fatigue Y	[0–0.20] low	[0.20–0.40] below average	[0.40–0.60] average	[0.60–0.80] above average	[0.80–1.00] high
Error rate Z	[0–0.01] insignificant	[0.01–0.05] noticeable	[0.05–0.10] significant	[0.10–0.20] significant	[0.20–1.00] high

Indicators X, Y and Z are dimensionless, unified with values in the range [0, 1].

At the second stage, there were two ways to select the parameters of a mathematical model.

1. Using the Excel Solution Search module, a system solution scenario was created for some initial parameters. It was based on a system of recurrent equations of a mathematical model in a discrete form. Then, the Solution Search output the optimal values of model parameters for the objective function, equal to the sum of the squares of the deviations of the calculated values of indicators X, Y and Z from the experimental ones.

2. In the Anylogic program[8], that allows you to automatically select the parameters of the considered mathematical models in the discrete form of recurrent relations and in the form of a system of differential equations. It is advisable to use Anylogic after analyzing the results of a preliminary assessment of the model parameters using the Excel Solution Search module.

To test the proposed methodology, ten people were selected — students and employees of the Donbass State Technical University. They worked as operators on training simulators with automatic and semi-automatic control. At the beginning and at the end of the working day, the subjective level of fatigue was assessed on the FAS scale. At the beginning of each hour, from 9.00 to 16.00, DCT tests were performed. The data were processed according to formulas (1–4) for each respondent. The test results and their unification (X, Y and Z) were used at the second stage to determine the parameters of the mathematical model.

In this paper, we applied a model in recurrent form [7], which was described by a system of equations:

$$\begin{cases} x_{i+1} = x_i + a_1 \dfrac{x_i}{d_1 x_i + c_1} \cdot \left(1 - \dfrac{x_i}{k_1}\right) - b_1 x_i y_i - h x_i z_i, \\ y_{i+1} = y_i + a_2 \dfrac{y_i}{d_2 y_i + c_2} \cdot \left(1 - \dfrac{y_i}{k_2}\right) + b_2 x_i y_i, \\ z_{i+1} = z_i + a_3 \dfrac{z_i}{d_3 z_i + c_3} \cdot \left(1 - \dfrac{z_i}{k_3}\right) + b_3 y_i z_i. \end{cases} \tag{5}$$

The solution of system (5) is three conjugate time series of length m indicators $X = \{x_i, i=0, 1, 2, ..., m\}$, $Y = \{y_i, i=0, 1, 2, ..., m\}$, $Z = \{z_i, i=0, 1, 2, ..., m\}$. Index i — variable that characterizes the discrete time in the system. Parameters a_j, b_j, k_j, h, d_j, c_j (j = 1, 2, 3) are determined as a result of solving the optimization problem based on the initial test data.

The mathematical model of the optimization problem is described by system of constraints (6) and objective function (7).

$$\begin{cases} \delta_{xi}(a_j, b_j, k_j, h, d_j, c_j) = (x_i^{\phi} - x_i^{p})^2 \le \Delta, \\ \delta_{yi}(a_j, b_j, k_j, h, d_j, c_j) = (y_i^{\phi} - y_i^{p})^2 \le \Delta, \\ \delta_{zi}(a_j, b_j, k_j, h, d_j, c_j) = (z_i^{\phi} - z_i^{p})^2 \le \Delta, \\ a_j, b_j, k_j, h, d_j, c_j \ge 0, \\ x_i^p \ge 0, y_i^p \ge 0, z_i^p \ge 0, \\ x_i^p \le 1, y_i^p \le 1, z_i^p \le 1, \\ i = 1, ..., m, \\ j = 1, 2, 3. \end{cases} \tag{6}$$

[8] AnyLogic: imitatsionnoe modelirovanie dlya biznesa. URL: https://www.anylogic.ru/ (accessed: 12.11.2023). (In Russ.).

$$\Psi(a_j, b_j, k_j, h, d_j, c_j) = \sum_{i=1}^{m} \delta_{xi} + \sum_{i=1}^{m} \delta_{yi} + \sum_{i=1}^{m} \delta_{zi} \rightarrow min\,. \qquad (7)$$

Here, index *ф* marks the actual values of indicators *X, Y* and *Z* found as a result of processing operator testing data, *p* — calculated values of *X, Y* and *Z* determined from the solution of system (5) and depending on variables a_j, b_j, k_j, h, d_j, c_j (j = 1, 2, 3) sought in this optimization problem. For variable variables a_j, b_j, k_j, h, d_j, c_j restrictions are set by the maximum allowable value of Δ squared deviations (δ_{xi}, δ_{yi}, δ_{zi}) calculated values of *X, Y* and *Z* from the actual values for all m values of the considered time series. Objective function $\Psi(a_j, b_j, k_j, h, d_j, c_j)$ is equal to the sum of the squared deviations (δ_{xi}, δ_{yi}, δ_{zi}).

The generalized reduced gradient (GRG) method was used to solve the optimization problem.

Results. The first stage was experimental. Test results of the participants in the experiment (respondents no. 1–no. 10), converted to unified indicators *X, Y* and *Z*, are shown in box plots (Fig. 2–4). The center of the distribution (median) is a dot, a rectangle indicates the boundaries of variation (quartiles 25%–75%), "whiskers" — the lower and upper limits of the indicator values (min — max). The diagrams were made using the "Statistica" software package.

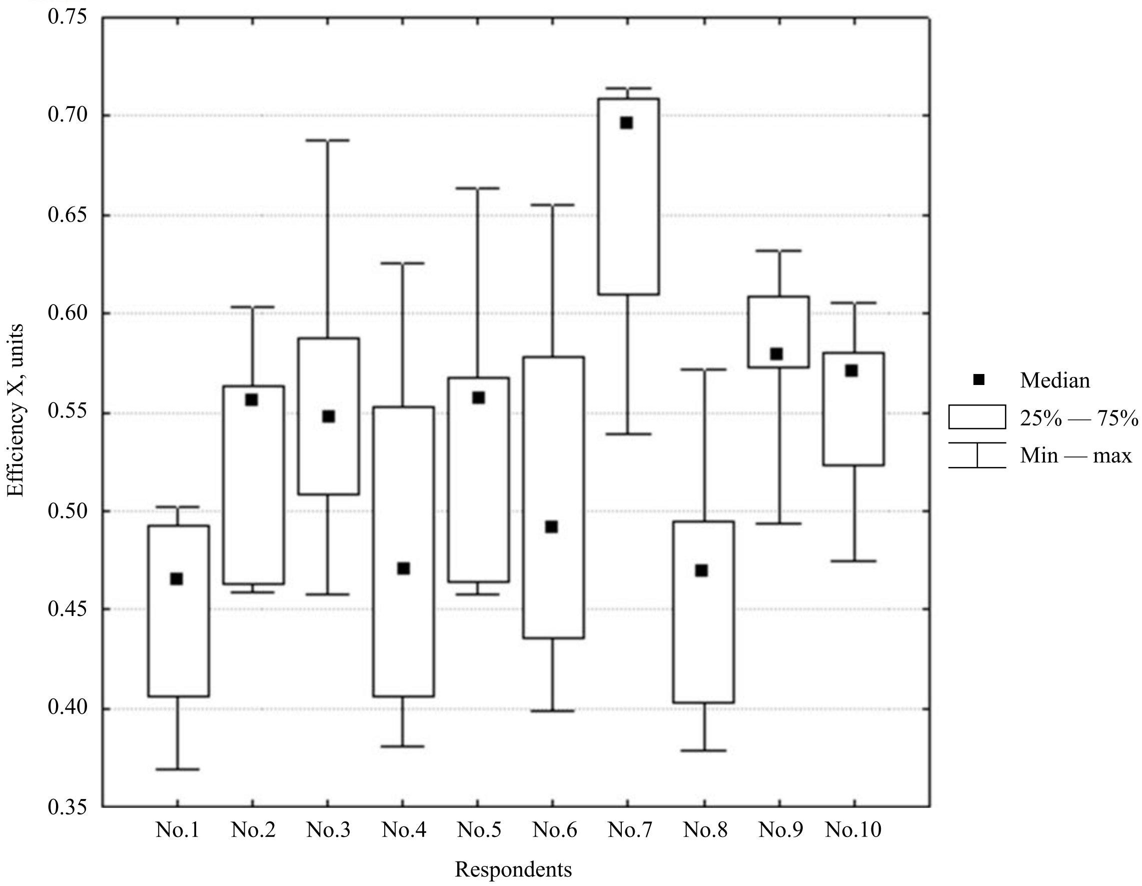

Fig. 2. Indicators of an operator's efficiency

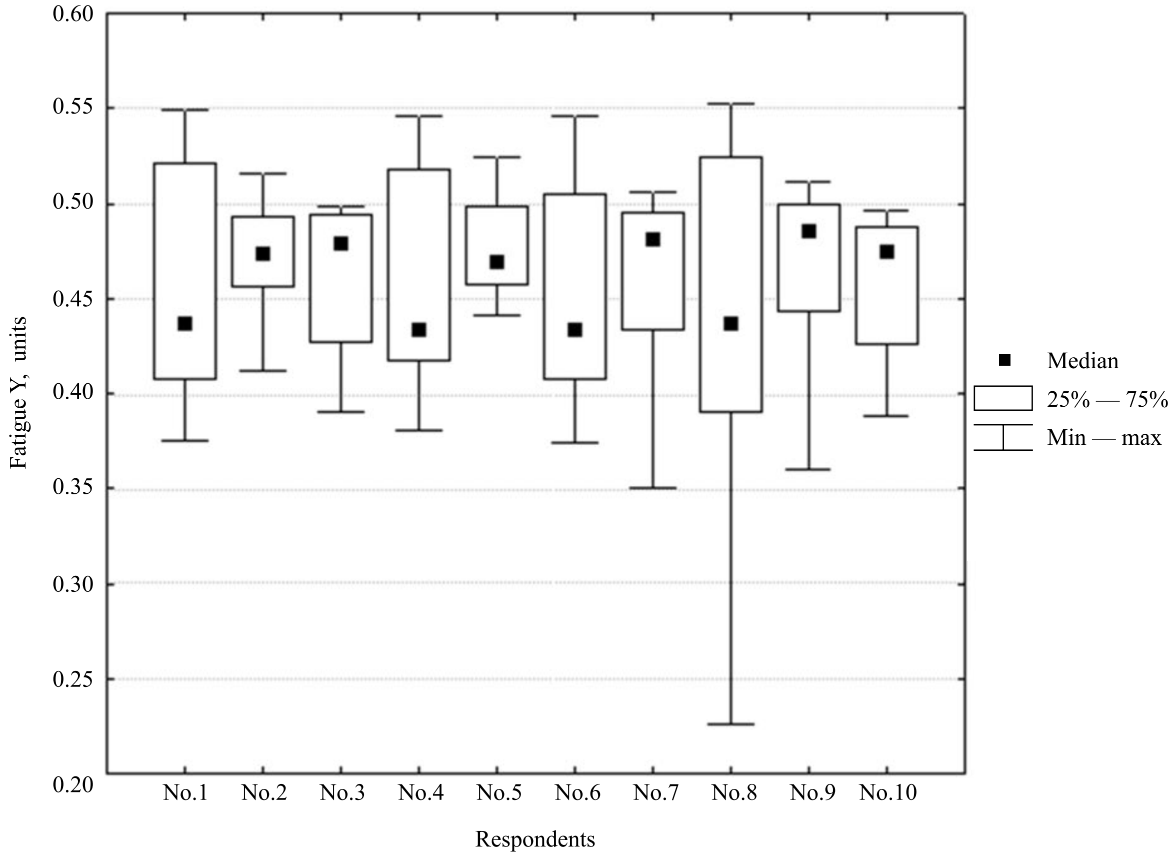

Fig. 3. Indicators of an operator's fatigue

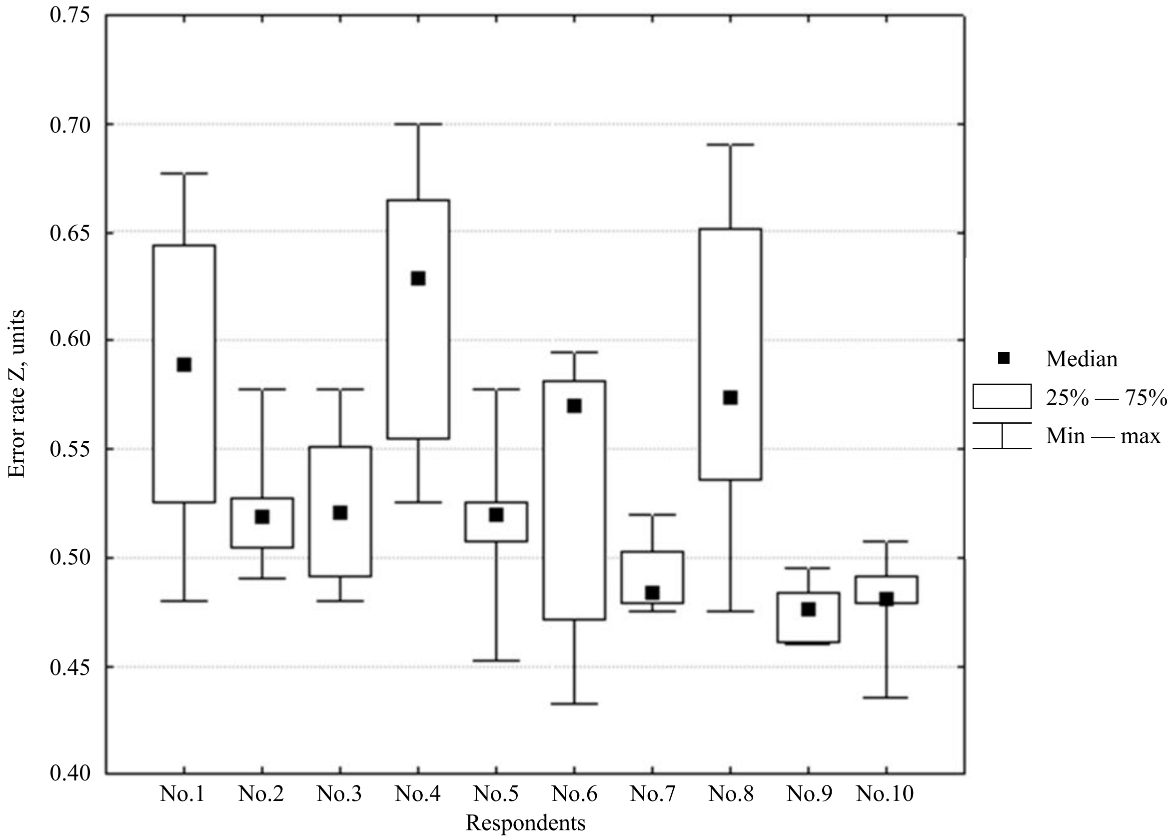

Fig. 4. Indicators of an operator's error rate

The analysis of Figures 2–4 allowed us to identify respondents with the best and the worst estimates of their performance (Table 2). The levels of indicators *X, Y* and *Z*, correlated with the gradations of Table 1, as well as quartiles and intervals of variation of indicators, were taken into account.

Table 2

Ranking of respondents based on test results

Evaluation criteria	Options (respondent's number)	
	the worst	the best
Efficiency *X* (the more, the better)	8, 1, 4, 6	7, 9, 3
Fatigue *Y* (the more, the worse)	8, 1, 4, 6	7, 10
Error rate *Z* (the more, the worse)	4, 8, 1	9, 10, 7
Integrally (taking into account *X*, *Y*, *Z)*	8, 4, 1	7, 10, 9

The graphs in Figure 5 reflect the performance dynamics for respondents no. 7 (dotted line, best result) and no. 8 (solid line, worst result).

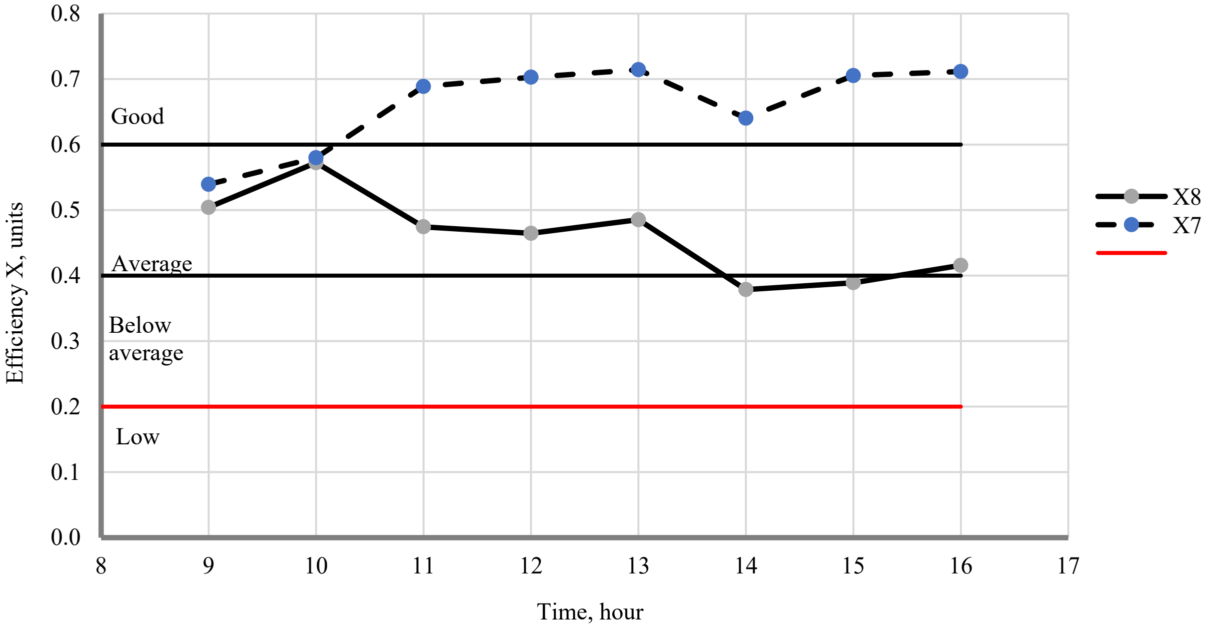

Fig. 5. Dynamics of an operator's efficiency

To explain a rather large difference in the data of respondents no. 7 and 8, we took into account their age, gender, occupation, well-being, etc. The chronotype factor turned out to be the most significant. The classification, adopted in 1970, implies three categories of people with distinctive behavioral characteristics and a genetic difference in biorhythms. These are the so-called "larks", "owls" and "pigeons" [11]. Respondent no. 8 according to the chronotype was "lark", no. 7 was "owl". As a result, the efficiency of no. 8 decreased by the day's end, and for no. 7 it increased (Fig. 5). The chronophysiological features of operators were also manifested in the dynamics of their fatigue and error rates.

The second stage was calculation. The parameters of model (5) calculated for each participant of the experiment were obtained. To this end, we solved the optimization problem (6)–(7). Table 3 provides the ranges of parameter changes.

Table 3

Ranges of parameters of mathematical model (5) for a group of experiment participants

Indicator	Parameter ranges	Indicator	Parameter ranges
a_1	0.0004–0.0300	b_3	0.0001–10.1400
b_1	0–0.9700	k_3	0.0020–0.0700
k_1	0.5900–1.0000	c_1	0.0010–0.2000
h	0–1.8100	c_2	0.0001–0.0010
a_2	0–0.0010	c_3	0.0100–0.3300
b_2	0.0070–0.2600	d_1	≈ 0
k_2	0,4200–1.0000	d_2	≈ 0
a_3	0.0005–0.0600	d_3	0.0400–0.9800

Table 4 presents the results of evaluating the quality of mathematical models of the dynamics of changes in indicators *X, Y* and *Z*, estimated by the standard error of the model and the average relative error for all respondents.

Table 4

Evaluation of the quality of mathematical models

Respondent's no.	1	2	3	4	5	6	7	8	9	10
Average relative error ε, %	14.27	4.54	20.93	12.80	7.28	12.00	9.66	15.03	12.23	9.70
Standard error, units	0.182	0.107	0.253	0.267	0.158	0.247	0.271	0.256	0.192	0.166

For different respondents, the quality indicators of the model varied in a wide range. Excellent quality ($\varepsilon \leq 5\%$) was obtained in one case, good ($\varepsilon \leq 10\%$) — in three cases, satisfactory ($\varepsilon \leq 15\%$) — in four cases. For two cases (no. 3 and no. 8), it was not possible to satisfactorily solve the problem of optimal selection of parameters of the mathematical model. This suggests that not all influencing factors were taken into account, or model (5) did not work in some cases.

According to the results of the analysis of the algorithm for solving the problem, a number of simplifications will improve the convergence of the results. For example, you can:

– reduce the number of system parameters (5) by three units, reducing the numerators and denominators of the second terms of the right parts of the system by c_1, c_2, c_3 respectively;

– remove the first, second and third restrictions from system (6), transferring them to the status of observed restrictions.

As a result, the algorithm of the GRG method will work better.

Figures 6 and 7 show comparative diagrams for evaluating the quality of the constructed mathematical models in two versions:

– 1 — the original model (5);

– 2 — modified model.

As it can be seen from the diagrams, the solution to the problem of selecting the parameters of the mathematical model of the dynamics of the operator's PPS indicators was significantly improved when using model 2 for all cases except no. 8.

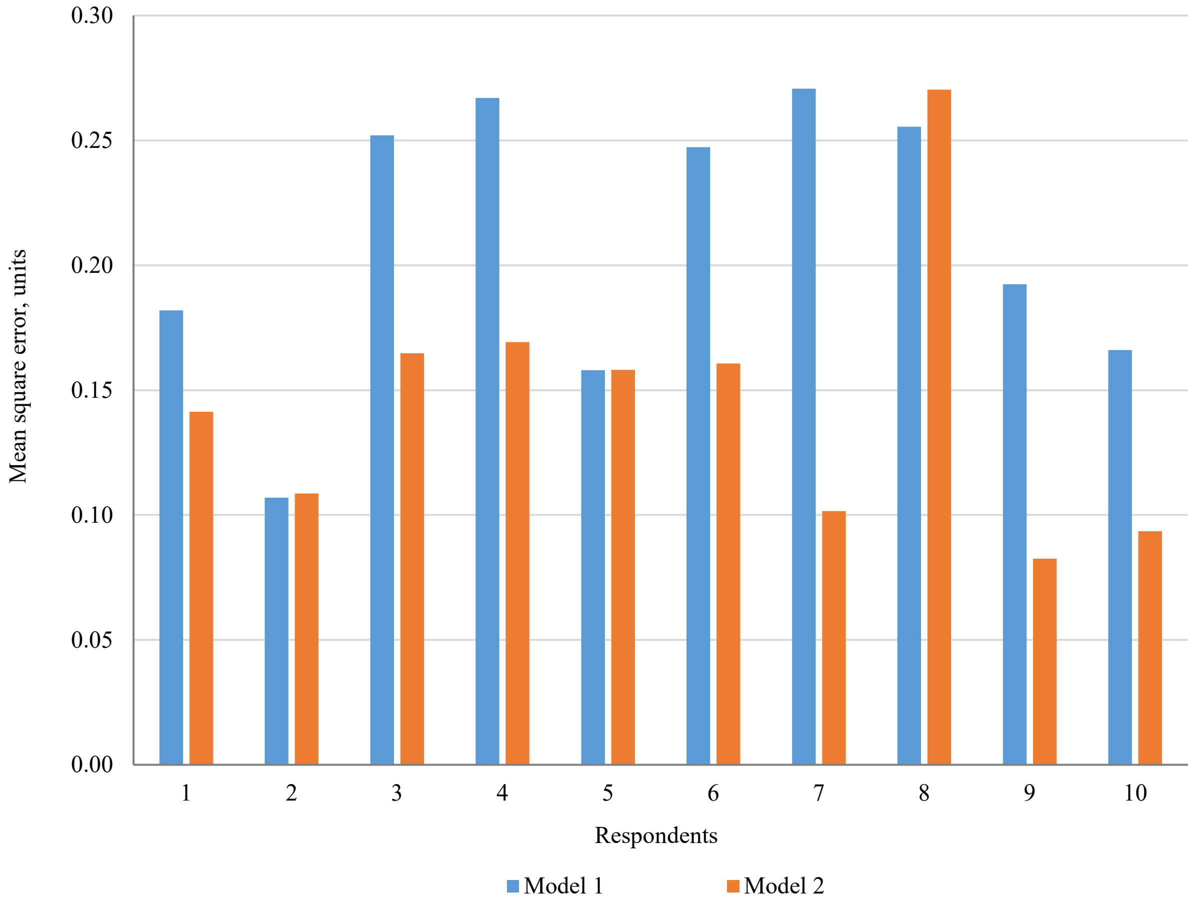

Fig. 6. Comparison of mathematical models based on the mean square error

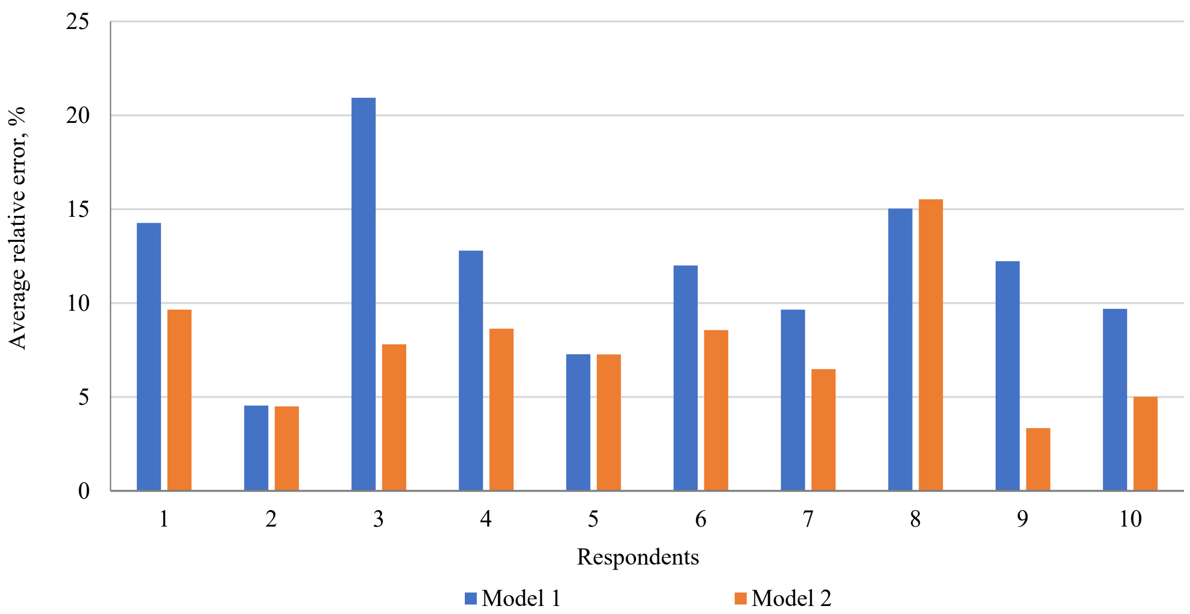

Fig. 7. Comparison of mathematical models by average relative error

Discussion and Conclusion. The proposed approach makes it possible to obtain and predict dynamic profiles of psychophysiological characteristics for each individual, and to create mathematical models of relationships. It is advisable to increase the sample size, reduce the step of discrete time and perform research for various working conditions, including technological, climatic, environmental, psychological and other factors that may affect an employee's efficiency. This should be done to expand the functionality of the models and their application in real-world conditions of operation of the operator of metallurgical equipment.

The discovered effect of the human chronotype on the PPS requires more thorough research. In article [12] devoted to the search for components of the circadian clock in humans, it was shown on large statistical samples that the chronotype depended on many factors (gender, age, work schedule, etc.). All this must be diagnosed and taken into account in mathematical models for evaluating the operators' PPS.

It is also interesting to supplement the model with components of industrial safety culture [13], which can be reduced to a quantitative form and used as correction factors.

In the future, it is planned to improve the model with additional variables. To do this, we will need to record psychophysiological indicators and determine the operator's location in real time.

The methodology presented in this paper can be used as a basis for solving the tasks described below.

– Compilation and analysis of the dynamic profile of an employee when applying for a job as an operator of a machine, unit or device, where such PPS characteristics as efficiency, fatigue and error rate are important. This task is solved for a specific person in certain production conditions, which allows you to choose the operator's optimal mode of work and rest, helps to preserve the health of a specialist and increase the level of industrial safety of the enterprise.

– Formation and maintenance of specialized databases of statistical data, including characteristics of workplaces and employees, and their psychophysiological state. Based on the collected statistical material and real-time monitoring systems of the operator's PPS, predictive models can be built to prevent abnormal and emergency situations at metallurgical enterprises.

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Received 21.12.2023
Revised 15.01.2024
Accepted 19.01.2024

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Claimed contributorship:

The authors made an equivalent contribution to the formulation of the task and the definition of the aim of the study, conducting experiments and calculations, drawing conclusions and correcting the text of the article.

Conflict of interest statement: the authors do not have any conflict of interest.

All authors have read and approved the final manuscript.

Поступила в редакцию 21.12.2023
Поступила после рецензирования 15.01.2024
Принята к публикации 19.01.2024

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Заявленный вклад соавторов:

Авторы внесли равноценный вклад в постановку задачи и определение цели исследования, проведение экспериментов и расчетов, формулирование выводов и корректировку текста статьи.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

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UDC 614.849
https://doi.org/10.23947/2541-9129-2024-8-1-20-29

Original article

EDN: TLVZMZ

Influence of Climatic and Geographical Features of the Subjects of the Russian Federation on the Activities of Fire Departments

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Abstract
Introduction. When determining the number and technical equipment of fire departments, regulatory documents on fire safety do not take into account natural, climatic and geographical features of the subjects of the Russian Federation in an explicit form. At the same time, there is some information in scientific literature about the influence of certain natural and climatic factors on the effectiveness of fire protection actions in extinguishing fires. The aim of this study was to determine the influence of the system of natural, climatic and geographical characteristics of the subjects of the Russian Federation on the rapid response indicators of territorial fire departments. The results obtained are recommended for further use in rationing the number and technical equipment of fire departments.
Materials and Methods. A factor analysis of statistical data for 2020–2022 was carried out. The statistical data were obtained from the Federal State Information System "Federal Database "Fires", from the website of the Federal State Statistics Service of the Russian Federation and from other sources. For the analysis, the authors selected ten indicators characterizing natural, climatic and geographical features of the subjects of the Russian Federation, two indicators of the rapid response of territorial fire departments and four indicators of the fire situation.
Results. Five significant factors were identified, the change of which explained the change in the observed indicators. The first factor characterized the relationship of climatic conditions with fire situation indicators. The second factor connected the indicators of the rapid response of fire departments with the terrain features of the subjects of the Russian Federation. The third factor described the relationship between fire situation indicators and rapid response indicators with population density and forest cover of the territory. Other factors did not significantly contribute to the indicators of fire situation and rapid response.
Discussion and Conclusion. By means of mathematical analysis and factor modeling, the authors investigated the interdependence of natural, climatic and geographical features of the subjects of the Russian Federation, fire situation indicators and indicators of rapid response of fire departments. The most significant factors influencing these indicators were identified. They included the average air temperature, the area covered by forest, the presence of mountain ranges, and population density. These indicators should be taken into account when determining the number and technical equipment of fire departments to increase the efficiency of their functioning.

Keywords: fire protection, factor analysis, subject of the Russian Federation, death, injury, arrival time, climatic and geographical indicators

Acknowledgements. The authors would like to thank the Editorial board and the reviewers for their attentive attitude to the article and for the specified comments that improved the quality of the article.

For citation. Streltsov OV, Bobrinev EV, Udavtsova EYu, Kondashov AA, Ryumina SI. Influence of Climatic and Geographical Features of the Subjects of the Russian Federation on the Activities of Fire Departments. *Safety of Technogenic and Natural Systems.* 2024;8(1):20–29. https://doi.org/10.23947/2541-9129-2024-8-1-20-29

Научная статья

Влияние природно-климатических и географических особенностей субъектов Российской Федерации на деятельность подразделений пожарной охраны

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Аннотация
Введение. Нормативными документами по пожарной безопасности при определении численности и технической оснащенности подразделений пожарной охраны в явном виде не учитываются природно-климатические и географические особенности субъектов Российской Федерации. При этом в научной литературе встречаются сведения о влиянии отдельных природно-климатических факторов на эффективность действий пожарной охраны при тушении пожаров. Целью настоящего исследования явилось определение влияния системы природно-климатических и географических характеристик субъектов Российской Федерации на показатели оперативного реагирования территориальных подразделений пожарной охраны. Полученные результаты рекомендованы для дальнейшего использования при нормировании численности и технической оснащенности подразделений пожарной охраны.
Методы и материалы. Проведен факторный анализ статистических данных за 2020–2022 гг. Статистические данные получены из федеральной государственной информационной системы «Федеральный банк данных «Пожары», с сайта Федеральной службы государственной статистики Российской Федерации и из других источников. Для анализа отобраны 10 показателей, характеризующих природно-климатические и географические особенности субъектов Российской Федерации, 2 показателя оперативного реагирования территориальных подразделений пожарной охраны и 4 показателя обстановки с пожарами.
Результаты исследования. Выделены пять значимых факторов, изменение которых объясняет изменение наблюдаемых показателей. Первый фактор характеризует связь климатических условий с показателями обстановки с пожарами. Второй фактор связывает показатели оперативного реагирования подразделений пожарной охраны с особенностями рельефа субъектов Российской Федерации. Третий фактор описывает взаимосвязь показателей обстановки с пожарами и показателей оперативного реагирования с плотностью населения и лесистостью территории. Остальные факторы в показатели обстановки с пожарами и оперативного реагирования существенного вклада не вносят.
Обсуждение и заключение. С помощью математического анализа и с использованием факторного моделирования авторами исследована взаимозависимость природно-климатических и географических особенностей субъектов Российской Федерации, показателей обстановки с пожарами и показателей оперативного реагирования подразделений пожарной охраны. Определены наиболее значимые факторы, влияющие на эти показатели. Среди них средняя температура воздуха, лесистость территории, наличие горных массивов, плотность населения. Данные показатели следует учитывать при определении численности и технической оснащенности подразделений пожарной охраны для повышения эффективности их функционирования.

Ключевые слова: пожарная охрана, факторный анализ, субъект Российской Федерации, гибель, травматизм, время прибытия, природно-климатические и географические показатели

Благодарности. Авторы выражают благодарность редакции и рецензентам за внимательное отношение к статье и указанные замечания, устранение которых позволило повысить ее качество.

Для цитирования. Стрельцов О.В., Бобринев Е.В., Удавцова Е.Ю, Кондашов А.А., Рюмина С.И. Влияние природно-климатических и географических особенностей субъектов Российской Федерации на деятельность подразделений пожарной охраны. *Безопасность техногенных и природных систем.* 2024;8(1):20–29. https://doi.org/10.23947/2541-9129-2024-8-1-20-29

Introduction. When determining the number and technical equipment of territorial fire departments, a survey of the territory of the subject of the Russian Federation is carried out. This includes an analysis of the state of the existing fire safety system of the subject of the Russian Federation, operational and tactical features of the territory under consideration, the frequency of fires, the risks of death and injury to people on them[1]. Among the factors influencing the state of fire safety in the subjects of the Russian Federation, climatic and geographical characteristics are of great importance. In this regard, in this work, using factor analysis, a study was conducted of the relationship between natural, climatic and geographical characteristics of the subjects of the Russian Federation, indicators of rapid response of territorial fire departments and fire situation indicators. Factor analysis is one of the most widely used methods aimed at isolating a small number of latent factors from a variety of heterogeneous indicators, the variation of which can explain the change in most of the observed indicators [1–5]. This allowed us to build a mathematical model in which the studied factors have a simple and visual structure [6]. Previously, the authors used factor analysis to study the rapid response of fire departments [7], the social consequences of fires [8], the situation with fires in rural settlements [9], and the readiness of fire departments [10].

Materials and Methods. The study included three stages. At the first stage, a matrix of initial indicators was created. For this purpose, the values of 16 indicators were determined in each subject of the Russian Federation, divided into three groups.

The first group included data characterizing the situation with fires (the designation of the indicator is indicated in parentheses):

– the number of fires per 1 thousand people of the population, units (Y_1);

– the average direct material damage from one fire, rubles (Y_2);

– the number of deaths from fires per 100 thousand people, people (Y_3);

– the number of people injured in fires per 100 thousand people, people (Y_4).

– The second group reflected the indicators of rapid response of fire departments:

– the average time it took for the first fire department to arrive, min. (Z_1);

– the average time spent on extinguishing a fire, min. (Z_2).

The third group consisted of indicators characterizing climatic, geographical and demographic characteristics of the subjects of the Russian Federation:

– the population density, people/km^2 (X_1);

– the percentage of water surface area in the territory of the region, % (X_2);

– the length of the sea coastline compared to the total length of the border of the subject, % (X_3);

– the share of forested areas in the territory of the subject, % (X_4);

– the average annual precipitation, mm per year (X_5);

– the average temperature in July, °C (X_6);

– the average temperature in January, °C (X_7);

– the seismic hazard (presence of settlements with the specified seismic intensity for the degree of seismic hazard), °C (X_8);

– the share of the territory occupied by mountains from the total area of the territory of the subject, % (X_9);

– the number of sunny days per year, (X_{10}).

Fire situation indicators and operational response indicators of fire departments were obtained from an electronic database of fires, which was maintained using an automated analytical support and management system by the control and supervisory authorities of the Ministry of Emergency Situations of Russia[2].

Information on population density and forest area in the subjects of the Russian Federation was taken from the data of the Federal State Statistics Service of the Russian Federation[3]. Climate characteristics of the subjects of the Russian Federation were obtained on the reference and information portal "Weather and Climate"[4]. When determining the seismic hazard in the subjects of the Russian Federation, the data from SP 14.13330.2014 were used[5].

The selected statistical indicators were characterized by a wide range, which was due to different sizes of the subjects of the Russian Federation (territory area and population), as well as differences in their natural, climatic and geographical conditions. In this regard, in order to make statistical data more uniform, a number of indicators have been normalized. This made it possible to transform many natural indicators into synthetic indicators. The normalization of

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[1] *Ob utverzhdenii metodik rascheta chislennosti i tekhnicheskoi osnashchennosti podrazdelenii pozharnoi okhrany.* Order of the Ministry of Emergency Situations of Russia from 15.10.2021 No. 700. URL: https://base.garant.ru/403136953/ (accessed: 18.12.2023) (In Russ.).

[2] *Ob utverzhdenii Reglamenta raboty v informatsionnoi sisteme "Avtomatizirovannaya analiticheskaya sistema podderzhki i upravleniya kontrol'no-nadzornymi organami MChS Rossii".* Order of the Ministry of Emergency Situations of Russia No. 954 from 04.10.2022. URL: https://fireman.club/normative-documents/prikaz-mchs-rossii-954-ot-04-10-2022-ob-utverzhdenii-reglamenta-raboty-v-informaczionnoj-sisteme/ (accessed: 11.12.2023) (In Russ.).

[3] *Regiony Rossii. Sotsial'no-ekonomicheskie pokazateli 2022.* Federal State Statistics Service of the Russian Federation. URL: https://rosstat.gov.ru/folder/210/document/13204 (accessed: 08.12.2023) (In Russ.).

[4] Spravochno-informatsionnyi portal "Pogoda i klimat".URL: http://www.pogodaiklimat.ru/ (accessed: 08.12.2023) (In Russ.).

[5] *Seismic building design code.* SP 14.13330.2018 from 25.11.2023. URL: https://docs.cntd.ru/document/550565571 (accessed: 08.12.2023) (In Russ.).

indicators was carried out for the area of the territory of the subjects (population density, the proportion of forests and water surface from the area of the territory of the subject) and for the population (number of fires, the number of deaths and injuries in fires).

Further modeling was carried out using the obtained matrix of synthetic indicators. Significant factors were identified using three of the most common methods: centroid, principal component, and maximum likelihood. All three methods gave similar results, which were consistent within statistical errors. Subsequently, the principal component method was used to perform factor analysis.

At the second stage, significant factors were obtained using the principal component method. To facilitate their interpretation, the rotation of the obtained factors was performed using the following methods:

– varimax (this method, by reducing the number of variables for each factor, allowed for a better separation of factors);

– quartimax (this method, by reducing the number of factors related to each variable, made it possible to identify the general factor and simplify interpretation);

– biquartimax;

– equimax.

Before performing the rotation, factor loads were normalized using the Kaiser method. This made it possible to exclude the influence of variables with great similarity on the result. In subsequent studies, the varimax rotation method was used, since the analysis of the results showed that factor loads did not significantly depend on the rotation method.

As a result of the factor analysis, five significant factors were obtained. The share of the total variance explained by these factors was distributed as follows: the first factor — 22.1%, the second factor — 15.4%, the third factor — 12.1%, the fourth factor — 9.7%, the fifth factor — 7.7%. These five significant factors explained 67.0% of the total variance.

Table 1 shows the values of factor loads for each of the five factors (significant indicators are highlighted in bold).

Table 1

Matrix of factor loads

Variable (indicator)	Factor				
	1	2	3	4	5
Y_1	0.019	-0.179	**0.681**	0.212	-0.308
Y_2	**0.692**	0.028	-0.241	0.027	0.123
Y_3	**0.692**	0.164	**0.484**	-0.123	0.021
Y_4	**0.821**	-0.095	0.229	0.046	-0.121
Z_1	-0.362	**0.587**	**0.417**	0.091	0.306
Z_2	0.009	0.218	**0.509**	-0.343	0.265
X_1	-0.093	0.069	**-0.587**	-0.086	-0.063
X_2	0.018	0.234	0.056	0.070	**-0.836**
X_3	0.000	-0.373	-0.155	-0.422	**-0.532**
X_4	0.236	-0.305	**0.536**	-0.357	0.002
X_5	-0.334	0.026	0.008	**-0.758**	0.016
X_6	**-0.636**	0.032	-0.062	**0.630**	0.200
X_7	**-0.646**	0.357	-0.343	-0.144	0.040
X_8	-0.073	**-0.833**	0.097	0.174	0.133
X_9	0.058	**-0.841**	0.180	-0.019	0.051
X_{10}	**-0.437**	-0.322	0.191	**0.630**	-0.081

At the third stage, a creative task was solved that went beyond the formal method. A meaningful interpretation of the obtained factors using subject terms was carried out.

Results. It was found that the following variables made the greatest contribution to the first significant factor:

– the average direct material damage from one fire, rub. (Y_2);

– the number of deaths from fires per 100 thousand people, people (Y_3);

– the number of injured people per 100 thousand people, people (Y_4);

– the average temperature in July, °C (X_6);

– the average temperature in January, °C (X_7);

– the number of sunny days per year (X_{10}).

Among fire situation indicators, the indicator "the number of injured people in fires per 100 thousand people of the population" made the greatest contribution to the first factor. This factor characterized the relationship of climatic conditions with indicators of the situation with fires. In those regions of the Russian Federation where the climatic conditions were more severe (low temperatures, few sunny days), there were more severe consequences of fires (more dead and injured people, higher property damage).

This relationship is demonstrated in Figures 1 and 2, which show the dependence of the number of victims (dead and injured people) in fires per 100,000 people on the average temperature in January. It can be seen that with a decrease in the average temperature, the number of victims of fires increased.

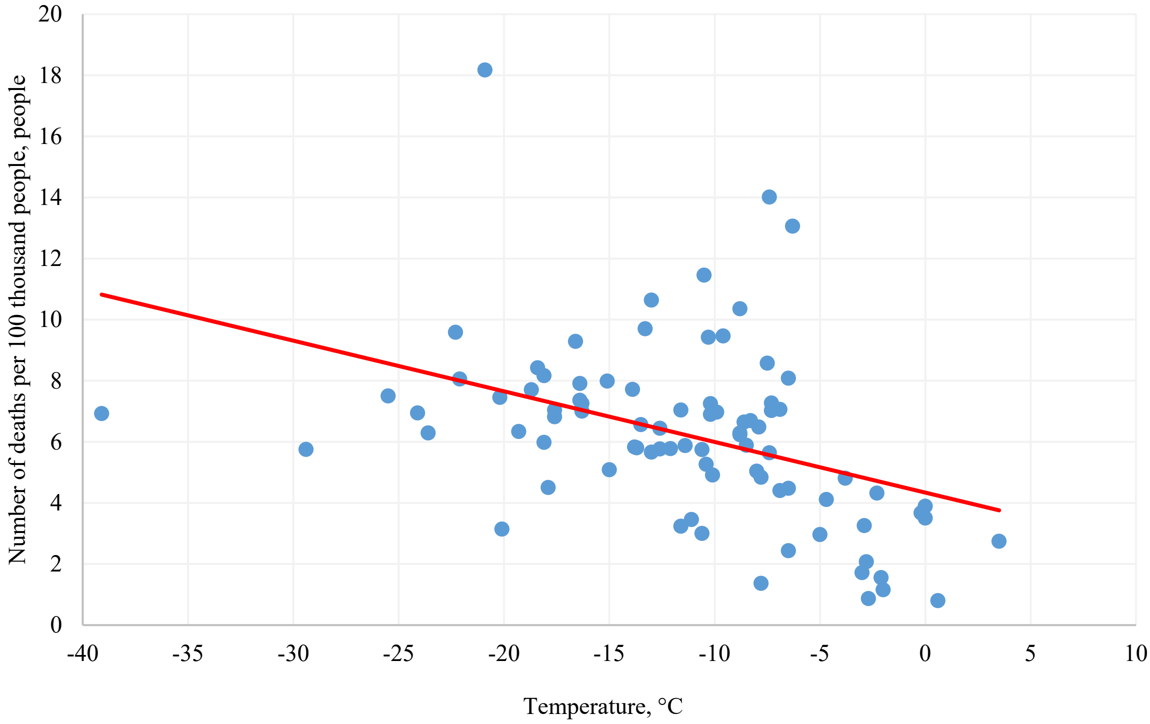

Fig. 1. Dependence of the number of deaths in fires per 100,000 people on the average temperature in January in the subjects of the Russian Federation. The straight line is the result of approximation by linear function $y = -0.166x + 4.338$

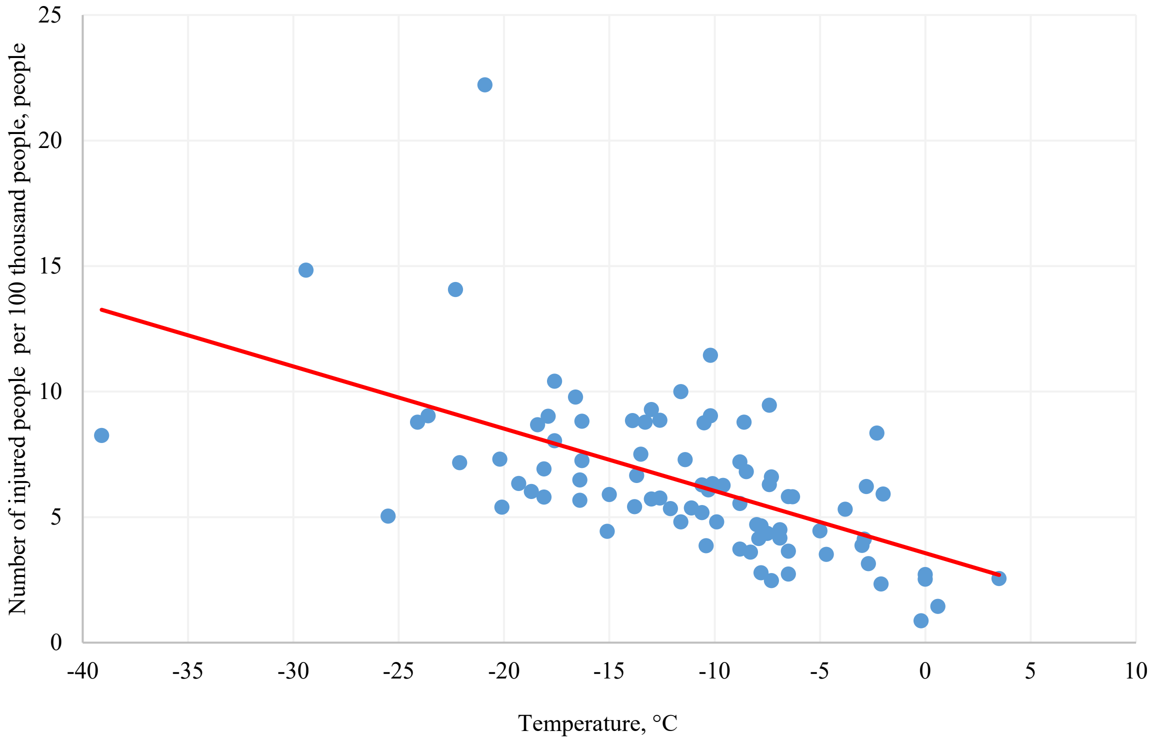

Fig. 2. Dependence of the number of injured people in fires per 100 thousand people on the average January temperature in the regions of the Russian Federation. The straight line is the result of approximation by linear function $y = -0.248x + 3.565$

For the second significant factor, the following variables were the most essential:

– average time it takes for the first fire department to arrive, min. (Z_1);

– seismic hazard (the presence of settlements with the specified seismic intensity for the degree of seismic hazard C) (X_8);

– percentage of the territory occupied by mountains from the total area of the territory of the subject, % (X_9).

The second factor characterized the relationship of the indicators of rapid response of fire departments with the geographical features of the subjects of the Russian Federation. There was an important dependence. The larger the territory of the subject was occupied by mountains, the shorter the average time for which the first fire department arrived at the place of the call was.

Figure 3 provides the distribution of factor loads for three groups of indicators in the plane of factors 1 and 2.

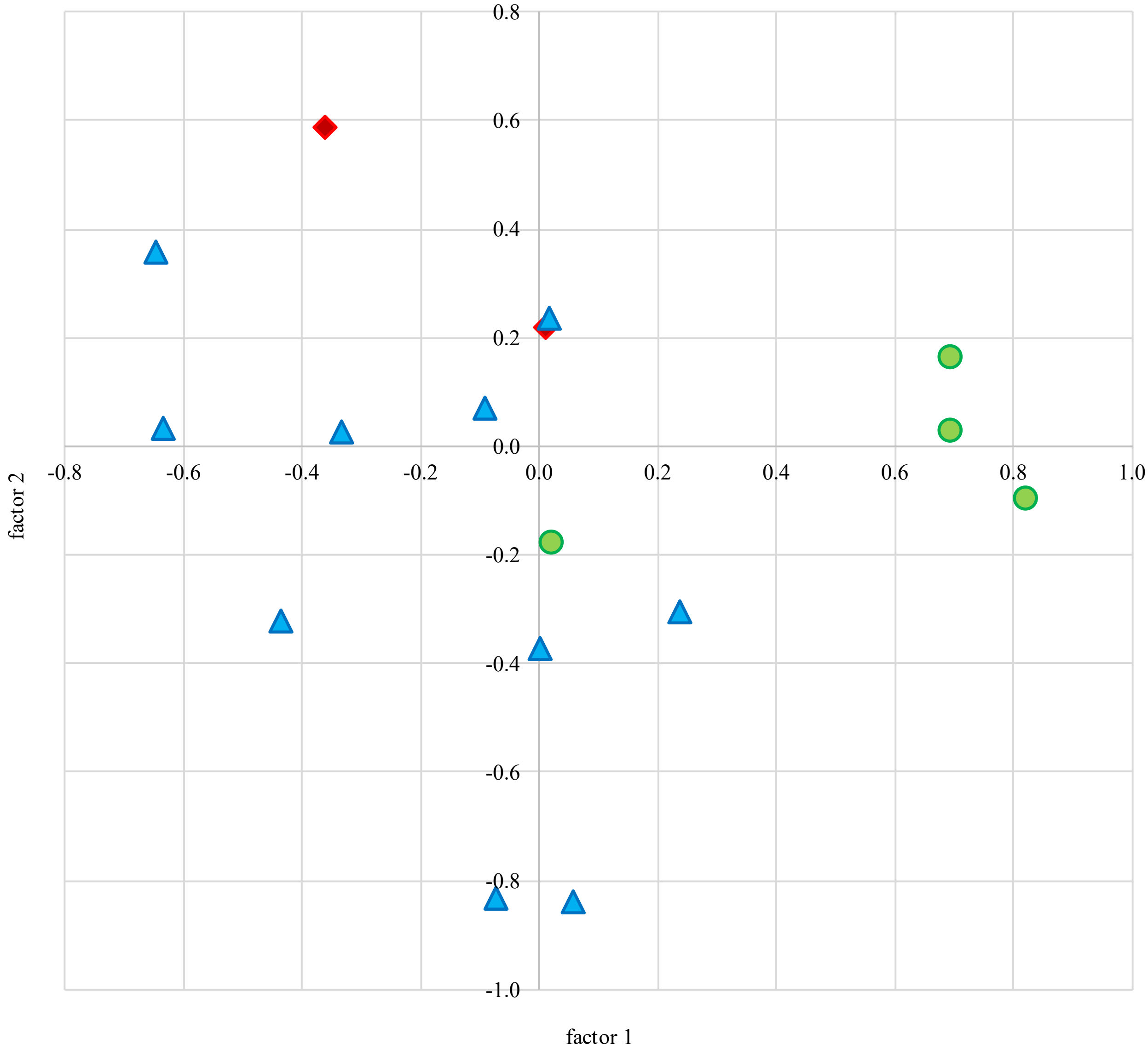

Fig. 3. Values of factor loads in the plane of factors 1 and 2. The indicators of the first group are indicated in green, the indicators of the second group are indicated in red, and the indicators of the third group are indicated in blue

The following variables made the greatest contribution to the third significant factor:

– the number of fires per 1,000 people, units (Y_1);

– the number of deaths in fires per 100,000 people, people (Y_3);

– the average time it takes the first fire department to arrive, min. (Z_1);

– the average time spent on extinguishing a fire, min. (Z_2);

– population density, people/km^2 (X_1);

– share of forests from the area of the territory of the subject, % (X_4).

The third factor describes the relationship between fire situation indicators and rapid response indicators with population density and forest cover of the territory. As previously conducted studies showed, with increasing density, the average area of the service area of one fire department decreased, resulting in a decrease in the arrival time of the first fire department. On the other hand, the lower the density, the larger the area of the territory where the same number of people lived, respectively, more fires occurred in a larger area. It is also interesting to note that with increasing population density, the number of fire victims per 100,000 people decreased.

The fire situation was also affected by the area of forests. With an increase in the share of the territory of the subject of the Russian Federation occupied by forests, the number of fires per 1,000 people increased.

The dependence of the number of fires per 1,000 people on population density was obtained. As it can be seen in Figure 4, the number of fires decreased with increasing population density. This dependence was described by an exponential function.

Figure 5 shows the distribution of factor loads for three groups of indicators in the plane of factors 1 and 3.

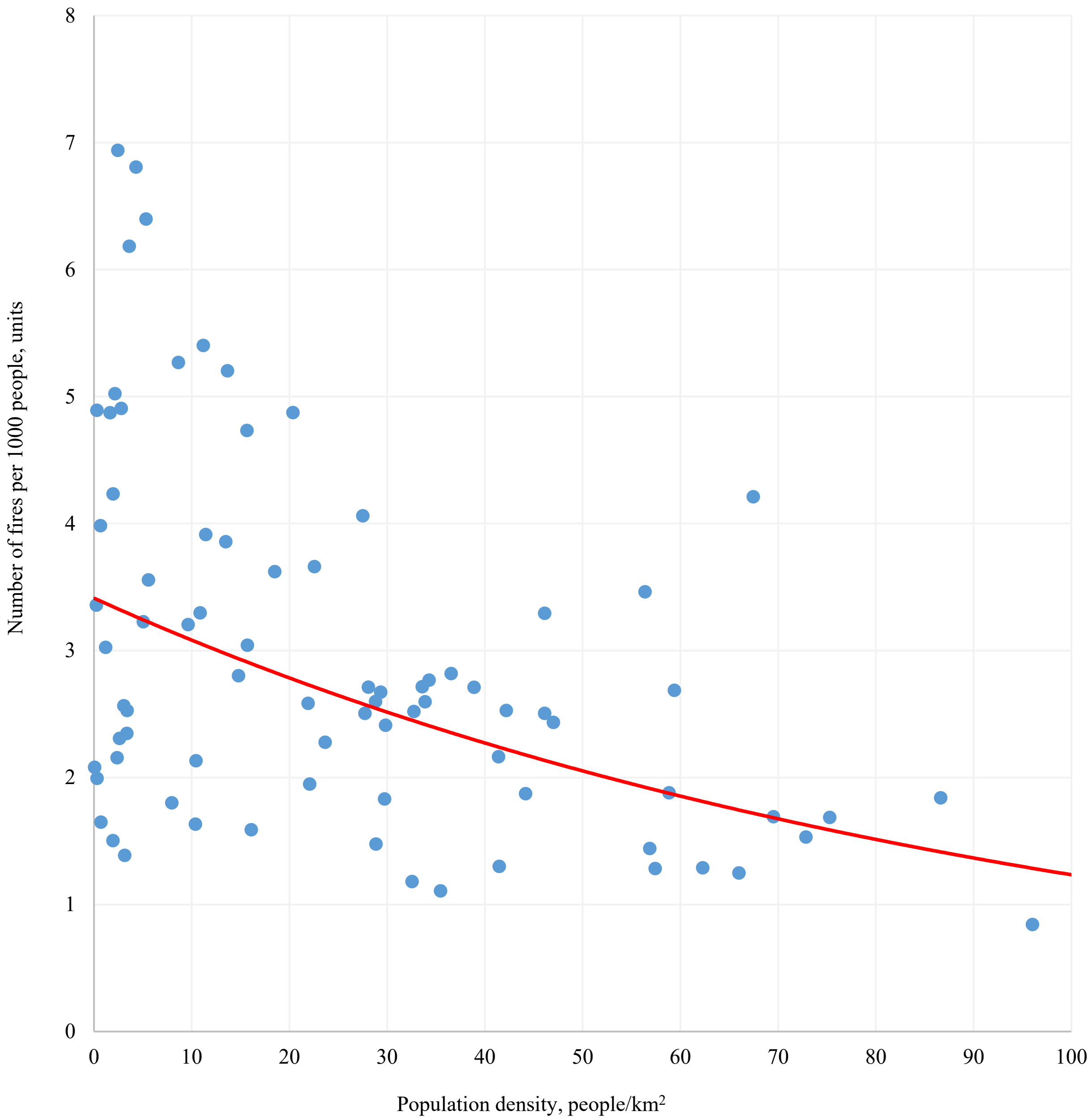

Fig. 4. Dependence of the number of fires per 1,000 people on population density. The curve is the result of approximation by exponential function $y = 3.412e^{-0,0102x}$

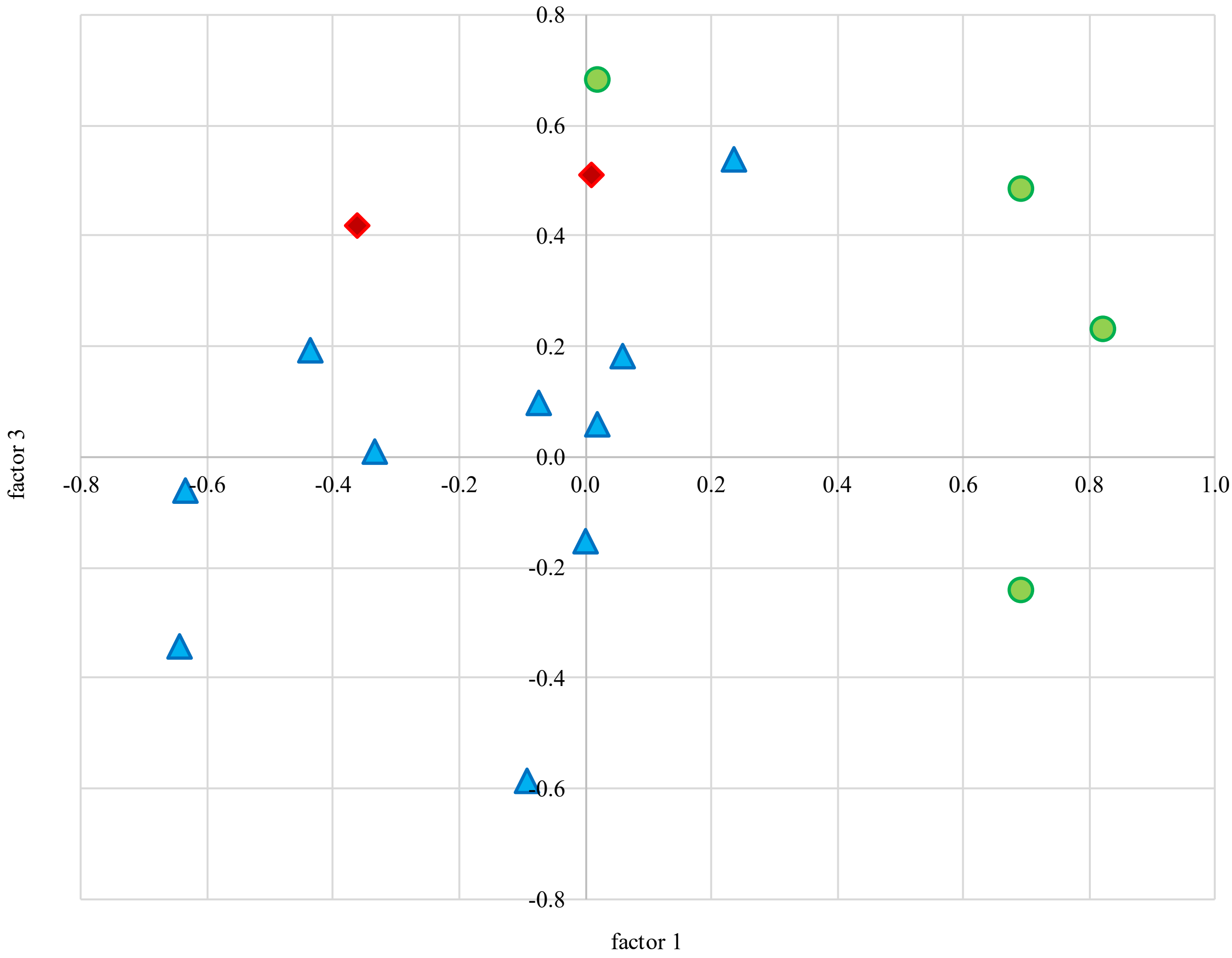

Fig. 5. Values of factor loads in the plane of factors 1 and 3. The indicators of the first group are marked in green, the indicators of the second group are marked in red, and the indicators of the third group are marked in blue

For the fourth significant factor, the following variables are the most important:

– average annual precipitation, mm per year (X_5);

– average July temperature, °C (X_6);

– number of sunny days per year (X_{10}).

This factor is related to climatic characteristics of the subjects of the Russian Federation. The indicators of the first and second groups did not make a significant contribution to this factor. It should be noted that the relationship between the climatic characteristics of the subjects and the indicators of the fire situation was well traced from the analysis of factor loads for the first factor (see above).

For the fifth significant factor, the following variables are decisive:

– the proportion of the water surface area of the territory of the subject, % (X_2);

– the length of the sea coastline of the total length of the border of the subject, % (X_3).

These hydrographic characteristics did not have a significant impact on the fire situation and on the operational response indicators of fire departments in the constituent entities of the Russian Federation.

Discussion and Conclusion. For the first time, using factor analysis, a study of the influence of natural, climatic and geographical features of the subjects of the Russian Federation on the level of fire safety was conducted. The analysis showed that the following climatic, geographical and demographic indicators most significantly affect the situation with fires and the activities of fire departments in the subjects of the Russian Federation: average temperature, forest cover of the territory, the presence of mountain ranges, population density. Thus, when determining the number and technical equipment of fire departments, it is necessary to take into account these features of the subjects of the Russian Federation.

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Received 26.11.2023
Revised 11.12.2023
Accepted 18.12.2023

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Claimed contributorship:
OV Streltsov: formulation of the basic concept, goals and objectives of the study.
EV Bobrinev: collection of statistical data, conclusions based on the results of calculations.
EYu Udavtsova: preparation of figures, editing of the final version of the article.
AA Kondashov: analysis of statistical data, writing the first version of the article.
SI Ryumin: formation of the list of references, editing of the final version of the article.

Conflict of interest statement: the authors do not have any conflict of interest.

All authors have read and approved the final manuscript.

Поступила в редакцию 26.11.2023
Поступила после рецензирования 11.12.2023
Принята к публикации 18.12.2023

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UDC 331.45
https://doi.org/10.23947/2541-9129-2024-8-1-30-40

Original article

EDN: WBSVBI

Determination of the Convergence of Intra-Laboratory Measurements of Dust Content on a Construction Site

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Abstract

Introduction. Intra-laboratory comparison tests play an important role in ensuring the quality and reliability of research outcomes in laboratories. These tests allow researchers to evaluate the accuracy and reproducibility of the methods they use in their work, as well as to identify potential sources of error and inconsistency. The results of these tests are shared with experts to confirm competence within the accreditation. Typically, comparison tests are carried out in laboratory conditions in a familiar and calm environment for the testers. However, when laboratories conduct research as part of a special assessment of working conditions (SAWC) they are required to conduct on-site comparisons at real-world facilities, where customers may unwittingly disrupt the process and directly affecting the quality of the measurements. The aim of this study is to evaluate the quality of on-site intra-laboratory comparison tests using the example of determining the dust content in a bricklayer's work environment on a construction site, and to determine the minimum number of measurements necessary and sufficient for this purpose.

Materials and Methods. To determine the dustiness of the bricklayer's workplace, a weighing method was used. This involved collecting dust on filters and then weighing them to determine the concentration. The quality assessment of intra-laboratory tests was conducted in accordance with GOST R ISO 5725-1-2002 "Accuracy (trueness and precision) of measurement methods and results. Part 1. General principles and definitions".

Results. At the bricklayer's workplace, a 1.6-fold excess of the one-time maximum permissible dust concentration was detected. The average dust concentration at the workplace under study was: $K_{p2} = 9.57 \pm 0.81$ mg/m^3, the convergence of the results obtained was $r = 8.68\%$, the relative error $\delta = 8.50\%$. It was revealed that the maximum allowable difference between the results of the two tests was 0.84 mg/m^3. The difference in direct measurements of the mass of the two samples should be no more than 0.1 mg.

Discussion and Conclusion. The results obtained demonstrated the possibility of conducting a minimum number of measurements that, under reproducible conditions, are considered satisfactory and could be provided to experts for confirming the competence of the laboratory. As part of a special assessment of working conditions, employees of the object under study are recommended to use personal respiratory protection equipment that offers protection against highly dispersed dust particles.

Keywords: convergence, intra-laboratory control, dust content, construction site, workplace, special assessment of working conditions (SAWC)

Acknowledgements. The authors would like to thank the Editorial board and the reviewers for their attentive attitude to the article and for the specified comments that improved the quality of the article.

For citation. Korol EA, Degaev EN, Pushenko SL. Determination of the Convergence of Intra-Laboratory Measurements of Dust Content on a Construction Site. *Safety of Technogenic and Natural Systems.* 2024;8(1):30–40. https://doi.org/10.23947/2541-9129-2024-8-1-30-40

Научная статья

Определение сходимости внутрилабораторных результатов измерений запыленности строительной площадки

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Аннотация

Введение. Внутрилабораторные сличительные испытания являются важным и актуальным мероприятием для обеспечения качества и достоверности результатов исследований в лабораториях. Они позволяют оценить точность и воспроизводимость применяемых в лаборатории методов, а также выявить возможные источники ошибок и несоответствий в ее работе. Результаты внутрилабораторных сличительных испытаний предоставляются экспертам при подтверждении компетентности в рамках аккредитации. Как правило, сличительные испытания проводят в лабораторных условиях в привычной и спокойной для испытателей обстановке. Однако лаборатории, проводящие исследования в рамках специальной оценки условий труда (СОУТ), вынуждены проводить выездные сличительные испытания на реальных объектах, где за испытаниями наблюдают заказчики, которые невольно отвлекают работников лаборатории, что напрямую влияет на качество измерений. Целью данной работы является оценка качества проведения выездных внутрилабораторных сличительных испытаний на примере определения запыленности рабочего места каменщика на строительной площадке и определение минимально необходимого и достаточного для этого количества измерений.

Материалы и методы. Для определения запыленности рабочего места каменщика использовался весовой метод, который заключается в сборе пыли на фильтры с последующим взвешиванием и определением концентрации. Оценка качества проведения внутрилабораторных испытаний производилась согласно ГОСТ Р ИСО 5725-1-2002 «Точность (правильность и прецизионность) методов и результатов измерений. Часть 1. Основные положения и определения».

Результаты исследования. На рабочем месте каменщика выявлено превышение разовой предельно допустимой концентрации пыли в 1,6 раза. Средняя концентрация пыли на исследуемом рабочем месте составила: $К_{п2}$ = 9,57 ± 0,81 мг/м^3, сходимость полученных результатов, r = 8,68 %, относительная погрешность, δ = 8,50 %. Выявлено, что максимально допустимая разница результатов двух испытаний составляет 0,84 мг/м^3. Разница прямых измерений массы двух образцов должна быть не более 0,1 мг.

Обсуждение и заключение. Полученные результаты показали возможность проведения минимального количества измерений, что по условиям воспроизводимости испытания признаются удовлетворительными и могут предоставляться экспертам для подтверждения компетентности лаборатории. В рамках СОУТ работникам исследуемого объекта рекомендуется использовать средства индивидуальной защиты органов дыхания, предохраняющие от высокодисперсной пыли.

Ключевые слова: сходимость, внутрилабораторный контроль, запыленность, строительная площадка, рабочее место, специальная оценка условий труда (СОУТ)

Благодарности. Авторы выражают благодарность редакции и рецензентам за внимательное отношение к статье и указанные замечания, которые позволили повысить ее качество.

Для цитирования. Король Е.А., Дегаев Е.Н., Пушенко С.Л. Определение сходимости внутрилабораторных результатов измерений запыленности строительной площадки. *Безопасность техногенных и природных систем.* 2024;8(1):30–40. https://doi.org/10.23947/2541-9129-2024-8-1-30-40

Introduction. Measurements on dustiness of workplaces are carried out as part of a special assessment of working conditions (SAWC) at the construction site in order to identify and assess harmful and hazardous production factors, as well as to develop measures to eliminate or minimize them [1]. The results of a special assessment of working conditions are the basis for the development and implementation of appropriate measures to improve working conditions [2]. This may be a change in work processes, the use of new technologies, updating equipment or improving sanitary conditions [3]. It is important to implement these measures taking into account the opinions of employees and meeting their needs [4].

Special assessment of working conditions on a construction site has its own characteristics related to the nature and working conditions [5]. Such features include:

– outdoor work, which can lead to exposure to adverse weather conditions;

– use of construction machinery and equipment that can create noise, vibration, dust and other contaminants;

– work at height, which requires special training and certification of personnel;

– work with various materials and substances that may be dangerous to the health of employees;

– need to comply with occupational health and safety requirements, including the use of personal protective equipment.

The result of SAWC is that classes of working conditions for each profession are established as well as measures are recommended to minimize the identified risks and consequences of the influence of harmful factors [6]. According to SAWC, the management of the organization develops measures to improve working conditions and safety. The amount of additional payments for workers employed in production with unfavorable or risky conditions is also determined [7]. In instrumental study of workplaces, measurements and analysis of noise, degree of dustiness, natural and artificial illumination, temperature, humidity, etc. are carried out [8].

Organizations with appropriate accreditation and experience have the right to conduct SAWC. These organizations can be either specialized organizations or laboratories engaged in studying working conditions.

In accordance with Federal Law No. 426 dated December 28, 2013 "On special assessment of working conditions", an organization engaged in SAWC must:

– have at least five full-time employees with a valid certificate for the right to conduct SAWC;

– be registered in the register of organizations conducting SAWC, which is maintained by the Ministry of Labor and Social Protection of the Russian Federation;

– have a quality management system (QMS) conforming to GOST ISO/IEC 17025-2019 "General requirements for the competence of testing and calibration laboratories" and GOST R 54934-2012/ OHSAS 18001:2007 "Occupational health and safety management systems. Requirements";

– have an accredited testing laboratory that carries out research and measurements of hazardous and harmful factors.

Testing laboratory (TL) must have a valid accreditation certificate, an appropriate accreditation scope reflecting the possibility of studying harmful and hazardous factors of production and working conditions, as well as certified testing equipment (TE) and certified measuring instruments (MI) [9]. According to Decree of the Government of the Russian Federation dated November 26, 2021 No. 2050 "On approval of the rules for accreditation in the national accreditation system ..." accredited laboratories, as part of the confirmation of competence, must conduct comparative tests to determine the convergence of measurement results. The convergence of measurement results during a special assessment of working conditions is one of the key indicators that determine the quality of measurements.

Previous research in this area has mainly focused on interlaboratory comparative tests (ILC) and has not considered intra-laboratory comparative tests. Thus, in the work of A.V. Kozlov, the results of ILC of geosynthetic material are presented [10]. The author points out the expediency of rationing the requirements of precision tests. In the study of M.M. Lekomtseva and E.V. Shendaleva the analysis of the results of ILC of petroleum products was carried out, according to the results of which it was recommended to convert data into a linear dependence in order to obtain a constant value of the standard deviation [11]. Yasin Durgut's work notes that interlaboratory comparative tests conducted in accordance with GOST ISO/IEC 17025-2019 "General requirements for the competence of testing and calibration laboratories" are performed more efficiently than comparative measurements in accordance with GOST ISO/IEC 17043 "Conformity assessment. General requirements for proficiency testing" [12].

Meanwhile, according to GOST ISO/IEC 17025-2019 "General requirements for the competence of testing and calibration laboratories", the results of intra-laboratory comparative tests are also very important, since they are used to carry out corrective measures, improve quality of laboratory work and increase accuracy of the results [13]. Therefore, the aim of this work is to assess the quality of on-site intra-laboratory comparison tests. Such an assessment is presented by the example of determining the dustiness of a bricklayer's workplace on a construction site. Laboratories operating within the SAWC framework are forced to conduct on-site intra-laboratory comparative tests, and their conditions differ significantly from the laboratory ones. Laboratory staff is limited by the time of admission to the facility, so it is important for them to perform research not only qualitatively, but also with a minimum number of tests. In this regard, the task of the authors of the article was to determine the minimum necessary and sufficient number of such tests.

Materials and Methods. General sanitary and hygienic requirements for the air of the working area, as well as methods for monitoring microclimate indicators and the content of harmful substances in the air, are regulated by GOST 12.1.005-88 "Interstate Standard. Occupational safety standards system. General sanitary requirements for working zone air". To determine the dust content, a weight method was used[1], which consists in collecting dust on filters, followed by weighing and determining the concentration.

Mass concentration K_p of dust is determined by formula:

$$K_p = \frac{(m_n - m_0)\cdot 1000}{V_{20}}, \tag{1}$$

where K_p — concentration of dust in the air, mg/m^3; m_0 — mass of the clean filter, mg; m_n — mass of the filter with settled dust particles, mg; V_{20} — volume of air brought to standard conditions, dm^3.

$$V_{20} = \frac{V_t \cdot 293 \cdot P}{(273+T)\cdot 101.33}, \tag{2}$$

where V_t — volume of air passed through the filter, dm^3; P — atmospheric pressure, kPa; T — workplace air temperature, °C.

According to the recommendations of the state system for ensuring the uniformity of measurements[2], a reduction method can be used to process the results of determining the dustiness of the workplace, which assumes the presence of the values of the measured arguments obtained as a result of multiple measurements.

The result of indirect measurement $\tilde{A}$ is found by formula:

$$\tilde{A} = \sum_{j=1}^{L} \frac{A_j}{L}, \tag{3}$$

where L — number of partial values of the measured value; A_j — *j-th* value of the measured value; j — serial measurement number from 1 to L.

Mean square deviation $S(\tilde{A})$ of random errors of the indirect measurement result is calculated using the following formula:

$$S(\tilde{A}) = \sqrt{\sum_{j=1}^{L} \frac{(A_j - \tilde{A})^2}{L(L-1)}}. \tag{4}$$

With a normal distribution of individual values of the measured value, the confidence limits of random errors are determined by formula:

$$\Delta = t_p \cdot S(\tilde{A}), \tag{5}$$

where t_p — Student's coefficient, depending on the confidence probability and the number of observation results.

Precision is estimated by the indicator of repeatability (relative standard deviation of repeatability), σ_r, and by the indicator of accuracy (limits of relative error), δ:

$$\sigma_r = \sqrt{\sum_{i=1}^{n} \frac{(x_i - \tilde{x})^2}{n-1}}, \tag{6}$$

where x_i — *i-th* test result obtained under repeatability conditions; $\tilde{x}$ — arithmetic mean of n test results under conditions of repeatability (convergence).

$$\delta = \frac{\Delta}{\tilde{x}} 100\% \le 25\%. \tag{7}$$

The percentage of convergence is determined in accordance with expression:

$$r = \frac{\sigma_r}{\tilde{x}} 100\%. \tag{8}$$

To evaluate the convergence of the results of two measurements, it is necessary to use formula:

$$r_2 = \frac{|x_1 - x_2|}{\tilde{x}} 100\%, \tag{9}$$

where x_1, x_2 — results of two parallel measurements.

The measurement results obtained under convergence conditions are considered satisfactory if the obtained convergence r is less than or equal to the normative convergence r_{norm}:

$$r \le r_{norm} = 15\%. \tag{10}$$

[1] *Metodika izmerenii massovoi kontsentratsii pyli gravimetricheskim metodom dlya tselei spetsial'noi otsenki uslovii truda.* MI APFD-18.01.2018. URL: https://normativ.kontur.ru/document?moduleId=1&documentId=390372 (accessed: 25.11.2023). (In Russ.).

[2] *Rekomendatsiya. Gosudarstvennaya sistema obespecheniya edinstva izmerenii. Izmereniya kosvennye. Opredelenie rezul'tatov izmerenii i otsenivanie ikh pogreshnostei. MI 2083–90.* Moscow: Committee of Standardization and Metrology of the USSR; 1991. URL:https://znaytovar.ru/gost/2/MI_208390_GSI_Izmereniya_kosve.html (accessed: 25.11.2023). (In Russ.).

Expression (8) is taken as the result:

$$x = \tilde{x} \pm \Delta . \quad (11)$$

The minimum number of observations depends on the coefficient of variation, i.e. the ratio of the standard deviation to the average value, and is selected previously from the experimental data. The error in determining the average value (statistical measurement error) must be sought under the assumption that the distribution law of the general set of measurements is normal. If we know the error and confidence probability, it is possible to unambiguously establish a confidence interval for the average value and estimate the maximum statistical error of measurements as the ratio of half the difference between the boundaries of the error of the average value to the average value from the experimental data [14].

Results. Measurements were carried out to determine the dust content of the construction site during the construction of an apartment building. Sampling was carried out at the bricklayer's workplace in the masonry wall area with AFA type filters (analytical aerosol filters) using two PU-4E aspirators, providing sampling with a given volume flow through an absorber through four parallel channels. To establish the statistical error of measurements by instruments and laboratory staff at a given confidence probability P = 0.95 eight parallel measurements were performed, the results of which are shown in Table 1.

Table 1

Results of eight parallel tests

Measurement no.	Filter weight, m_0, mg	Filter weight, m_n, mg	Air consumption, l/min	Atmospheric pressure, kPa	Measurement time, min.	Air temperature in the work area, °C	Partial values of dust concentration, mg/m³	Average dust concentration, mg/m³	Mean square deviation, mg/m³	Relative error, δ, %	Convergence of results, r, %
n=8											
No.1	30965.6	30966.5	2	102.2	60	21.1	7.46	9.33	1.39	10.29	14.85
No.2	31346.8	31347.8	2	102.2	60	21.1	8.29				
No.3	33980.5	33981.6	2	102.2	60	21.1	9.12				
No.4	35572.3	35573.6	2	102.2	60	21.1	10.78				
No.5	34926.9	34928.3	2	102.2	60	21.1	11.61				
No.6	30477.7	30479.0	2	102.2	60	21.1	10.78				
No.7	32678.4	32679.5	2	102.2	60	21.1	9.12				
No.8	32678.4	32679.6	2	102.2	60	21.1	9.95				

To check whether the data obeyed the normal distribution law, a frequency histogram was constructed as one of the ways to visually represent the distribution of data (Fig. 1). The histogram has the shape of a bell and is close to the curve of normal distribution (Fig. 2)

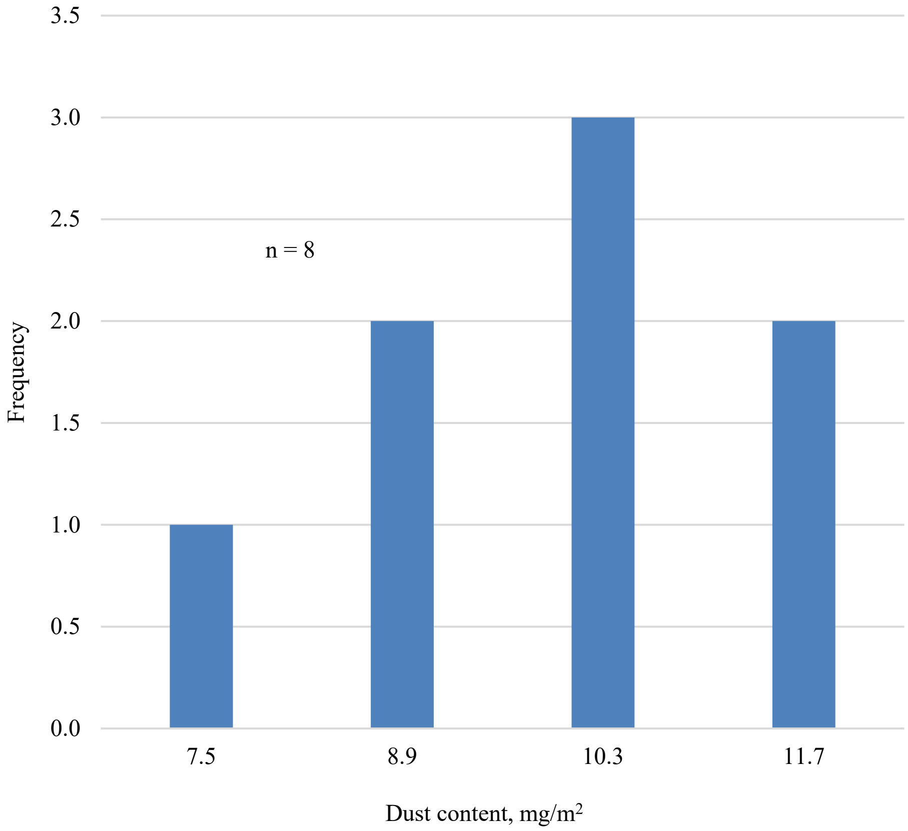

Fig. 1. Frequency histogram at $n = 8$

The average value and confidence interval of the measurements were calculated and shown on the graph of density functions of normal distribution (Fig. 2).

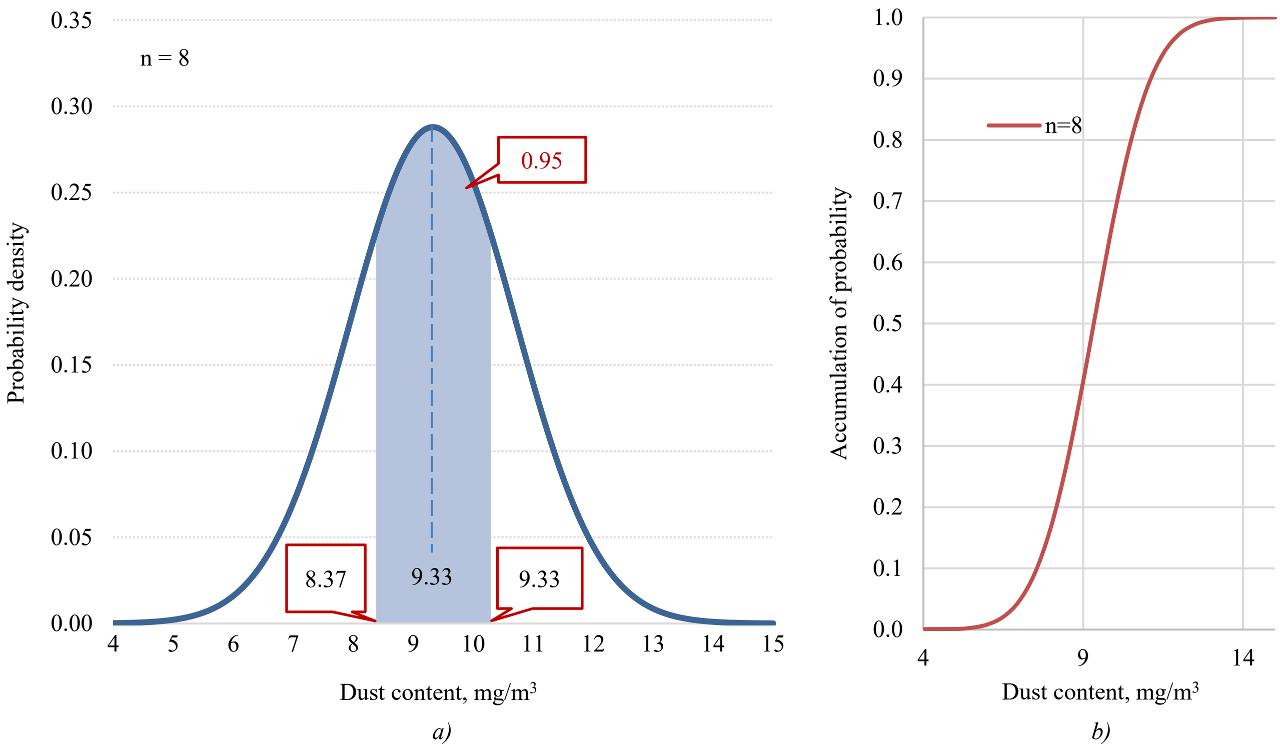

Fig. 2. Graphs of normal distribution an$n = 8$: *a* — density function of normal distribution; *b* — integral distribution function

The average value is taken as the result, indicating the confidence interval:

$$K_{p8} = 9.33 \pm 0.96 \text{ mg}/\text{m}^3 .$$

To determine the minimum number of measurements, the coefficient of variation, the average sampling error and the marginal sampling error were found (Fig. 3). The maximum statistical error was 0.26 mg/m^3. μ = ±1.16 mg/m^3

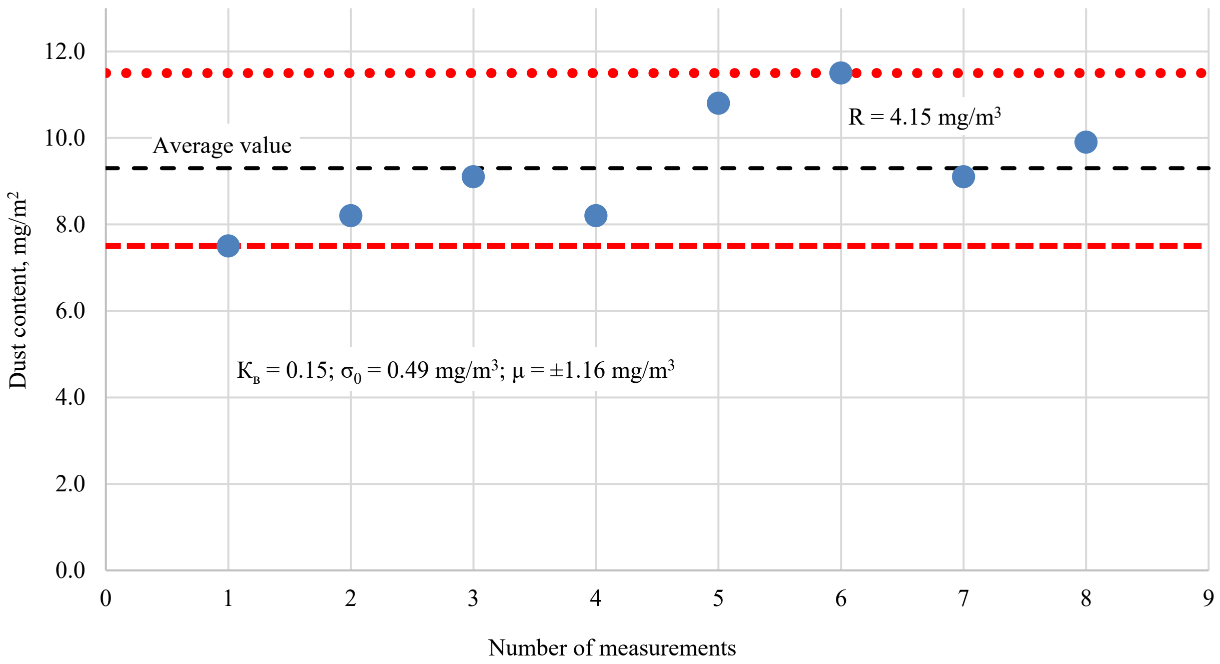

Fig. 3. Scope of measurement results

The minimum number of measurements is determined by formula [11]:

$$n_{min} = \frac{t^2 К_в{}^2}{\delta^2}, \quad (12)$$

$$n_{min} = 1.20 \approx 2.$$

According to the obtained value of the minimum number of tests, two parallel tests were carried out to determine dust concentration at the bricklayer's workplace (Table 2).

Table 2

Results of two parallel tests

Measurement no	Filter weight, m_0, mg	Filter weight, m_n, mg	Air consumption, l/min	Atmospheric pressure, kPa	Measurement time, min.	Air temperature in the work area, °C	Partial values of dust concentration, mg/m^3	Average dust concentration, mg/m^3	Mean square deviation, mg/m^3	Relative error, δ, %	Convergence of results, r, %
n=2											
No.1	34563.8	34565.0	2	102.2	60	22.0	9.98	9.57	0.59	8.50	8.68
No.2	30654.3	30655.4	2	102.2	60	22.0	9.15				

Confidence interval of the results of two tests to determine dust concentration with a probability of 0.95 was 0.81 mg/m^2 (Fig. 4).

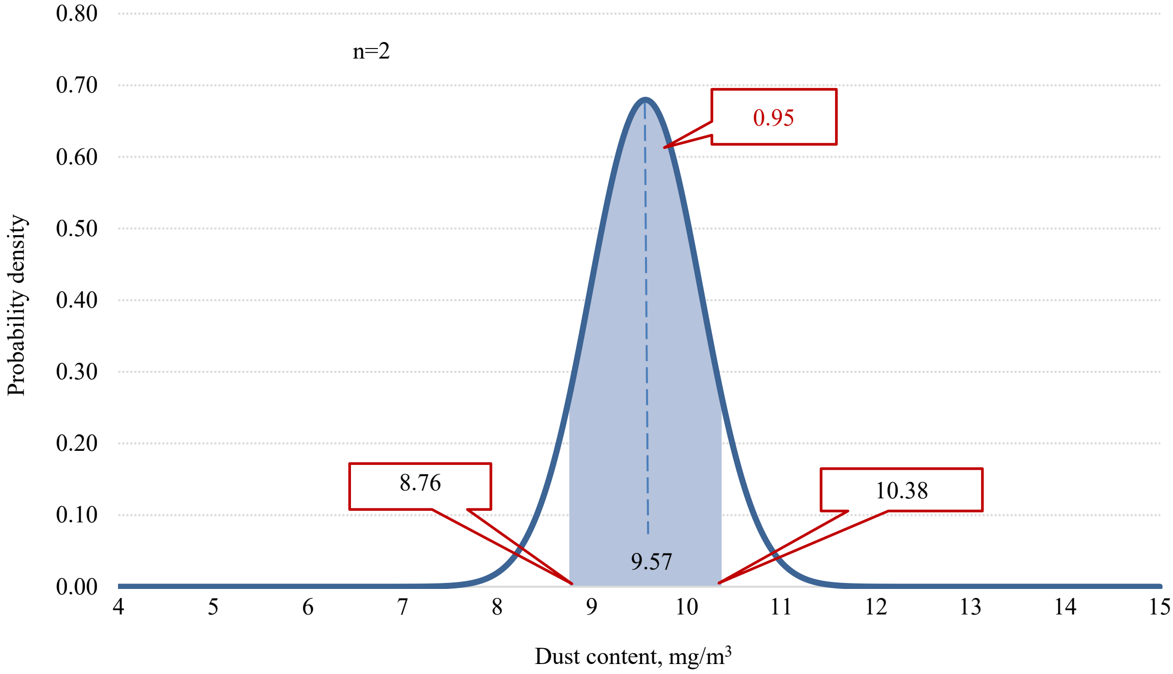

Fig. 4. Density function of normal distribution

According to convergence conditions in conformity with GOST R ISO 5725-1-2002 "Accuracy (trueness and precision) of measurement methods and results. Part 1. General principles and definitions" and GOST R 51672-2000 "Metrological ensuring of product testing for the assurance of conformity. General principles" the results of parallel measurements can be considered satisfactory, since conditions (7) and (10) are fulfilled (Fig. 5):

$$r_2 = 8.68\% < r_{\text{norm}} = 15\%,\ \delta_2 = 8.50\% < \delta_{\text{norm}} = 25\%.$$

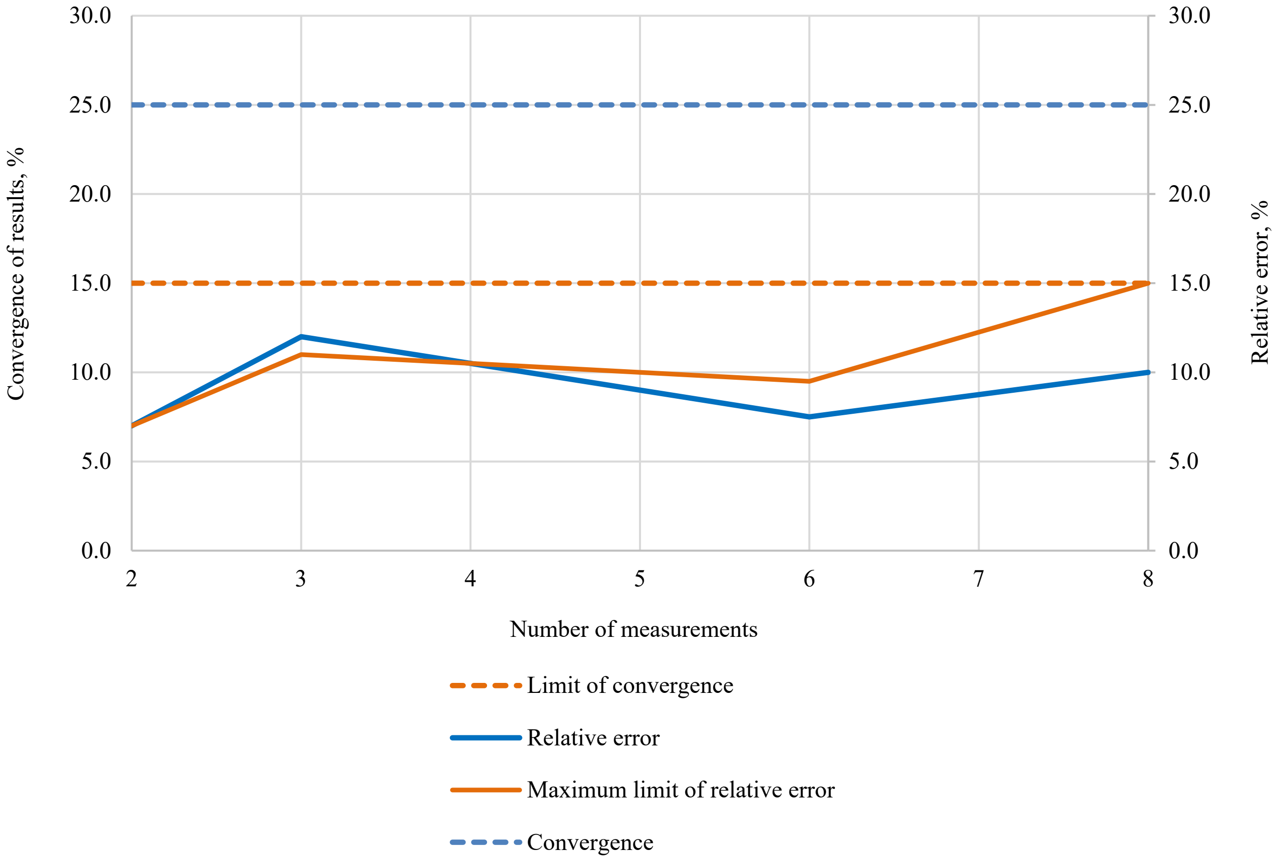

Fig. 5. Dependence of the convergence of measurement results and relative error on the number of tests

Based on the results of processing, it is accepted:

$$K_{p2} = 9.57 \pm 0.81 \text{ mg/m}^3.$$

Determination of dust concentration by the weight method has a sufficiently high component of errors of measuring instruments used and operations performed. The maximum allowable difference between the results of two measurements is 0.84 mg/m^3. The difference in direct measurements of the mass of two samples should be no more than 0.1 mg. With a mass difference of 0.2 mg, the convergence rate of the results of two parallel measurements becomes more than 18% and does not meet the precision conditions. When conducting tests to determine dust content of the considered technique, it is possible to limit two parallel measurements, while the measurement error will be equal to the instrumental error.

Construction dust is classified as low-hazard (Class IV), the single maximum permissible concentration (MPC) is 6 mg/m^3, the daily concentration is 10 mg/m^3. According to the test results, a 1.6-fold excess of the one-time maximum permissible concentration was revealed. To reduce the concentration of dust at the bricklayer's workplace, comprehensive measures are recommended to reduce dust formation on the construction site, since the main sources of dust are access roads, places of unloading and loading of building materials, as well as technological processes related to the processing and cutting of construction materials [15]. It is necessary to take measures to reduce the concentration of dust on the construction site and beyond [16].

Hygienic standard GN 2.1.6.3492-17 "Maximum permissible concentrations of pollutants in the atmospheric air of urban and rural settlements" establishes a single maximum permissible concentration of construction dust in urban air of no more than 0.5 mg/m^3.

Discussion and Conclusion. Determination of dust concentration by the weight method has a sufficiently high component of errors of measuring instruments used and operations performed. It was revealed that the maximum allowable difference between the results of two tests was 0.84 mg/m^3. The difference in direct measurements of the mass of two samples should be no more than 0.1 mg.

Processing of test results showed the possibility of carrying out two measurements to determine dustiness of the bricklayer's workplace on the construction site. The convergence of test results within the framework of laboratory competence confirmation is an important indicator of the quality of the assessment and indicates the reliability of the data obtained, therefore, it is recommended to use at least six measurements within the framework of intra-laboratory comparison tests [17]. The higher the convergence of the results, the less likely errors and inaccuracies in the assessment of working conditions. This, in turn, provides more objective information about the state of working conditions in the workplace and allows you to take reasonable measures to improve them [18].

Employees of the investigated facility are recommended to use personal respiratory protection equipment that protects against highly dispersed dust. To reduce the concentration of construction dust on the construction site, as well as outside it, it is necessary to spray the construction site with water to settle highly dispersed dust, to spray water on access roads, to wash the wheels of vehicles both at the entrance to the construction site and at the exit [19].

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Received 18.12.2023
Revised 15.01.2024
Accepted 17.01.2024

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Claimed contributorship:
All authors have made an equivalent contribution to the preparation of the publication.

Conflict of interest statement: the authors do not have any conflict of interest.

All authors have read and approved the final manuscript.

Поступила в редакцию 18.12.2023
Поступила после рецензирования 15.01.2024
Принята к публикации 17.01.2024

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Заявленный вклад соавторов:

Все авторы внесли эквивалентный вклад в подготовку публикации.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

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UDC 602.807.2
https://doi.org/10.23947/2541-9129-2024-8-1-41-49

Original article

EDN: WDNKXY

Assessment of the Spraying System Impact at the Preparation Stage of Iron Ore Concentrate Products

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Abstract
Introduction. Harmful components of ore dust, formed during the unloading of products in the preparation of iron ore concentrate (PPIOC) at the mixing stage, cause damage to both workers and equipment. To address this issue, liquid aerosol spraying using nozzles with large diameters (>20 µm) is used. However, this method proves ineffective in capturing fine-dust particles. Therefore, enhancing the efficiency of the dust deposition method through PPIOC dust spraying becomes a pressing challenge. The aim of this study is to investigate the impact of the Dry Fog technology, generating liquid droplets up to 20 µm in size, during the unloading stage of PPIOC at a mining and metallurgical enterprise in the precipitation of suspended fine-dust particles. The primary goal of this research was to assess the effectiveness and potential advantages of applying the Dry Fog technology for dust spraying with subsequent precipitation, as this technology has not been previously applied to PPIOC dust.
Materials and Methods. The experiment on the PPIOC dust deposition was conducted in a specially designed laboratory setup. Through physical modeling in the laboratory setup, parameters of the precipitation process were obtained. Subsequently, the results were analyzed to understand the dependence of dust precipitation over time, taking into account the influence of the Dry Fog technology. An experiment program was developed for physical modeling. According to the devised program, dust was uniformly loaded into the interior of the laboratory setup (from the top), distributed in the air stream throughout the volume of the setup by a fan, and an instrument located at the bottom recorded changes in concentration over time. Experiments on dust precipitation were then conducted using liquid spraying (filtered water as the liquid) introduced into the setup through nozzles generating droplets with sizes of 10 and 15 µm, concurrently with the loading of dust into the laboratory setup. The effectiveness of the Dry Fog technology in the deposition of PPIOC dust was determined visually and further analyzed based on a comparison of graphs. The dynamics of changes in the average dust concentrations depending on time was studied both during precipitation without spraying and using the Dry Fog technology. During the experiment, the characteristics of the microclimate inside the laboratory setup (humidity, temperature and air velocity) and the parameters of two nozzles — their operating pressure and the supplied liquid spraying time — were recorded.
Results. The comparison of the results showed a reduction in the dust precipitation time by 40% and 75% when using nozzles with sizes of 10 µm and 15 µm, respectively.
Discussion and Conclusion. The experiment results confirm the effectiveness of the Dry Fog technology for PPIOC dust precipitation during unloading at the mixing stage. Fundamental findings have been obtained, providing a basis for further assessment of the efficiency of dust precipitation with the additional application of pulsating ventilation. In such a combination, an additional 20–25% increase in precipitation efficiency is anticipated compared to the results presented in this article. The obtained results will support the justification of rational parameters and the implementation of the described method in production to enhance dust precipitation efficiency. Additionally, they will aid in developing a methodology to accelerate the PPIOC dust precipitation using the pulsating ventilation method.

Keywords: ore dust, dust from iron ore concentrate preparation products, iron ore concentrate, liquid spraying, mass transfer, dust deposition experiment, liquid aerosol, dust aerosol, pulsating ventilation method

Acknowledgements. The authors would like to express their gratitude to the Editorial team of the journal and the reviewer for their competent expertise and valuable recommendations for improving the article. Additionally, the authors would like to thank the team and the head of the Technosphere Safety Department at NUST MISIS for their support in establishing the laboratory and conducting the research.

For citation. Kurnosov IYu, Filin AE, Tertychnaya SV. Assessment of the Spraying System Impact at the Preparation Stage of Iron Ore Concentrate Products. *Safety of Technogenic and Natural Systems.* 2024;8(1):41–49. https://doi.org/10.23947/2541-9129-2024-8-1-41-49

Научная статья

Оценка влияния системы орошения на этапе подготовки продуктов железорудного концентрата

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Аннотация

Введение. Вредные компоненты рудной пыли, образующейся при разгрузке продуктов подготовки железорудного концентрата (ППЖК) на стадии смешивания, наносят ущерб как работникам, так и оборудованию. Для решения этой проблемы применяется орошение жидкостным аэрозолем с использованием форсунок больших диаметров (>20 мкм). Однако данный метод неэффективен в улавливании мелкодисперсных частиц пыли, поэтому повышение эффективности метода осаждения орошением пыли ППЖК становится актуальной задачей. Целью данного исследования является изучение воздействия технологии «Сухой туман», генерирующей капли жидкости размером до 20 мкм, на этапе разгрузки ППЖК горно-металлургического предприятия при осаждении взвешенной мелкодисперсной пыли. Основной задачей данного исследования являлась оценка эффективности и возможных преимуществ применения технологии «Сухой туман» для орошения пыли с последующим осаждением, поскольку к пыли ППЖК описанная выше технология ранее не применялась.

Материалы и методы. Эксперимент по осаждению пыли ППЖК проводился в специально созданном лабораторном стенде. Посредством физического моделирования были получены параметры процесса осаждения. Далее полученные результаты подвергались анализу с точки зрения получения зависимости осаждения пыли с течением времени с учетом влияния технологии «Сухой туман». Для физического моделирования была разработана программа эксперимента. Согласно данной программе, пыль равномерно загружалась внутрь лабораторного стенда (сверху), распределялась в воздушном потоке по всему объему стенда крыльчаткой, а прибор, расположенный в нижней части, фиксировал изменение концентрации во времени. Далее были проведены эксперименты по осаждению пыли с применением жидкостного орошения. Совместно с загрузкой пыли в объем лабораторного стенда посредством форсунок, генерирующих капли размером 10 и 15 мкм, подавалась жидкость — отфильтрованная вода. Эффективность технологии «Сухой туман» при осаждении пыли ППЖК определялась визуально, и далее — на основании сопоставления графиков. Изучалась динамика изменения усредненных концентраций пыли от времени как при осаждении без орошения, так и с применением технологии «Сухой туман». В процессе эксперимента фиксировались характеристики микроклимата внутри лабораторного стенда (влажность, температура и скорость движения воздуха) и параметры двух форсунок — их рабочее давление и время распыления подаваемой жидкости.

Результаты исследования. Сравнение результатов эксперимента показало уменьшение времени осаждения на 40 % и 75 % при использовании форсунок на 10 мкм и 15 мкм соответственно.

Обсуждение и заключение. По результатам эксперимента подтверждена эффективность технологии «Сухой туман» для осаждения пыли ППЖК при разгрузке на стадии смешивания. Полученные базисные результаты позволят в дальнейшем оценить эффективность осаждения пыли с применением дополнительно режима пульсирующей вентиляции. В таком сочетании ожидается повышение эффективности осаждения еще на 20–25 % относительно результатов, представленных в данной статье. Полученные результаты дают возможность обосновать рациональные параметры и применить на производстве вышеописанный способ для повышения эффективности осаждения пыли. Помимо этого, они создают основу для разработки методики ускорения осаждения пыли ППЖК с применением метода пульсирующей вентиляции.

Ключевые слова: рудничная пыль, пыль продуктов подготовки железорудного концентрата, железорудный концентрат, жидкостное орошение, массоперенос, эксперимент по осаждению, жидкостный аэрозоль, пылеводяной аэрозоль, метод пульсирующей вентиляции

Благодарности. Авторы благодарят редакционную команду журнала и рецензента за компетентную экспертизу и ценные рекомендации по улучшению статьи. Также авторы благодарят коллектив и руководителя кафедры «Техносферная безопасность» НИТУ МИСИС за поддержку в создании лаборатории и реализации исследований.

Для цитирования. Курносов И.Ю., Филин А.Э., Тертычная С.В. Оценка влияния системы орошения на этапе подготовки продуктов железорудного концентрата. *Безопасность техногенных и природных систем.* 2024;8(1):41–49. https://doi.org/10.23947/2541-9129-2024-8-1-41-49

Introduction. In order to reduce the level of atmospheric dust in production sites, the mining and metallurgical complex has successfully employed a range of innovative methods and advanced dust control technologies. Filtration systems, cyclones and ventilation systems are used, that are designed to effectively capture and remove the smallest dust particles [1–3]. In addition, engineers use methods of liquid spraying, aerial flotation and other advanced technologies that together provide an integrated approach to solving the problem of dust. The effectiveness of dust control measures is closely related to the unique features of the production processes, the characteristics of the equipment used, the design features of the premises and other important factors. Systematic maintenance of technical condition of the equipment is not just part of the technological process, but acts as an important element of the strategy to reduce the impact of production activities on the environment, contributes to the optimization of production efficiency. Comprehensive implementation of the above measures, combining various methods and technologies, allows you to achieve maximum efficiency in reducing the level of dust load within the working area.

At the stage of unloading and preparation of iron ore concentrate, where a significant amount of the smallest dispersed dust is formed, a liquid spraying system is used for a long time [4–6]. To create the smallest liquid aerosol, various types of nozzles are used, forming droplets with a diameter from 30 to 150 microns. In addition, nozzles with a larger diameter are also used. Deposition time t of the smallest dispersed dust (d = 1–10 microns) when using such nozzles can be quite long and reach 25,400 s (about 7 hours) [6]. At other stages of production, advanced Dry Fog technology is used for effective dust deposition. This technology uses nozzles of a smaller diameter that spray liquid with a droplet dispersion in the range from 1 to 20 microns [7]. In this technology, each drop of liquid serves as an effective tool for capturing and ensuring the settling of the smallest particles, creating a unique combination of technology and engineering in the fight against the problem of atmospheric dust.

Studies related to the use of the above-described technology for the deposition of fine dust in the preparation of iron ore concentrate products have not been conducted before. Therefore, the aim of this work was to analyze the effects of the Dry Fog technology, which generates liquid droplets up to 20 microns in size, at the stage of unloading the PPIOC of a mining and metallurgical enterprise during the deposition of suspended fine dust. The task was to evaluate the effectiveness and possible advantages of using the Dry Fog technology for dust spraying with subsequent precipitation.

Materials and Methods. To evaluate the effectiveness of the innovative Dry Fog technology, a series of experiments were conducted to measure dust deposition of the smallest particles of iron ore concentrate products using nozzles with diameters of 10 and 15 microns. To perform the experiment, a laboratory setup was developed (Fig. 1). This setup was used to analyze the deposition of coal dust in [8]. It was a cubic container with a volume of 1 m^3, made of organic glass in an aluminum frame.

A high-precision aerosol particle mass concentration meter, AEROCON-P, was used as a means to monitor the concentration of particles in the atmosphere. This measuring device has been developed taking into account the requirements for determining the mass concentration of dust with a diverse origin and chemical composition. The mass concentration meter has a unique ability to register the dispersion of the studied particles, including those with a diameter of up to 10 microns.

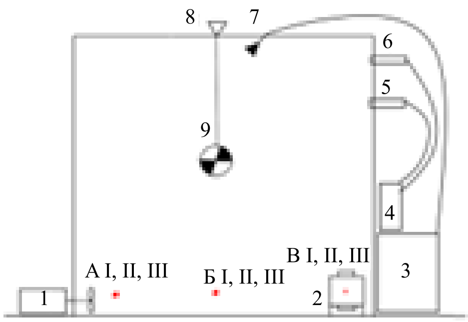

Fig. 1. Laboratory setup for dust deposition with a layout of equipment and measurement points:
1 — air flow generator; 2 — high-precision mass concentration meter for aerosol particles — AEROKON-P; 3 — fog generator; 4 — meteometer; 5 — humidity sensor; 6 — temperature sensor; 7 — nozzle; 8 — filling funnel; 9 — air pulsator

The order of measurements is indicated in Figure 1 by letters A, Б, В (location of the Aerocon-P sensor) (2). Values I, II and III (located next to the letters) correspond to the measurement points. According to the above scheme, the experiment was carried out over the entire area of the bottom of the laboratory box, namely at its 9 points (measurement points I, II, III should be understood as located in perspective, i.e. one after the other).

The experiments on dust deposition were carried out while monitoring the microclimate parameters. At the time of the deposition experiment, these parameters were controlled using a TESTO 435 (4) meteometer. During the experiments on dust deposition, the meteometer was used to control the parameters of the dust-air environment in the laboratory box — air temperature and humidity. This made it possible to establish the initial conditions of the experiment and conduct it under controlled conditions. The measuring device described above was used to monitor and maintain air humidity inside the setup in the range of 25–30% and temperature in the range from 22°C to 25°C. The assessment of the velocity of the air flow coming from the generator was carried out using a digital vane anemometer, which ensured a stable air velocity at the level of 4 m/s. To simulate the spraying system in the laboratory setup, an E218 installation was used, designed for misting by spraying liquid from various nozzles (Fig. 1). The operating pressure of this unit was 5.4 MPa, and the maximum was 12.41 MPa. For the experiment, nozzles with a diameter of 15 microns and 10 microns were used in this installation (Fig. 1).

The size of dust particles used in the deposition experiment, according to granulometric analysis, ranged from 1 micron to 40 microns (Fig. 2). Since the device for recording the concentration of particles in the air measured particles up to 10 microns in diameter, it was necessary to determine the percentage of these particles in the dust sample. According to this analysis, the required dust particle size used for the deposition experiment was approximately 10% of 1 gram of the sample used in dust analysis [9]. To correctly determine the concentration change by the device, the sample of the dust under study was increased to 5 grams in order to increase the concentration of fine dust with a diameter from 1 micron to 10 microns.

Dust deposition experiment was carried out in the laboratory setup described above, in compliance with all microclimate parameters regulated by appropriate measuring devices. A predetermined amount of dust weighing $m = 5$ g was placed into the laboratory box for 3–5 seconds using a filling funnel (Fig. 1). During this process, the air flow generator was activated, providing air supply at a speed of $V = 4$ m/s. The AEROCON-P measuring device, used as a mass concentration meter for aerosol particles, periodically recorded dust concentration data with an interval of 5 seconds, automatically transmitting the obtained values to a computer monitor [10]. The stage of the dust deposition experiment was completed when the dust concentration value recorded by the device was equal to $n = 0.00$ mg/m^3. The achievement of this value was considered as an indicator of completion of the experiment, in which all dust in the laboratory box was considered settled.

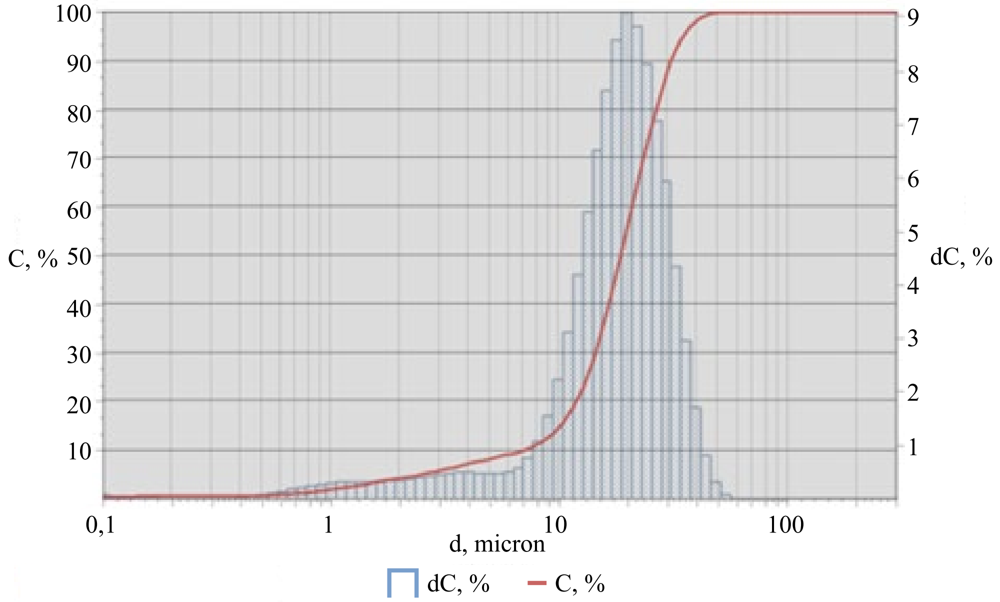

Fig. 2. Granulometric analysis of dust of sinter production of the mining and metallurgical complex:
C — percentage distribution of the number of particles in the sample by size, %;
dC — integral distribution of the percentage of particles in the sample by size, %;
d — particle size in the sample

Using similar parameters of temperature, humidity and air velocity during the dust deposition experiment, studies of the deposition of a dust-water aerosol were carried out with the alternate use of two nozzles (d = 10 and d = 15 microns) and control of the supplied pressure (p = 5.4 MPa) of the liquid. In addition, spraying time t = 2 minutes was monitored (after two minutes, the air humidity in the laboratory setup became maximum and amounted to 98.5%).

Results. Under the described conditions, a series of 10 dust deposition experiments was performed to ensure the reliability of the experimental data. The results of these experiments were processed, summarized in graphs and analyzed. Figure 3 provides graphs of the change in dust concentration values over time during 10 experiments from the deposition time.

According to the graph shown in Figure 3, the average dust deposition time without spraying and the use of pulsating ventilation was on average 1,828 seconds (30.5 minutes). During this time, dust in the production environment was in the air of the work area and caused harm not only to the equipment, but also to the personnel of the enterprise.

The results of 10 experiments on the deposition of a dust-water aerosol using two nozzles were also presented in the form of graphs of the dynamics of changes in the average concentration values from the time of aerosol deposition (Fig. 4, 5).

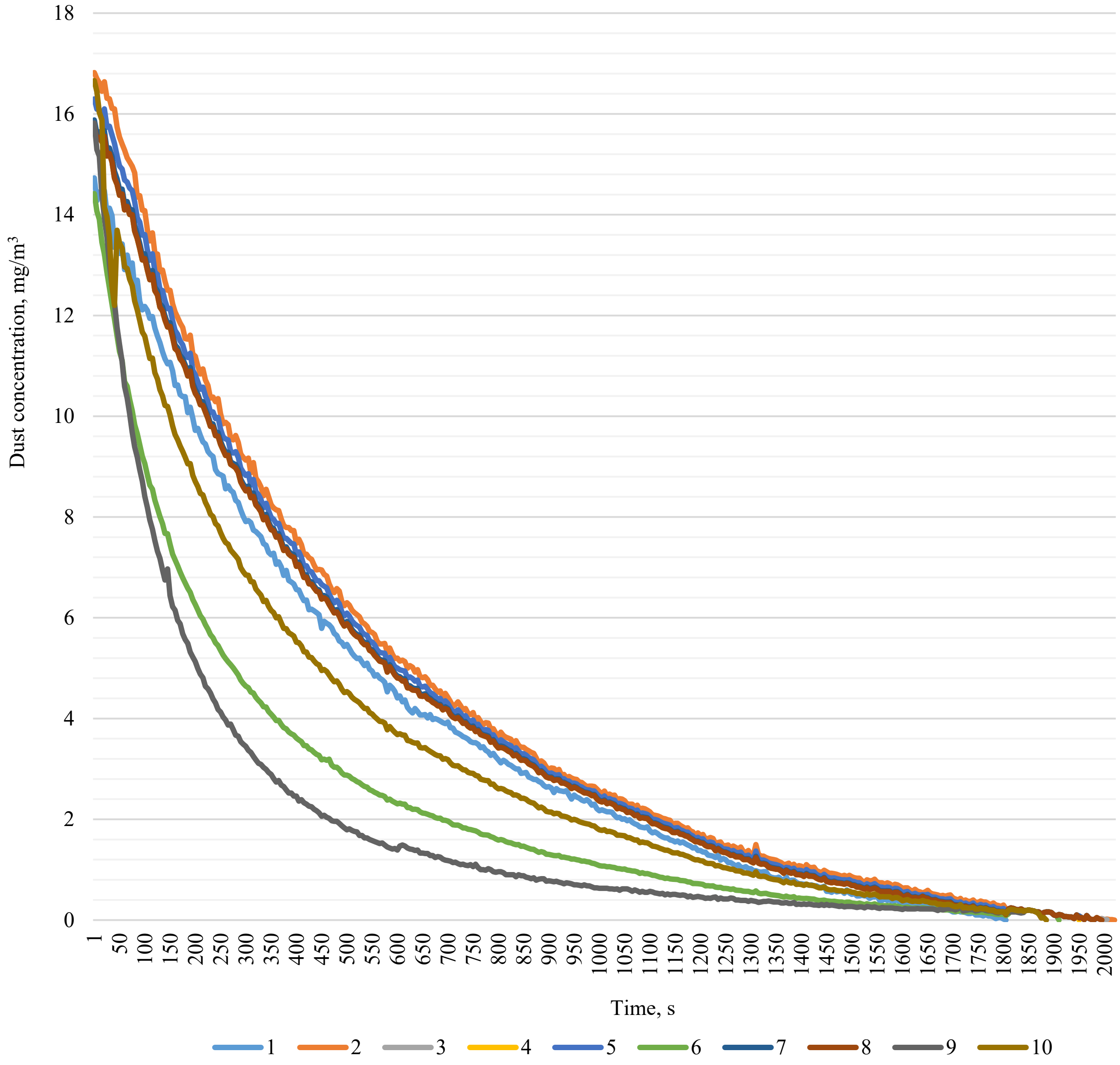

Fig. 3. Graphs of changes in dust concentration over time based on the results of 10 experiments

According to the graphs shown in Figure 4, the average deposition time of a dust-water aerosol when using nozzles with a diameter of 10 microns was 1115 s (18.5 min). The efficiency of this method, relative to the time of self-deposition of dust, was about 40%. However, according to Figure 5, when using a nozzle with a diameter of 15 microns, the average deposition time of a dust-water aerosol was 475 s (≈ 8 min.). The effectiveness of this method was 74%.

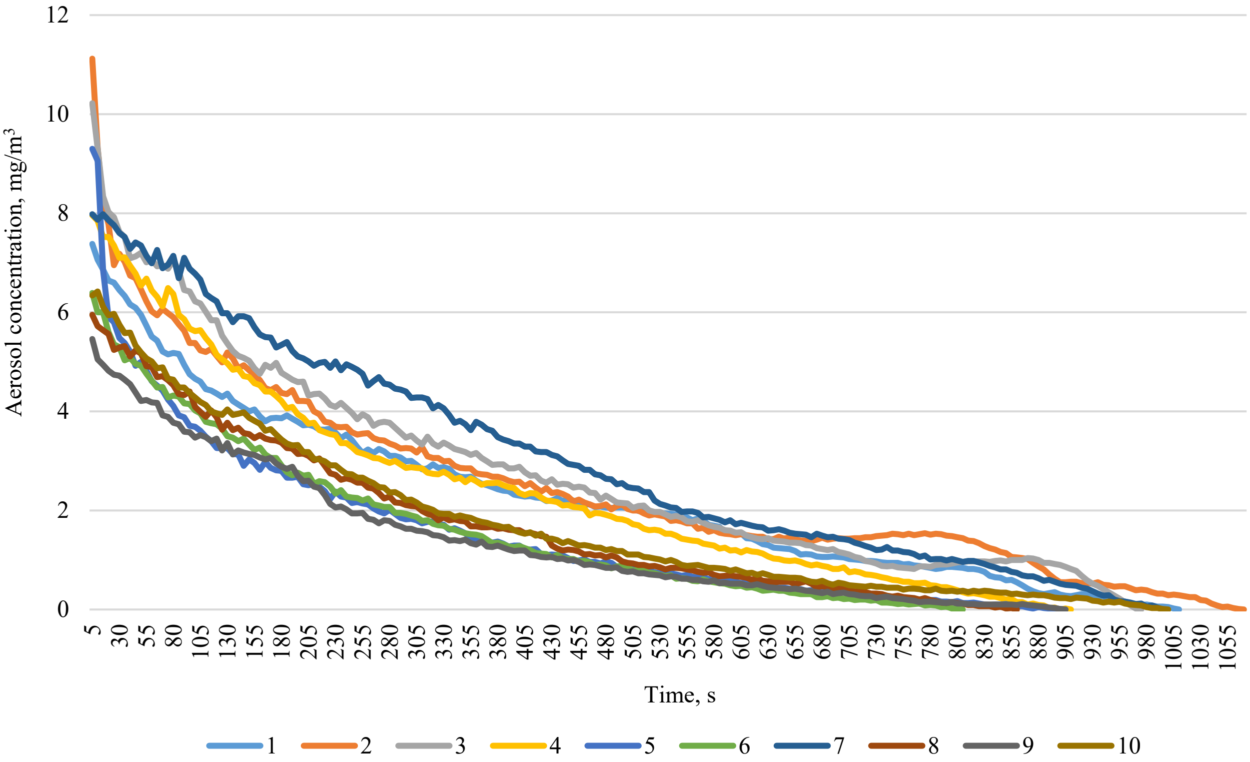

Fig. 4. Graphs of changes in the concentration of the dust-water aerosol over time
(nozzle dimeter 10 microns)

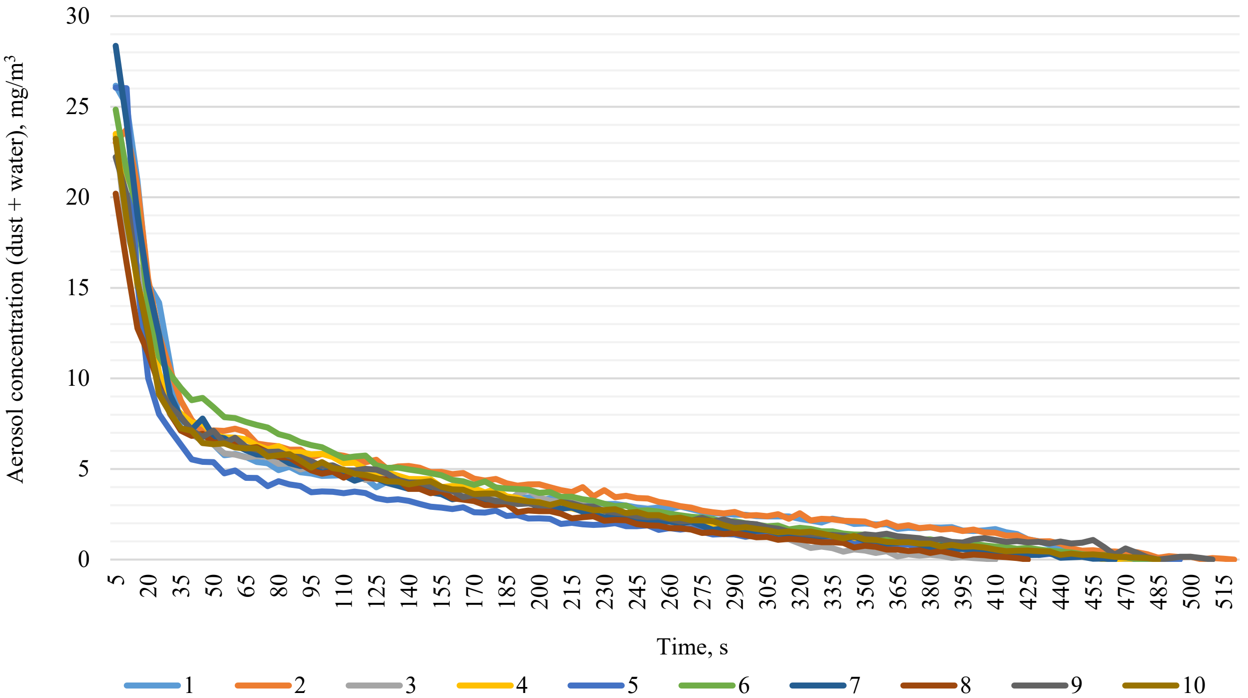

Fig. 5. Graphs of changes in the concentration of the dust-water aerosol over time
(nozzle dimeter 15 microns)

Figure 6 shows the recalculated dependences of aerosol concentrations obtained as a result of spraying experiments using nozzles with a diameter of 10 microns and 15 microns. During the experiments, different dust concentrations were detected, which were recorded by the device. For ease of presentation, these concentrations were recalculated and expressed as a percentage depending on the deposition time.

When comparing the previously determined values of the efficiency of dust deposition using nozzles of 10 and 15 microns, the latter gave a significant effect. With the use of a 15 micron nozzle, the dust deposition efficiency was about two times higher than with a 10 micron nozzle. When using a 15 micron nozzle, dust particles exhibited low tendency to stick together and formed large liquid droplets less effectively, which reduced the effect of "condensate" during spraying. Fine droplets filled the dusty air environment better and could be used in those places of technological production where large droplets could cause damage.

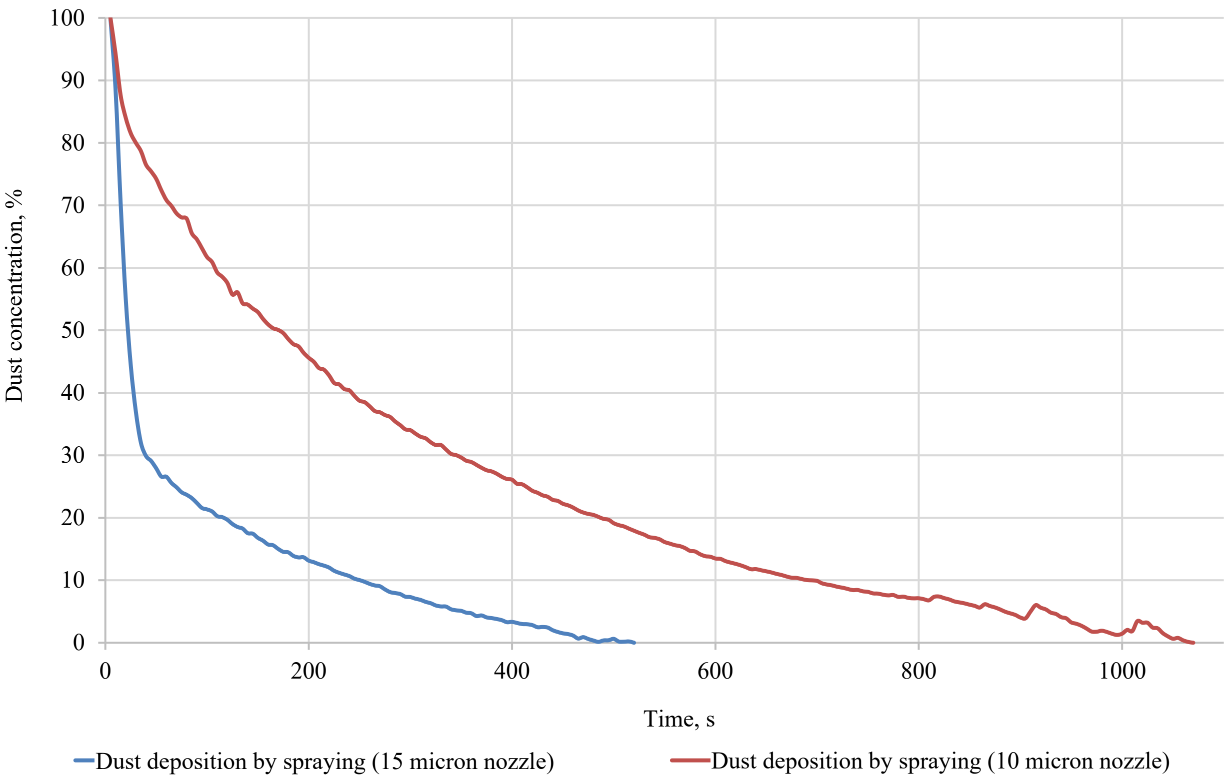

Fig. 6. Graph of changes in dust concentrations (%) over time under the conditions of dust deposition by spraying when using nozzles with dimeters of 15 microns and 10 microns

Discussion and Conclusion. As a result of the conducted experiments on dust deposition in the laboratory setup, the time of dust deposition was determined under two different scenarios: during the natural deposition of dust and during the deposition of a dust-water aerosol (by exposure to a liquid aerosol using nozzles with diameters of 10 and 15 microns).

In the future, to develop a technique for dust deposition, it is necessary to use the following parameters as rational:

– humidity of air inside the laboratory — φ = 25–30%;

– air temperature in the laboratory setup — T = 22–25°C;

– air velocity generated by the airflow generator should be at the level of V = 4 m/s.

The following technical parameters of the spraying system should also be used:

– it is recommended to use nozzles with diameters of 10 microns and 15 microns to disperse the liquid;

– working pressure in the liquid supply system — p = 5.4 MPa;

– spraying time of the liquid aerosol — 2 min.

The results obtained show different values of the efficiency of dust deposition using nozzles that generate different droplet diameters used in the spraying process. The nozzles described in the article demonstrate a significant improvement in the process of dust deposition by spraying when using nozzles of 10 and 15 microns, rather than when using nozzles generating droplets larger than 15 microns in the spraying process [7]. In addition, reducing the amount of moisture in the air of the production workshops will have less negative impact on the equipment.

The analysis of the data obtained confirmed the higher efficiency of dust deposition process when using the Dry Fog technology during the unloading of the PPIOC at the mixing stage. The results obtained provide a basis for further evaluation of the effectiveness of dust deposition process using the pulsating ventilation method. Based on the work of other authors who use this technology [7], an additional increase in deposition efficiency values by 20–25% is predicted, relative to the use of the Dry Fog technology. The results obtained in this work will be used in further development of a technique for dust deposition of iron ore concentrate products using the pulsating ventilation method.

The obtained values of the efficiency indicators of the Dry Fog technology give reason to recommend it for implementation in production for dust deposition in mining and metallurgical production sites with a high dust load.

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Received 10.11.2023
Revised 05.12.2023
Accepted 12.12.2023

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SV Tertychnaya: processing of literary sources, providing a scientific base, forming research conclusions, editing the text and graphs of the manuscript.

Conflict of interest statement: the authors do not have any conflict of interest.

All authors have read and approved the final manuscript.

Поступила в редакцию 10.11.2023
Поступила после рецензирования 05.12.2023
Принята к публикации 12.12.2023

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Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

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UDC 331.453
https://doi.org/10.23947/2541-9129-2024-8-1-50-57

Original article

Ensuring Safe Working Conditions under the Influence of Vibroacoustic Factors on Train Crew Workers

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Abstract
Introduction. The increased intensity of noise and vibration of railway traffic may become not only an urgent problem in the field of occupational safety, but also a serious environmental problem in the near future due to the constant need to increase the weight of freight trains, the speed of passenger trains and the capacity of railway lines. Recently, a lot has been done to minimize the negative effects of noise and vibration in railway transport. However, the problem of exceeding the indicators of vibration noise factors remains relevant. Reducing the harmful effects helps to improve the working conditions of train crew employees and improve the comfortable conditions of transport passengers. As a rule, the main focus of the analysis is on the external impact of vibroacoustic factors on residential areas and less attention is paid to the impact on rolling stock. However, these studies do not provide a complete picture of how noise and vibration actually affect the train in motion. The aim of the study was to obtain the result of an analysis of the impact of vibroacoustic factors on train crew workers and to propose a method of comprehensive protection based on the use of vibration damping materials.
Materials and Methods. In the course of the work, regulatory documents were studied, a comprehensive analysis of relevant information on this topic was carried out, and methods for calculating vibration and vibration acceleration were used. The values of the sound pressure levels were obtained using a SPM-101 sound level meter. The object of the study was a carriage of the "reserved seat" type in the process of movement. As part of the research plan, sound pressure was measured at selected sites and a class of working conditions was determined.
Results. The result of the analysis of the impact of vibroacoustic factors on train crew workers indicated the need to strengthen comprehensive measures to protect them. The obtained calculation of the vibration force became the basis of the method proposed by the authors to minimize the harmful effects of vibroacoustic factors, which was based on the use of vibration and sound insulation materials suitable for the necessary acoustic parameters in the construction of the car. In particular, it was proposed to cover the floor of the car with dense rubber and the ceiling of the car with an inorganic fiber material for sound insulation. The work also provides an economic assessment of the effectiveness of measures to minimize harmful vibration noise effects.
Discussion and Conclusion. The proposed methods for minimizing noise and vibration impacts can help reduce the level of sound pressure and vibration indicators to standard values, which will significantly reduce the negative impact of vibroacoustic factors on train crew workers and railway passengers. The considered complex for minimizing vibration and noise includes a set of methods in which affordable materials based on recycled substances have found application.

Keywords: sound pressure, vibration, noise pollution, sound insulation

Acknowledgements. The authors would like to thank Professor, Doctor of Engineering Science Vyacheslav Yakovlevich Manokhin for his mentoring.

For citation. Sokolov DA, Golovina EI. Ensuring Safe Working Conditions under the Influence of Vibroacoustic Factors on Train Crew Workers. *Safety of Technogenic and Natural Systems.* 2024;8(1):50–57. https://doi.org/10.23947/2541-9129-2024-8-1-50-57

Научная статья

Обеспечение безопасных условий труда при воздействии на работников поездных бригад виброакустических факторов

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Аннотация
Введение. Повышенная интенсивность шума и вибрации на железнодорожном транспорте может стать не только актуальной проблемой в области охраны труда, но и серьезной экологической проблемой в ближайшем будущем из-за необходимости постоянного увеличения веса грузовых поездов, повышения скорости движения пассажирских поездов и возрастания пропускной способности железнодорожных линий. В последнее время немало сделано для минимизации негативного воздействия шума и вибрации на железнодорожном транспорте. Однако проблема превышения показателей виброшумовых факторов остается актуальной. Уменьшение вредного воздействия шума и вибрации способствует улучшению условий труда работников поездных бригад и повышению комфортных условий для пассажиров. Как правило, основное внимание при анализе воздействия виброакустических факторов уделяется внешнему их воздействию на селитебную территорию и меньше — воздействию на подвижной состав. К тому же такие исследования не являются комплексными, так как не дают полного представления о воздействии шума и вибрации непосредственно на состав в движении. Цель данного исследования — анализ воздействия виброакустических факторов на работников поездных бригад и пассажиров для разработки метода их комплексной защиты, основанного на применении виброгасящих материалов.

Материалы и методы. В ходе работе были изучены нормативные документы, проведен комплексный анализ актуальной информации по данной теме, использованы методики по расчету вибрации и виброускорения. Значения уровней звукового давления были получены с помощью шумомера SPM-101. Объектом исследования был выбран вагон типа «плацкарт» во время движения. В рамках исследования было измерено звуковое давление на выбранных участках дороги и определен класс условий труда.

Результаты исследований. Результат анализа воздействия виброакустических факторов на работников поездных бригад свидетельствует в необходимости усиления комплексных мер их защиты. Полученный расчет силы вибрации стал основой предложенного авторами метода минимизации вредного воздействия виброакустических факторов, в основе которого использование в конструкции вагона вибро- и звукоизолирующих материалов, подходящих по необходимым акустическим параметрам. В частности, предложено с целью шумоизоляции на пол вагона уложить плотную резину, а на потолок — материал из неорганического волокна. В работе также дана экономическая оценка эффективности мероприятий по минимизации вредного виброшумового воздействия.

Обсуждение и заключение. Предложенные методы минимизации шумового и вибрационного воздействия могут способствовать снижению уровня звукового давления и показателей вибрации до нормативных значений, что сократит негативное воздействие виброакустических факторов на работников поездной бригады и пассажиров. Рассмотренный комплекс по минимизации вибрации и шума включает в себя совокупность методов, в которых нашли применение бюджетные материалы, созданные на основе вторично переработанного сырья.

Ключевые слова: звуковое давление, вибрация, шумовое загрязнение, шумоизоляция

Благодарности. Авторы благодарят профессора, доктора технических наук Вячеслава Яковлевича Манохина за наставничество.

Для цитирования. Соколов Д.А., Головина Е.И. Обеспечение безопасных условий труда при воздействии на работников поездных бригад виброакустических факторов. *Безопасность техногенных и природных систем.* 2024;8(1):50–57. https://doi.org/10.23947/2541-9129-2024-8-1-50-57

Introduction. Rail transport has always created and continues to create noise and vibration, which, in most cases, cannot be fully eliminated and are likely to have a negative impact on the environment, despite the use of various mitigation measures. The problem of reducing the impact of noise and vibration of railway transport on people and the impact on engineering structures is very difficult due to the large number of parameters and factors of distribution of noise and vibration energy. The negative impact of vibroacoustic factors is growing every year due to an increase in the number and weight of freight cars, their high wear and tear, untimely maintenance of passenger cars, as well as the lack of free space in urban areas, as a result of which new business and residential facilities are located in close proximity to the railway. The problem of noise and vibration from railway transport is especially acute in large cities with large railway connections, mainly due to short distances from the railway tracks to the nearest buildings. This fact limits the possibilities for taking measures to reduce noise and vibration. To date, the primary task is to protect against excess sound pressure using the "external noise source — environment" system. The system implies the impact of noise on nearby infrastructure facilities, residential areas, and nature. Protection against such impacts is achieved by installing acoustic screens. With their help, it is possible to significantly reduce the sound pressure.

The problem of complex protection against vibroacoustic effects is still poorly studied. It is also worth noting the lack of vibration damping devices that would be able to reduce the combined effects of noise and vibration. According to the authors, the scientific novelty of this study lies precisely in the fact that an integrated approach to solving the problem of minimizing the impact of vibroacoustic factors is considered and simple noise-absorbing materials for their mass installation are proposed.

Vibration from rail transport can have negative effects directly or in combination with background noise. A significant excess of noise level standards causes discomfort not only to employees and passengers, but also to residents of areas adjacent to the railway track, and is often a significant cause of deterioration in well-being and decreased performance. The specificity of noise pollution in railway transport is such that, with long-term exposure in combination with vibration, it has a very negative effect on railway transport workers [1]. Prolonged and systematic exposure to excessive noise pressure can lead to the development of chronic diseases of the nervous system, musculoskeletal system, be the cause of loss of vigilance, deterioration of well-being, discomfort, feelings of irritation [2]. Constant exposure to noise, even at nominal values (especially at night), can cause sleep disorders and chronic neuroses [3]. The number of people with sleep disorders is very large — most are exposed to constant noise of 50-60 dB at night, which, in the absence of other daytime noise sources, is one of the main factors of insomnia [4].

Of all the harmful environmental factors, vibration is one of the most widespread ones. From 50 to 70% of the population is under its influence [5]. The analysis of vibrations resulting from the movement of rolling stock is very important, since the railway is the main transport system covering most of the territory of our country and neighboring countries. The volume and quantity of goods transported by rail are growing every year [6].

Working vibration of the rails occurs at the junction of the wheel and the rail (wheel — rail system) and spreads not only through the track support system to the ground cover and surrounding buildings, but also directly to the rolling stock. In some cases, passengers can directly feel the vibration, which is usually referred to as vibration from the interaction of the rolling stock and the railroad bed. Ground vibrations caused by railway traffic mainly occur in the contact area between the wheel and the rail [7]. Therefore, it is important that the effect of this mechanism of occurrence of a negative factor is minimized. The main source of vibration on the railway is rolling vibration caused by an imperfect working surface of the wheel and defects on the working surface of the rail. These vibrations are transmitted to the wheel and track structures, which leads to the occurrence of the values exceeding the threshold for the main octave levels. As a result, vibration, transmitted through the wheelsets, the car truck, causes vibration of the car body, which is especially noticeable at high train speed. High-amplitude vibrations can lead to a critical condition of car components, damage to the structure of the rail rolling stock. In order to preserve equipment, vibrations of this kind should be reduced not only in the wheel — rail system, but also by directly taking measures to protect the main parts of the car. This, in turn, minimizes the appearance of secondary vibration from the car body. To minimize the mechanical impact of the wheel and rail, the surface of the rail should be as smooth as possible. The vibrations created by the construction of the car and car truck should also be minimized in order to reduce the amount of vibrations transmitted to people in the car [8]. In order to create a system with the desired acoustic and structural-dynamic properties, while minimizing human exposure to noise and vibration, it is necessary to take into account the design of the track, wheels, trucks, and cars. Another important aspect is to ensure that these parts are maintained appropriately (timely maintenance and scheduled repairs).

Current vibration reduction methods are generally divided into two main categories: the category of passive measures and the category of active measures. Currently, passive measures are most often used. These include the use of traditional vibration dampers, shock absorption systems of various kinds (collision of cars) and insulation of the base [5]. However, modern vibration reduction methods should be aimed at passive-active vibration control, which consists in the active application of a force equal to the opposite forces created by external vibration. Sometimes, to dampen the vibrations, it is proposed to use developed control systems and damping forces that create vibration, as well as structures created on the basis of new composite materials. In particular, piezoelectric elements can be used to dampen excessive vibration[1]. The essence of this method is that a piezoelectric element generates electrical energy under mechanical tension and reacts in the form of deformation if electric energy is applied to it. Another method of minimizing noise and vibration is the method of using disc brakes instead of cast iron pads. The replacement of cast-iron blocks with agglomeration or composite ones is an alternative to disc brakes, which are more difficult to adapt, install and are expensive. All the methods mentioned above are aimed at the main components of the car. The authors carried out a calculation of vibration insulation in the car itself in the passenger seats.

Materials and Methods. A "reserved seat" type car was considered as the research material. The measurements were carried out using a sound pressure measuring device — SPM-101 sound level meter. The areas with the most negative impact of the vibroacoustic factor were selected based on the design features of the car truck and the internal structure of the car space. Consequently, the research plan included measuring the sound pressure in the car and determining the class of working conditions.

To analyze the possibility of noise reduction in the source of a "reserved seat" type car, the scheme of the car was considered and the areas of the most negative impact of vibroacoustic factors were marked on it (Fig. 1). These sections implied the highest sound pressure levels in the car, and as a result, a critical negative impact from vibroacoustic effects under various conditions (speed, state of the railway track, etc.)

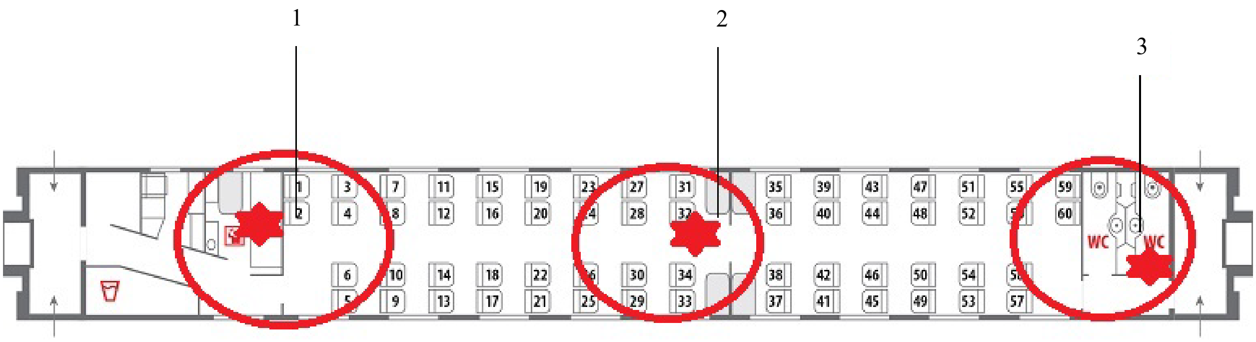

Fig. 1. Sound pressure values in the car by sections (1, 2, 3)

The next method of studying the minimization of vibration effects was the calculation of vibration insulation of passenger seats in the car based on methodology[2]. Vibration-proof inserts made of rubber material were used. The floor of the car at the base of the seat vibrated with frequency $f = 50$ Hz, with vibration velocity $v = 0.4$ m/s and a seat weight of 22 kg. Let us assume a passenger weighs 70 kg. Modulus of elasticity: $\sigma_{доп} = 0.04$ MPa, $E = 2.5$ MPa, $h = 0.1$ m, coefficient of resistance $\xi = 600$ H·s/m.

Let us determine the mass of inserts when the passenger is sitting. The passenger's weight per seat is 70%, which means:

$$m_{ч} = 70 \cdot 0.7 = 49 \text{ kg}, \tag{1}$$

$$m_{об} = 49 + 22 = 71 \text{ kg}. \tag{2}$$

Let us determine the maximum static deflection of the inserts:

$$Z = h\frac{\sigma_{доп}}{E_{д}} = 0.1 \cdot \frac{4}{250} = 16 \cdot 10^{-4}. \tag{3}$$

Frequency response of natural vibrations of an amortized passenger seat will be:

$$\omega = 2\pi\frac{0,5}{\sqrt{Z}} = 2 \cdot 3.14 \cdot \frac{0.5}{16 \cdot 10^{-4}} = 79 \text{ s}^{-1}. \tag{4}$$

Vibration transmission coefficient is determined by formula:

[1] Snizhenie urovnya shuma v krivykh. *Zheleznye dorogi mira.* 2009;6:70–76. URL: https://zdmira.com/images/pdf/dm2009-06_70-76.pdf (accessed: 14.11.2023). (In Russ.).

[2] *Posobie po akusticheskoi vibroizolyatsii tsentrobezhnykh mashin.* Moscow: Izdatel'stvo literatury po stroitel'stvu; 1973. 35 p. URL: https://meganorm.ru/Data2/1/4293801/4293801338.pdf (accessed: 14.11.2023). (In Russ.).

$$T_z = \frac{1+\left(2D\dfrac{\omega}{\omega_0}\right)^2}{\left[1-\left(\dfrac{\omega}{\omega_0}\right)^2\right]^2+\left(2D\dfrac{\omega}{\omega_0}\right)^2}. \tag{5}$$

Let us find relative damping D and circular frequency ω:

$$D = \frac{\xi}{2\omega_0 \cdot m_{об}} = \frac{600}{2\cdot 79\cdot 71} = 0.05. \tag{6}$$

$$\omega = 2\pi f = 2\cdot 3.14\cdot 50 = 314\ \text{s}^{-1};\ \frac{\omega}{\omega_0} = \frac{314}{79} = 4. \tag{7}$$

We get:

$$T_Z = \sqrt{\frac{1+(2\cdot 0.05\cdot 4)^2}{\left[1-(4)^2\right]^2+(2\cdot 0.05\cdot 4)^2}} = 0.071. \tag{8}$$

Then we determine the vibration velocity on the seat:

$$v = 0.4\cdot 0.071 = 0.028\ \text{m/s}. \tag{9}$$

Frequency of oscillation of the seat will be:

$$f_0 = \frac{\omega_0}{2\pi} = \frac{79}{2\cdot 3.14} = 12.57\ \text{Hz}. \tag{10}$$

Results. According to GOST 33787-2019, for a frequency of 12.57 Hz, vibration velocity should not exceed 0.0056 m/s[3]. The indicator obtained as a result of the calculation did not meet this requirement. To improve it, a vibration-proof material with other characteristics could be used — this could be a composite sheet made of tough rubbers (Fig. 2). Due to a higher coefficient of resistance, vibration exposure could be minimized.

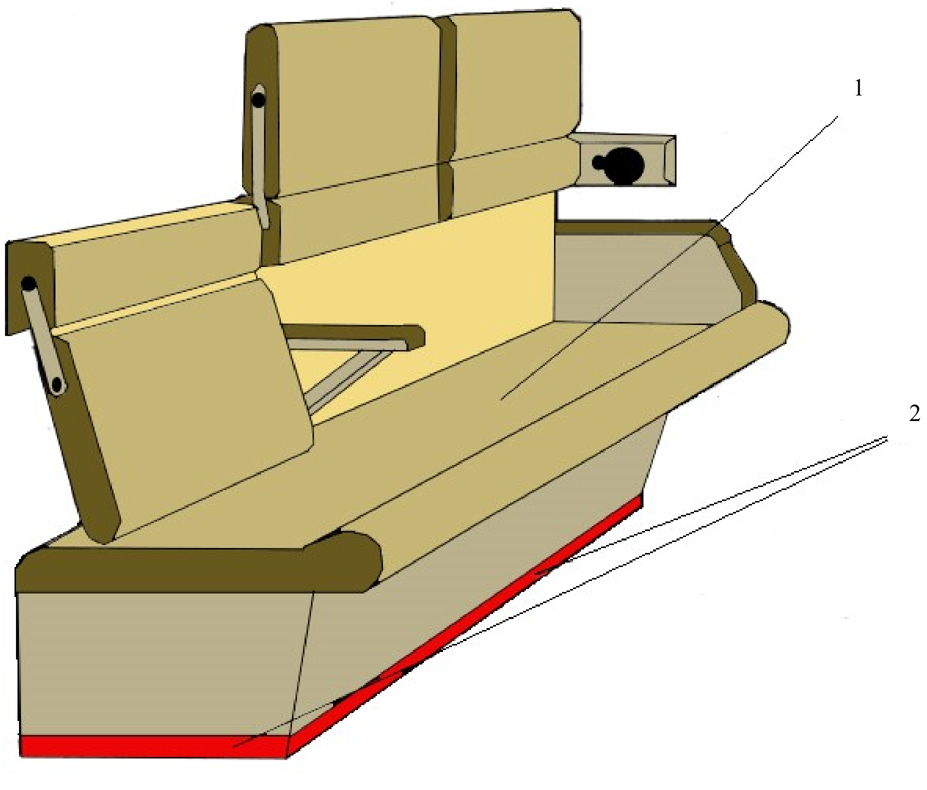

Fig. 2. Location of the vibration-proof material:
1 — passenger seat; 2 — vibration-proof insert

[3] GOST 33787-2019. *Rolling stock equipment. Shock and vibration tests*. URL: https://docs.cntd.ru/document/1200170805 (accessed: 14.12.2023). (In Russ.).

Table 1 shows the results of measuring sound pressure levels in the areas shown in Figure 1. Comparing them with the norms of the sound level in the car according to SP 2.5.3650-20, we could conclude that there was an excess of indicators[4].

Table 1

Noise pressure indicators in the car by zones

Section, no.	Sound level, dB
1	77.5
2	74.1
3	78.5

The calculations carried out in this work allowed the authors to conclude that it was necessary to use a method for minimizing vibroacoustic factors based on the use of vibration-damping materials. Its effectiveness was confirmed by the presented study. The authors have proposed a set of measures, including the installation of noise-absorbing material in the lining of the ceiling of the car in the most noise-prone areas to minimize noise pollution. The material was a composite of inorganic fibers with a sheet thickness of 2 to 4 cm. Additionally, to reduce noise and vibration, it was suggested to install inserts in the car's floor, similar to the creation of a shock-absorbing system. To calculate the effectiveness of the method, the vibration effect on the passenger seat was calculated taking into account the vibration of the floor of the car. The material was safe in operation for humans and the environment, met the fire safety criteria that were established for a passenger car in accordance with order of JSC "Russian Railways" dated November 5, 2009 No. 2255р[5].

Discussion and Conclusion. The assessment of the effects of vibration and noise obtained in this study shows that it significantly affects the working conditions of train crew workers and passengers. Workers who spend a lot of time on the road, workers who repair tracks in the immediate vicinity of the railway track, and train passengers are exposed to extremely harmful noise and vibration effects, which have a devastating effect on their health. Therefore, it is so important to minimize this harmful effect at the source of its occurrence. Undoubtedly, the improvement of the existing and the introduction of new methods to minimize the effects of noise and vibration factors on the railway will positively affect the health of employees and will contribute to the creation of a favorable social environment. It is worth emphasizing that measures to minimize the negative effects of noise and vibration from railway trains give a relatively small economic effect, but at the same time, they are of great value for ensuring the protection of the health of both employees and passengers, creating conditions that are more comfortable for them.

The complex of measures proposed by the authors to minimize vibration and noise uses materials created from recycled raw materials. Tough rubber is used for the floor of the car, and an inorganic fiber composite with a thickness of 2–4 cm is used for the ceiling. By equipping wagons with these materials, it is possible to achieve:

– minimization of noise pressure in the car by 7–12 Db;

– reduction of the vibration effect.

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Received 20.11.2023
Revised 16.12.2023
Accepted 22.12.2023

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Claimed contributorship:

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EI Golovina: academic advising, formulation of the basic concept, goals and objectives of the study.

Conflict of interest statement: the authors do not have any conflict of interest.

All authors have read and approved the final manuscript.

Поступила в редакцию 20.11.2023
Поступила после рецензирования 16.12.2023
Принята к публикации 22.12.2023

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Заявленный вклад соавторов:

Д.А. Соколов — проведение эксперимента, анализ результатов исследований, подготовка и оформление текста статьи, формирование выводов.

Е.И. Головина — научное руководство, формирование основной концепции, цели и задачи исследования.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

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UDC 622.8
https://doi.org/10.23947/2541-9129-2024-8-1-58-72

Original article

Determination of Sulfur Content in Mineral Mass for Prediction of Hazardous Properties of Coal Mine Seams

EDN: WUYPWO

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Abstract

Introduction. Sulfur is found in the organic and mineral parts of all types of solid fuels, and its concentration determines the extent of the hazardous characteristics of mine seams. Therefore, research on the determination of sulfur content in fossil fuels has not lost its relevance. The total sulfur content and its varieties has been studied in most cases in terms of the efficiency of fuel processing processes, the quality and environmental safety of coal products. Less attention was paid to the hazardous properties of mine seams, forecasting and developing preventive measures for endogenous fires in coal mines. This work aims to develop an engineering method to calculate the elemental sulfur content in the mineral mass of coal to predict the hazardous properties of mine seams.

Materials and Methods. According to the results of the correlation analysis, we established how the sulfur content in the combustible part of the fuel depended on the total sulfur. We analyzed data on coals from almost all mine seams of the Donetsk and Lviv-Volyn coal basins. We presented the ash ratios for the formation and basin samples, as well as the information about the total sulfur and sulfur content in the combustible part. This allowed us to estimate the sulfur content in mineral impurities by calculation. The initial data for developing the method were taken from reference and regulatory documents.

Results. Seven aggregates were considered, which included from 149 to 1827 mine seams. For each, reference and calculation data were summarized:

- sulfur content — total (S_t^d) and in the combustible part of the fuel ($S_г$);
- conditional points for adjusting the indicators to avoid obtaining negative average values;
- empirical equations that describe the calculated and corrected dependencies based on the ratio of S_t^d and $S_г$;
- correlation of these indicators;
- ranges of change in ash yield.

All this information was presented for clean and raw coals, for ash yields of more and less than 10%. In one case, satisfactory results were noted for determining the calculated sulfur content in a conditionally non-combustible mass. This was an aggregate of 149 mine layers. For 13 of them, the difference in indicators ($S_t^d - S_г$) was greater than or equal to zero. For 136 — less than zero. For 81, the sulfur content in the conditionally non-combustible part of the fuel $S_н$ was less than zero. At the same time, there was a sufficient level of correlation (0.79) and a limited range of changes in ash yield (2.4–10). The empirical equation corresponding to this aggregate was recommended for predicting the hazardous properties of mine seams with an ash yield of less than 10%.

Discussion and Conclusion. The results of this study can be used to improve regulations for the safe conduct of mining activities, taking into account sulfur content in organic matter and in mineral impurities of fossil coal.

Keywords: sulfur in fossil coal, engineering method for determining sulfur in the mineral mass of coal, prevention of endogenous fires in coal mines

Acknowledgements. The authors would like to thank the Editorial board and the reviewer for their professional analysis and recommendations for correcting the article.

For citation. Pronskaya NV, Filatieva EN, Filatiev MV, Shashlo NV. Determination of Sulfur Content in Mineral Mass for Prediction of Hazardous Properties of Coal Mine Seams. *Safety of Technogenic and Natural Systems.* 2024;8(1):58–72. https://doi.org/10.23947/2541-9129-2024-8-1-58-72

Научная статья

Определение содержания серы в минеральной массе для прогноза опасных свойств угольных шахтопластов

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Аннотация

Введение. Сера присутствует в органической и минеральной части всех видов твердого топлива, причем от ее содержания зависит проявление опасных свойств шахтопластов. В связи с этим не теряют актуальность научные изыскания, связанные с определением количества серы в ископаемом топливе. Содержание общей серы и ее разновидностей изучалось в большинстве случаев с позиций эффективности процессов переработки топлива, качества и экологической безопасности угольной продукции. Меньше внимания уделяли проявлению опасных свойств шахтопластов, прогнозированию и разработке профилактических мероприятий по предотвращению эндогенных пожаров в угольных шахтах. Цель представленной работы — создание инженерного метода расчетного определения элементного содержания серы в минеральной массе углей для прогноза опасных свойств шахтопластов.

Материалы и методы. По результатам корреляционного анализа установили, каким образом содержание серы в горючей части топлива зависит от общей серы. Рассмотрели данные по углям практически всех шахтопластов Донецкого и Львовско-Волынского бассейнов. Представили соотношения зольности пластовых и обогащенных проб, а также сведения о содержании общей серы и серы в горючей части. Это позволило расчетным путем оценить содержание серы в минеральных примесях. Исходные данные для разработки метода взяли из справочно-нормативных документов.

Результаты исследования. Рассмотрены семь совокупностей, которые включали от 149 до 1827 шахтопластов. По каждой обобщили справочные и расчетные данные:

– содержание серы — общей (S_t^d) и в горючей части топлива ($S_г$);

– условные точки для корректировки показателей во избежание получения отрицательных усредненных значений;

– эмпирические уравнения, которые описывают расчетные и скорректированные зависимости по соотношению S_t^d и $S_г$;

– корреляцию этих показателей;

– диапазоны изменения выхода золы.

Все эти сведения представлены для обогащенных и не обогащенных углей, для выхода золы более и менее 10 %. В одном случае отмечены удовлетворительные результаты определения расчетного содержания серы в условно негорючей массе. Это совокупность из 149 шахтопластов. Для 13 из них разность показателей ($S_t^d – S_г$) больше или равна нулю. Для 136 — меньше нуля. Для 81 содержание серы в условно негорючей части топлива $S_н$ меньше нуля. При этом отмечается достаточный уровень корреляции (0,79) и ограниченный диапазон изменения выхода золы (2,4–10). Соответствующее этой совокупности эмпирическое уравнение рекомендуется для прогноза опасных свойств шахтопластов с выходом золы менее 10 %.

Обсуждение и заключение. Полученные результаты можно использовать для совершенствования нормативных документов по безопасному ведению горных работ с учетом содержания серы, как в органической массе, так и в минеральных примесях ископаемого угля.

Ключевые слова: сера в ископаемом угле, инженерный метод определения серы в минеральной массе угля, предотвращение эндогенных пожаров в угольных шахтах

Благодарности. Авторы выражают благодарность редакционной коллегии журнала и рецензенту за профессиональный анализ и рекомендации по корректировке статьи.

Для цитирования. Пронская Н.В., Филатьева Э.Н., Филатьев М.В., Шашло Н.В. Определение содержания серы в минеральной массе для прогноза опасных свойств угольных шахтопластов. *Безопасность техногенных и природных систем.* 2024;8(1):58–72. https://doi.org/10.23947/2541-9129-2024-8-1-58-72

Introduction. Sulfur is an element of compounds found in the organic and mineral parts of various fuels. In the mineral mass of coals, sulfur is found as a rule in the form of sulfates (mainly calcium and iron) and iron disulfides FeS_2 (pyrite and marcasite). In the organic mass, sulfur is found in the form of organic compounds.

There are several basic forms of sulfur in coals. These are parts of the total sulfur:

- sulfate S_{SO_4} — is a part of the inorganic mass of coal in the form of metal sulfates;
- pyrite S_p — is a part of the inorganic mass of coal in the form of metal disulfides (pyrite and marcasite);
- organic S_o — is a part of organic compounds.

Total sulfur and its varieties, unlike ash sulfur, are conditionally converted to elemental sulfur [1]:

$$S_t = S_{SO_4} + S_p + S_o . \quad (1)$$

Sulfur content in ash is usually calculated in the form of sulfur trioxide (SO_3). Sulfur is an undesirable and harmful part of fuel. When burning coal, sulfur is released as SO_2. It pollutes the environment, causes corrosion of metal surfaces, and reduces the heat of combustion of fuel. During coking, sulfur turns into coke, deteriorating its properties and the quality of the metal. For these reasons, the content of total sulfur and its varieties has been studied in most cases from the standpoint of the efficiency of fuel processing processes, the quality and environmental safety of coal products. Good results have been obtained in this direction, which is confirmed by the development and successful use of modern industrial classification of coals according to genetic and technological parameters. To a large extent, it is based on data from reference books, in which, based on the results of experiments, information was summarized on the quality of hard coals and anthracites [2], as well as on their processing [3].

The successes in forecasting and developing preventive measures to prevent endogenous fires during work in coal mines are less significant. Thus, for twenty years (from 1994 to 2015), more than two hundred endogenous fires occurred in the mines of Ukraine [4]. According to open data, similar accidents occur in many coal-mining countries. Thus, the problem that has been relevant since the 19th century has not been solved. At first, it was associated with spontaneous combustion of coal in warehouses and during transportation. Then accidents began to occur in coal mines caused by endogenous fires [5].

Sulfur content in coal not only determines its consumer qualities, but also significantly affects the manifestation of hazardous properties of coal seams during mining operations [6]. In particular, with an increase in the total sulfur content in coal by 1–6%, the probability of endogenous fire increases by more than three times [7]. There have been attempts to figure out how dangerous properties of mine seams can be identified by mineral impurities [8]. However, even now it is almost unknown how the studied risks depend on the type and form of sulfur in fossil coal. As a result, in regulatory documents[1, 2] the probability of endogenous fires in coal seams was determined only by the content of total sulfur[3].

Studies [5] have shown that spontaneous combustion is largely due to the nature of not only coal, but also the associated rocks[4]. It is extremely important to establish the component of the fuel, on which the probability of spontaneous combustion depends. Without this, laboratory research methods do not provide acceptable answers to the questions posed. Along with laboratory studies of coal matter, it was assumed to take into account the presence of carbonaceous rock from mineral interlayers, as well as from cover and soil rocks in fossil fuels. To do this, it is necessary to additionally consider the ash yield and the content of all types of sulfur [5].

Guidelines for the prevention and extinguishing of endogenous fires[5], as well as other regulatory documents on safe conduct of mining operations, do not take into account the presence of mineral impurities. These issues are not addressed in dust control measures in coal mines, predictions of gas emissions[6] and sudden emissions[7] or in general, in regulatory documents governing mining activities.

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[3] *Rukovodstvo po preduprezhdeniyu i tusheniyu endogennykh pozharov na ugol'nykh shakhtakh Ukrainy.* KD 12.01.402-2000. Donetsk: NIIGD; 2000. 216 p. (In Russ.).

[4] GOST 25543-2013. *Brown coals, hard coals and anthracites. Classification according to genetic and technological parameters.* URL: https://files.stroyinf.ru/Data2/1/4293772/4293772639.pdf (accessed: 11.01.2023). (In Russ.).

[5] *Rukovodstvo po preduprezhdeniyu i tusheniyu endogennykh pozharov na ugol'nykh shakhtakh Ukrainy.* KD 12.01.402-2000 from 18.12.2000. Donetsk: Nauchno-issledovatel'skii institut gornospasatel'nogo dela; 2000. 216 p. (In Russ.).

[6] *Rukovodstvo po proektirovaniyu ventilyatsii ugol'nykh shakht.* Kyiv: Osnova; 1994. 311 p. (In Russ.).

[7] *Pravyla vedennya hirnychyx robit na plastax, sxyl"nyx do hazodynamichnyx yavyshh. Standart Minvuhlepromu Ukrayiny* No. SOU 10.1.00174088.011-2005. Kyiv: Ministerstvo ugol'noi promyshlennosti Ukrainy; 2005. 224 p. (In Ukr.).

Content of mineral impurities, judging by the ash yield from coal seam samples [2] and [3], can significantly exceed 40%. This undoubtedly affects the reliability of the forecast of hazardous properties of coal seams in mining operations and indicates the relevance of improving the regulatory framework. To do this, it is necessary to develop an engineering method for determining sulfur in the mineral mass of coals.

The aim of the presented work is to prove the fundamental and practically the only possibility of calculating the elemental sulfur content in the mineral mass of coals for predicting the hazardous properties of coal seams during mining operations. It should be noted that when implementing this approach, some standard indicators are used, which are recorded in the reference and regulatory documentation on the consumer qualities of fuel for each coal seam. We are referring to experimental data on sulfur content — common and in the combustible part of the fuel. Due to this information, it is possible to establish the relationship between the sulfur content in the organic mass and mineral impurities. According to ash yield, it is possible to determine the ratio between the organic mass and mineral impurities for clean coal samples. The ratio of ash content of bed and clean samples allows us to estimate sulfur content in the removed treatment products.

Materials and Methods. The research methodology is based on a close correlation ($r = 0.93$) of sulfur content in the combustible part of fuel ($S_г$) and total sulfur (S_t^d) for coals of almost all mine seams of the Donetsk and Lviv-Volyn basins (Fig. 1)

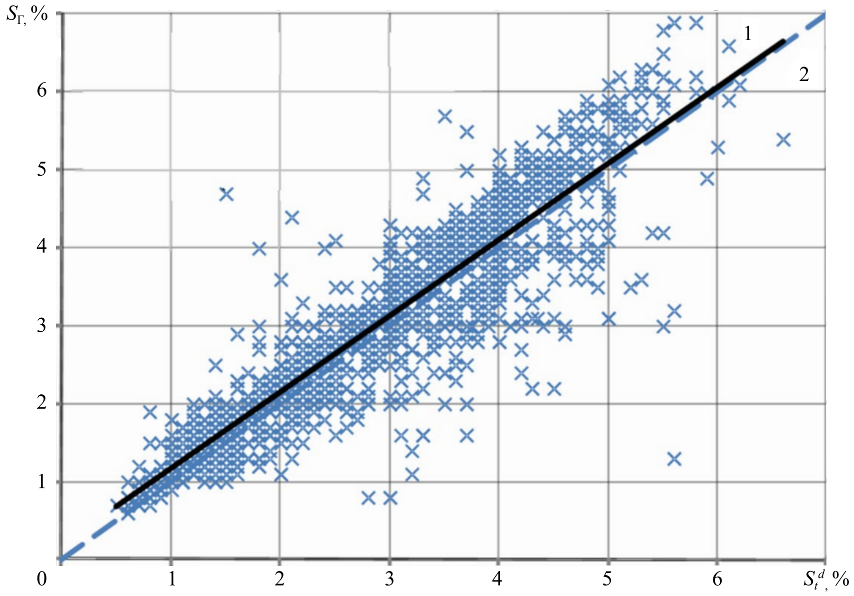


Fig. 1. Dependence of sulfur content in the combustible part of fuel ($S_г$) on total sulfur (S_t^d) according to the statistical processing of experimental data: 1 — averaging line; 2 — bisector of the coordinate grid (the authors' figure based on [2] and 3])

Statistical processing of dependence $S_г$ on S_t^d was performed for 1827 mine seams, for which the sulfur content was known — total and in the combustible part of fuel.

Reference normative document [3] provides general information on the consumer qualities of coal for 734 mine seams, and reference [2] provides it for 1379 mine seams.

The proximity of averaging line 1 and bisector 2 of the coordinate grid (Fig. 1) shows that, in general, the sulfur content in the combustible part of fuel ($S_г$) can be higher or lower than total sulfur value (S_t^d). Difference between S_t^d and $S_г$ ($S_t^d - S_г$) in the first approximation can be a criterion for the ratio of the elemental sulfur content in the combustible mass and in the conditionally non-combustible part of the fuel. Indicator ($S_t^d - S_г$) for 1315 coal seams was negative, which indicated a predominant sulfur content in the combustible part of the mass. For 429 coal seams, this indicator had positive values, which indicated the predominant presence of sulfur in the conditionally non-combustible part of the fuel. Zero difference ($S_t^d - S_г$) for 83 mine seams meant that the sulfur content in the combustible and conditionally non-combustible parts of the coals was the same for the entire aggregate of mine seams considered in the article.

Information is available for 2113 coal seams. For some of them, the data in different documents match, and this is an argument in favor of the reliability of the information. The values of ash yield from bed samples are not given for four mine seams (Table 1). For this reason, it is possible to analyze the experimental data on ash yield for 2109 mine seams. Of these, processing was carried out for 1,622 mine seams, and for 487 it was not carried out.

Table 1

Information on mine seams for which data on ash yield from bed samples is not provided

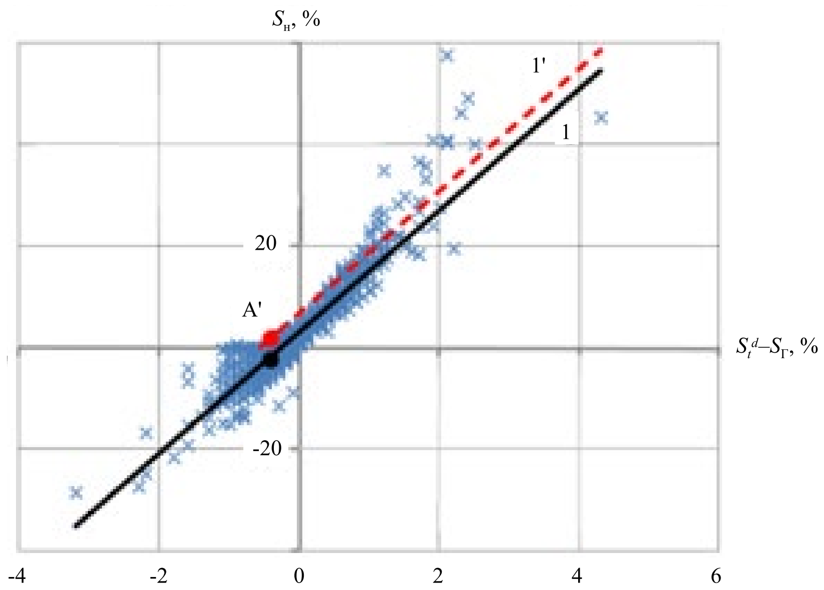
Source	Source page	Mine	Formation index	Ash content, %		Sulfur content, %	
				bed sample, $A_п^c$	clean sample, $A_о^c$	total, S_t^d	in the combustible part, $S_г$
[3]	74	№ 144	l_1	–	6.3	6.3	1.9
			k_8	–	6.1	2.8	3.0
		10-bis	m_3	–	7.0	3.2	3.5
[4]	106	named after Voykov	l_2	–	–	–	–

Results. The indicators from [2] and [3] made it possible to calculate sulfur content in the conditionally non-combustible part of fuel $S_н$ for 827 mine seams:

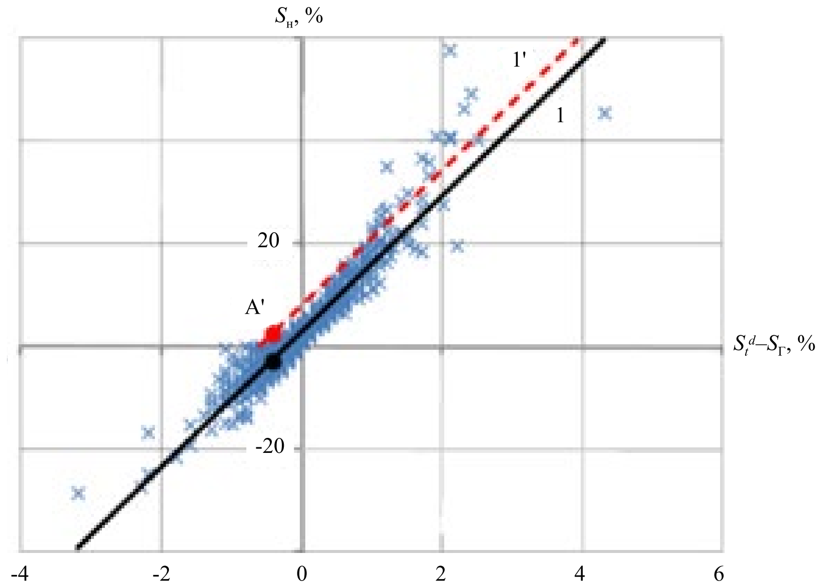
$$S_н = \frac{100 \cdot S_t^d - \left(100 - A_o^c\right) \cdot S_Г}{A_o^c}, \% \qquad (2)$$

where $A_о^c$ — ash yield from clean samples, %.

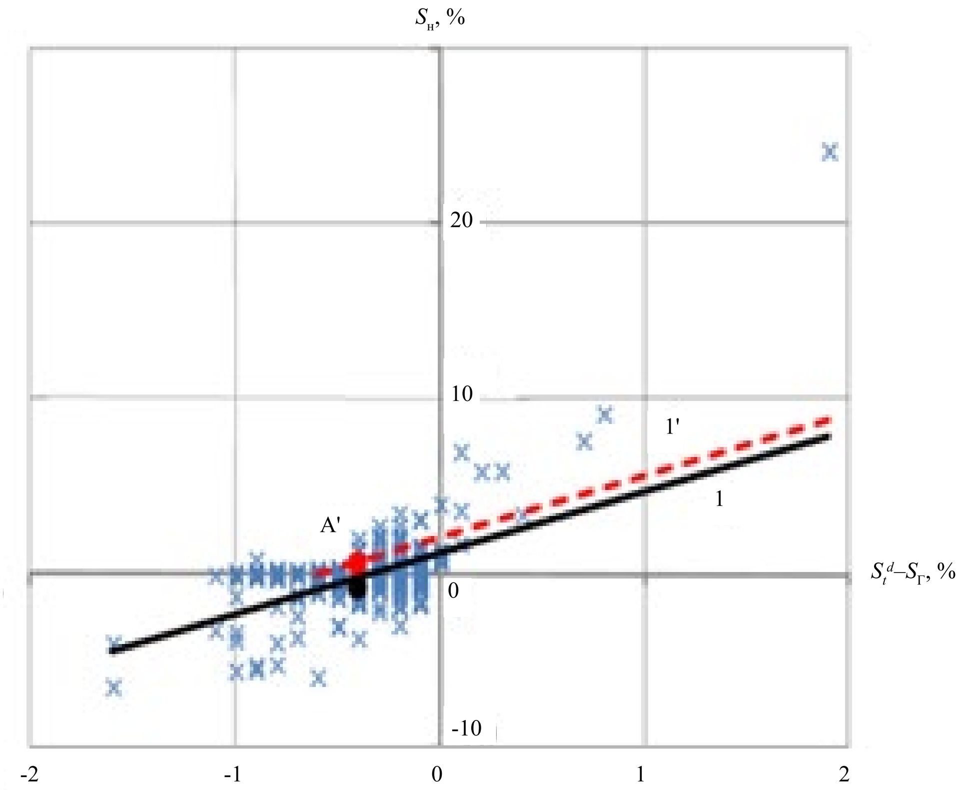
Calculated values $S_н$ were related to indicator (S_t^d–$S_г$) by a close directly proportional correlation (r = 0.91, Fig. 2 *a*).



a)



b)



c)

Fig. 2. Dependence on criterion ($S_t^d - S_г$) of calculated values of sulfur content ($S_н$) according to equation (2) in the conditionally non-combustible part of fuel: *a* — for the entire aggregate of 1827 mine seams; *b* — for 1352 mine seams, the coals of which were pre-cleaned; *c* — for 475 mine seams with raw coals; 1 — averaging lines; 1' — adjusted positions of averaging lines; A' — conditional position of a point to correct the location of line 1' and exclude negative ("wild") averaged values $S_н$; × — calculated values $S_н$ according to equation (2) [3, 4]

At the same time, we got a significant number of negative calculated values $S_н$ for 802 mine seams. Close correlation of the indicators and the presence of "wild" (negative) results indicated possible influence of systematic errors in determining the difference between total sulfur content (S_t^d) and in the combustible part of the fuel ($S_г$). The presence of negative calculated values $S_н$ could indicate that systematic errors in the determination of criterion ($S_t^d - S_г$) were due to both an underestimation of the experimental values of total sulfur and an overestimation in the combustible part of fuel.

In order to understand the origin of "wild" calculated values of sulfur content in the conditionally non-combustible part of fuel according to equation (2), methods for determining the indicators from this dependence were considered.

Several approaches to the determination of total sulfur in coals are known — from the classical gravimetric Eschka method to modern types of instrumental analysis [1]. The Eschka method, proposed in 1874, is still widely used in world practice. It is regulated by GOST[8]. Coal sample is burned by sintering with a mixture of magnesium oxide and anhydrous sodium carbonate (ratio 2:1 by weight) in an oxidizing atmosphere at a temperature of (800 ± 250) °C. The organic mass of fuel is burned, and sulfur is converted into sodium and magnesium sulfates. They are transferred to a solution. The sulfate ion is quantitatively precipitated in a hydrochloric acid medium with barium chloride in the form of barium sulfate $BaSO_4$. The total sulfur content is calculated by the mass of $BaSO_4$. The disadvantages of this approach are high time costs (at least 6–7 hours) and the possibility of losing part of the organic sulfur during sintering with a mixture [1]. In most cases, the method is used in case of disagreement. The total sulfur in standard fuel samples for calibration of analyzers is determined only by the Eschka method.

For practical purposes, an accelerated standard method for determining total sulfur, regulated by GOST[9] is recommended. The fuel sample is burned in a stream of oxygen or air in a tube furnace at 1350°C. Ash residue and gaseous combustion products are formed, which include sulfur oxides (mostly SO_2) and chlorine oxides. The analysis is

[8] *Pravyla vedennya hirnychyx robit na plastax, sxyl"nyx do hazodynamichnyx yavyshh. Standart Minvuhlepromu Ukrayiny* No. SOU 10.1.00174088.011-2005. Kyiv: Ministerstvo ugol'noi promyshlennosti Ukrainy; 2005. 224 p. (In Ukr.).

[9] GOST 2059-95 (ISO 351-96). *Solid mineral fuel. Determination of total sulfur.High temperature combustion method.* Moscow: Stansartinform; 2008. 14 p. URL: https://files.stroyinf.ru/Data2/1/4294832/4294832840.pdf (accessed: 11.11.2023). (In Russ.).

carried out in 40–60 minutes. This method was used in determining total sulfur content to establish the consumer qualities of coals. Experimental values are given in reference and regulatory documents [2, 3]. An accelerated method for determining total sulfur is recommended for monitoring the sulfur content in low-ash fuels. It is undesirable to use it in the analysis of high-ash fuels with a significant content of calcium compounds. Due to the variety of the composition of the mineral mass and sulfur compounds, it is impossible to be completely sure that some of the sulfur will not remain in the ash in the form of $CaSO_4$. As a result, the results are underestimated [1].

For most coal seams, after coal cleaning, the ash yield is less than 10%, but this indicator can also be much higher (Fig. 3).

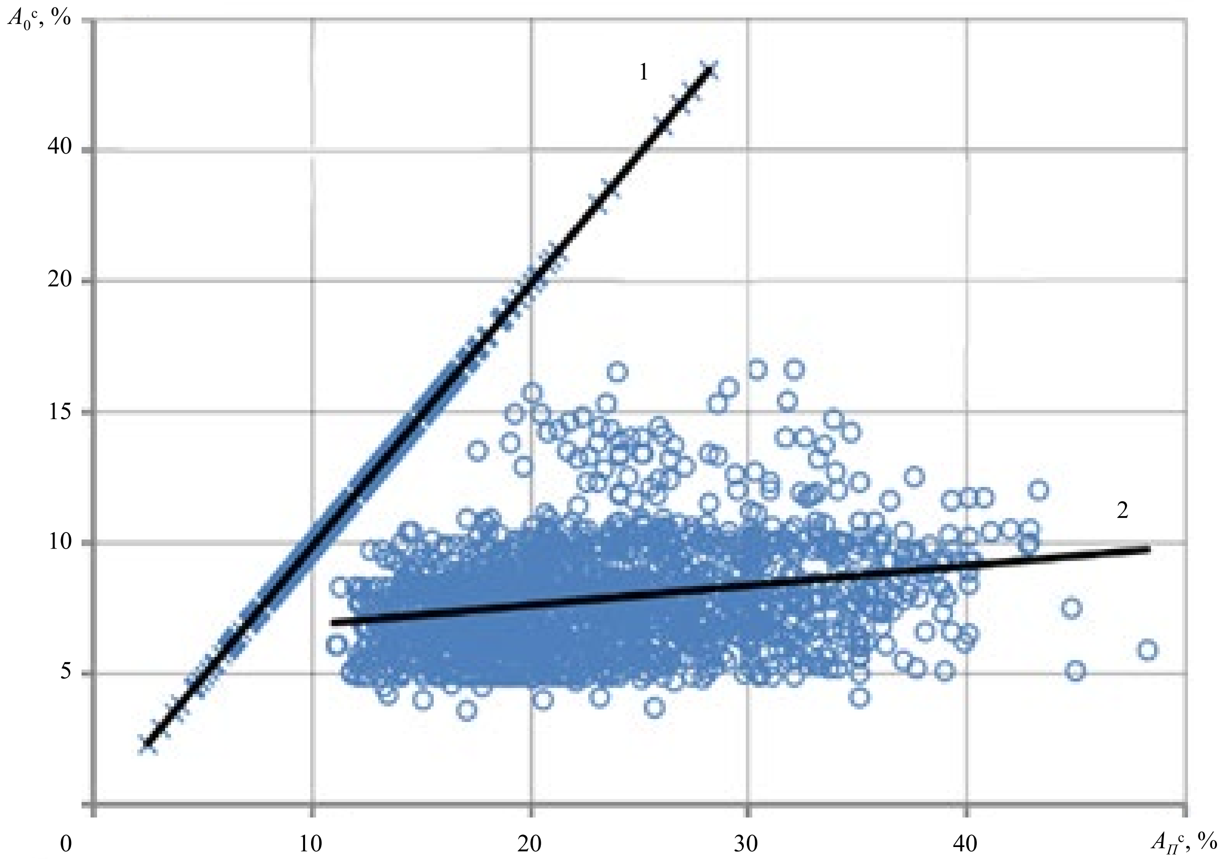


Fig. 3. Dependence of ash yield from clean coal samples ($A_о^c$) on ash yield from bed samples ($A_п^c$) according to experimental data [2, 3]

For this reason, even after cleaning a significant part of the samples, there was no reason to consider all coals low-ash. According to data [2, 3], no cleaning was carried out for 487 mine seams and the ash yield in many cases exceeded 10%, which also did not allow the coals of this aggregate of mine seams to be classified as low-ash.

Calcium compounds are present in the mineral impurities of the coals of all mine seams. This is evidenced by the typification of the composition of the ash (Table 2), according to which the *CaO* content can generally reach 40%.

Table 2

Typification of coal ash composition according to [2] and [3]

Types of coal ash	Composition fluctuation limits, %			
	Al_2O_3	SiO_2	Fe_2O_3	CaO
Siliceous	8–30	40–70	to 20	to 20
Alumina	30–45	40–55	to 20	to 20
Ferriferous	10–20	30–55	> 20	to 20
Lime	5–20	15–40	5–20	20–40

One of the reasons for obtaining "wild" calculated values $S_н$ according to equation (2) is an underestimation S_t^d when determined by the accelerated method. This conclusion is justified by:

- the analysis of ash yield from clean and bed samples;
- the possible content of calcium compounds in all types of ash.

The second factor in obtaining negative calculated values $S_н$ is an overestimation of the proportion of the combustible part of fuel using $(100–A_o^c)$ as a multiplier in equation (2). Total sulfur content S_t^d refers to both organic part and mineral mass (MM) of the fuel. For this reason, it would be more logical to use MM values in equation (2) instead of ash yield A_o^c which have not been experimentally determined for the considered mine seams. According to known empirical dependencies, the MM values always exceed the ash yield to the dry state. Accounting for such an excess requires additional (missing) information about hydrate moisture, carbon dioxide released during complete decomposition of carbonates, pyrite and sulfate sulfur. For an approximate estimate of the mineral mass content, ratio MM ≈ 1.1 A_o^c is sometimes used [1].

The analysis showed the reasons for the systematic underestimation of product $100 \cdot S_t^d$ and overestimation of difference $(100–A_o^c)$ $S_г$ in determining the calculated values $S_н$ according to equation (2).

The presence of negative values $S_н$ for an aggregate of 802 mine seams (Fig. 2 *a*) makes it possible to estimate the average underestimation of criterion $\overline{S_t^d - S_г}$, at which "wild" results were obtained

$$\overline{S_t^d - S_г} = \frac{\sum_i^n \left(S_t^d - S_г\right)_i}{n} = \frac{-336.3}{802} = -0.42, \% \quad (3)$$

Here $n = 802$ — number of mine seams for which negative values $S_н$ were obtained; $\Sigma\left(S_t^d - S_г\right)_i$ — sum of negative values $S_t^d – S_г$ for the aggregate of $n = 802$ mine seams.

Average negative value $\overline{S_t^d - S_г} = -0.42\%$ corresponds to average negative value $\overline{S_н}$:

$$\overline{S_н} = \frac{\sum_i^n S_{нi}}{n} = \frac{-1682.18}{802} = -2.10, \%, \quad (4)$$

where $\sum_i^n S_{нi}$ — sum of negative calculated values $S_н$ for the aggregate of $n = 802$ mine seams.

To exclude negative averaged values $S_н$, it is necessary to adjust the position of line 1 (Fig. 2*a*) taking into account coordinates $\overline{S_t^d - S_г} = -0.42\%$ and $\overline{S_н} = -2.10\%$. Adjusted line 1' should pass at least below point A' with coordinates $\overline{S_t^d - S_г} = -0.42\%$ and $\overline{S_н} = -2.10\%$. Directly proportional dependence $S_н$ on $(S_t^d – S_г)$ ($r = 0.91$) indicates the fact that the true position of corrected line 1' will be close to its parallelism with line 1. The use of values $S_н$' in engineering calculations, determined by equation 1' (Fig. 2 *a*), guarantees, at least, the absence of their negative averaged values.

Empirical equation 1' was obtained based on the experimental data for 1827 mine seams. Of these, pre-cleaning was performed for coal samples from 1.352 mine seams. Ash yield from the bed samples of coals of the remaining 475 mine seams was slightly lower, therefore, cleaning was not applied to them.

Preliminary cleaning significantly affected the ash yield compared to raw samples (Fig. 3). It was necessary to find out how the accuracy of the calculated determination of sulfur according to equation (2) in the conditionally non-combustible part of the fuel depended on cleaning. To do this, we considered individual characteristic sets of mine seams. One aggregate of 1.352 variants included mine seams, the coals of which were subjected to preliminary cleaning (Fig. 2 *b*). Before cleaning, the ash yield from bed samples was 11.0–48.2%, and after — 3.7–16.7% (Fig. 3).

In the second aggregate of 475 mine seams, the option was considered for mine seams, the coals of which were not previously cleaned (Fig. 2 *c*), since they were conditionally classified as low-ash. The yield of ash from the untreated coals of this aggregate of mine seams ranged from 2.4% to 28.1% (Fig. 3).

The ash yield for both considered aggregates of mine seams in many cases significantly exceeded 10%. The yield ranges were 3.7–16.7% and 2.4–28.1%, respectively. This indicated the absence in some cases for both aggregates of a reasonable application of an alternative accelerated standard method for determining total sulfur S_t^d [9]. As a result, calculated values S_t^d were underestimated for most of the considered mine seams. As a consequence, the "wild" values calculated according to equation (2) were obtained for 558 and 244 mine seams of both (second and third) aggregates, respectively (Table 3).

Table 3

Summary results of determination of calculated values $S_н$ according to statistical processing of experimental data for different aggregates of mine seams

No.	Number of mine seams				Coordinates of points A', %		Empirical equations	Correlation		Range of ash yield change, %	Explanation
	total	$S_t^d - S_г \geq 0$	$S_t^d - S_г < 0$	$S_н < 0$	$\overline{S_t^d - S_г}$	$\overline{S_н}$		σ, %	r		
1	1827	512	1315	802	–0.42	2.1	$S_н^* = 11.97(S_t^d - S_г) + 3.34$	0.91	2.67	2.4–48.2	Whole aggregate of mine seams with clean and raw coals
							$S_н'^{**} = 11.97(S_t^d - S_г) + 7.12$	–	–		
2	1352	491	861	558	–0.42	2.69	$S_н = 13.15(S_t^d - S_г) + 3.11$	0.94	2.43	3.7–16.7	Cleaning was carried out
							$S_н' = 13.50(S_t^d - S_г) + 8.21$	–	–		
3	475	21	454	244	–0.41	0.71	$S_н = 3.50(S_t^d - S_г) + 1.24$	0.56	1.5	2.4–28.1	Mine seams with presumably low-ash coals
							$S_н' = 3.50(S_t^d - S_г) + 2.15$	–	–		
4	1181	452	729	487	–0.41	2.88	$S_н = 13.84(S_t^d - S_г) + 3.00$	0.95	2.28	3.7–10	Clean coals with an ash yield of less than 10%
							$S_н' = 13.84(S_t^d - S_г) + 8.55$	–	–		
5	171	39	132	71	–0.50	1.36	$S_н = 7.50(S_t^d - S_г) + 2.84$	0.92	1.47	10.1–16.7	Ash yield after cleaning of more than 10%
							$S_н' = 7.50(S_t^d - S_г) + 5.11$	–	–		
6	149	13	136	81	–0.26	1.13	$S_н = 8.27(S_t^d - S_г) + 1.57$	0.79	1.61	2.4–10	Ash yield from raw samples of less than 10%
							$S_н' = 8.27(S_t^d - S_г) + 3.28$	–	–		
7	326	8	318	163	–0.48	0.5	$S_н = 2.53(S_t^d - S_г) + 1.13$	0.56	1.04	10.1–28.1	Ash yield from bed raw samples of more than 10%
							$S_н' = 2.53(S_t^d - S_г) + 1.71$	–	–		

Notes. In the first column, No. — number of the bed aggregate; * — dependencies according to calculated values $S_н$ according to equation (2) and experimental data of criterion ($S_t^d - S_г$); ** — adjusted dependencies $S_н'$; σ — standard deviation.

Average negative values $\overline{S_t^d - S_Г}$ of the second and third aggregates were calculated using equation (3). They were –0.42% and –0.41%, respectively. This indicated that the average errors of underestimation of the calculated total sulfur content by an alternative accelerated method for both aggregates were almost identical when calculating $S_н$ according to equation (2). Due to these circumstances, the accelerated method for determining total sulfur and possible underestimations of its true values did not relate to the differences between the second and third aggregates of mine seams.

Logic of equation (2) shows that different calculated values $S_н$ of the second and third aggregates can be obtained only taking into account the different ash yield from clean and bed samples of coals. For the convenience of analyzing the potential impact of ash yield from clean and raw coal samples, equation (2) was presented in the form of terms.

For clean samples (aggregate 2):

$$S_н^o = \frac{100}{A_с^o} \cdot S_t^d - \frac{100}{A_с^o} \cdot S_г^o + S_г^o, \%. \quad (5)$$

For raw bed samples (aggregate 3):

$$S_н^п = \frac{100}{A_п^с} \cdot S_t^d - \frac{100}{A_п^с} \cdot S_г^п + S_г^п, \%. \quad (6)$$

Comparing the terms of equations (5) and (6), we determined the direction of their influence on the calculated values $S_н$. The first term $\left(100/A_с^o\right) \cdot S_t^d$ of equation (5) was obviously larger than the corresponding term $\left(100/A_п^с\right) \cdot S_t^d$ of equation (6). This was determined by the undeniable excess of ash yield from bed samples compared with ash yield from raw samples ($A_п^с > A_о^с$). The inequality suggested that the values of total sulfur determined by the accelerated alternative method would be more underestimated for bed samples. For this reason, S_t^d values of equation (5), were at least not less than in (6).

The second terms with a minus sign of equations (5) and (6) $\left(\left(100/A_о^с\right) \cdot S_г^о \text{ and } \left(100/A_п^с\right) \cdot S_г^п\right)$ characterize an increase in the proportion of sulfur content in the combustible part of fuel after coal cleaning compared with the content in bed samples before cleaning. Under the influence of cleaning processes, the ash yield is reduced several times ($A_о^c < A_п^c$, Fig. 3). As a result, the proportion of the combustible part of fuel of clean coals increases $\left(100/A_с^o\right)$ compared with its share in bed samples $\left(100/A_п^с\right)$. This, as well as the stability of sulfur compounds, cause an increase in the relative (percentage) content of sulfur $S_г^о$ in the combustible part of fuel after cleaning. These values always exceed the percentage of sulfur in the bed raw samples, i.e. the inequality $S_г > S_г^п$ is observed. Negative terms of equations (5) and (6) $\left(\left(100/A_о^с\right) \cdot S_г^о \text{ and } \left(100/A_п^с\right) \cdot S_г^п\right)$ in any ratio, make up only a certain part of the sulfur content in the combustible mass. As a result, the total values of the second and third terms of equations (5) and (6) will be positive.

Let us consider the inequality of terms in (5) and (6): $S_г^о > S_г^п$ and $\left(100/A_о^с\right) \cdot S_t^d$ and $\left(100/A_п^с\right) \cdot S_t^d$. This suggests that cleaning leads to a percentage increase in the sulfur content in the non-combustible part of fuel ($S_н$) and its close, almost functional dependence ($r = 0.94$) on criterion S_t^d–$S_г$ (Fig. 2 *b*). Strong correlation $S_н$ and $S_t^d - S_г$ for clean coal of the second aggregate is due to a significant forced reduction in the content of conditionally non-combustible (mineral) impurities. This is evidenced by a reduction in the range of ash yield from bed raw samples from 11.0–48.2% to 3.7–16.7% after cleaning. For the considered aggregate of mine seams, in most cases (about 90%), the ash yield was less than 10%, which indicates an insignificant proportion of mineral impurities in coals after cleaning. Cleaning is largely explained by the approximation of mass fraction of combustible part of fuel to the organic mass. Correlation dependence 1 (Fig. 2 *b*) refers to an insignificant proportion (less than 10%) of mineral (conditionally nonflammable) impurities preserved after cleaning. The relatively high regression coefficient of equation 1 (13.15) indicates a disparity in the indicators:

- reduction of ash yield after coal cleaning;
- sulfur content in the preserved part of conditionally nonflammable (mineral) impurities [10].

As it can be seen from equation (5), high correlation dependence of $S_н$ on indicator $S_t^d - S_г$ for mine seams of the second aggregate was ensured by a relative consistency of ash yield $A_о^с$ for most mine seams in the range of 3.7–10.0%. This effectively eliminates the significant influence of unpredictable fluctuations in the proportion of conditionally non-combustible (mineral) impurities in wider ranges. Values $S_н^о$ for the second aggregate of mine seams, calculated according to equation (5), are determined by experimental data from S_t^d and $S_г^о$. This was confirmed by the results of statistical processing (Fig. 2 *b*). Influence of fluctuations in ash yield $A_о^с$ after coal cleaning was minimized, and calculated values $S_н^o$ were more dependent on two indicators — S_t^d and $S_г^o$.

Such a stable relationship between $S_н$ and ($S_t^d - S_г$) is not observed in the absence of cleaning processes (Fig. 2 *c*). This resulted in a lower correlation coefficient ($r = 0.56$) and a decrease in regression coefficients of empirical equations 1 from 13.15 (Fig. 2 *b*) to 3.50 (Fig. 2 *c*).

When calculating $S_н^п$ according to equation (6) for the third aggregate of mine seams, the range of unpredictable fluctuations in values $A_п^c$ of ash yield expanded to 2.4%–28.1%. This is significantly more than with a stable ash yield from clean coal samples of the second aggregate. We note the increased influence of an additional factor associated with significant fluctuations in the ash yield from bed samples in wider intervals. This led to a weakening of correlation dependence 1 to value $r = 0.56$ (Fig. 2 *c*).

The vast majority of coals of the third aggregate of coal seams according to criterion $S_t^d - S_г < 0$ should be classified as low-ash. Out of 475 coal seams of the entire aggregate under consideration, 454 (i.e., 95.6%) criterion values were negative. According to negative values of $S_t^d - S_г$ criterion, the main percentage of sulfur had to be conditionally attributed to the combustible mass of the coals of these mine seams. Determination of $S_н$ according to equation (6) for 244 mine seams gave "wild" values. For the remaining 231 mine seams, calculated values $S_н$ were positive (210 variants) or equal to zero (21 variants). The study revealed an approximately equal number of near-zero calculated values $S_н$. This confirms the presence of systematic errors of experimentally determined parameters included in (6). The proof is also the approximate equality in absolute magnitude of the average negative (–0.71%) and average positive (+0.80%) calculated values $S_н$. This makes it possible to reasonably make quantitative adjustments to the calculations in order to exclude "wild" results.

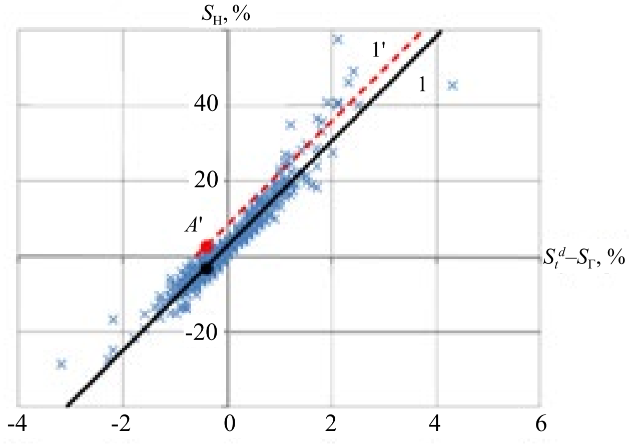
Comparison of calculated values of sulfur content in the non-combustible part of fuel for the second and third aggregates demonstrates a significant difference in the initial parameters of the indicators that were used to determine $S_н$ and $S_н^п$ according to equations (5) and (6), respectively. The main difference was due to the preliminary cleaning of coals of the second aggregate. Cleaning changed disproportionately the ratio of ash yield and sulfur content in the combustible part of fuel. The initial ratios were formed in natural conditions and were associated with the individual geological history of the formation of each mine seam, namely:

- consistent accumulation of precipitation;
- immersion and transformation of the initial substance at the stages of peat formation and diagenesis preceding metamorphism.

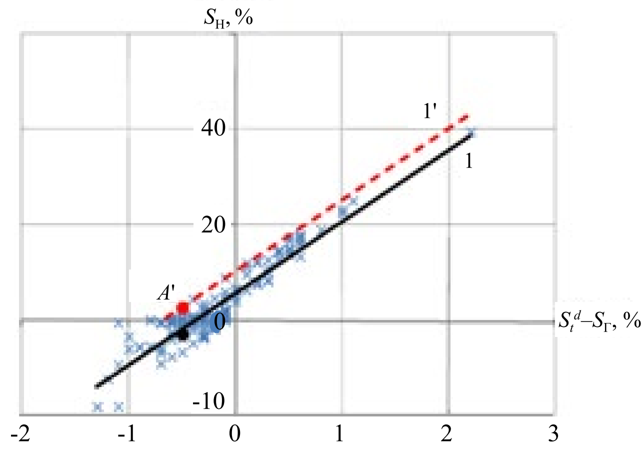
In coals of the third aggregate of mine seams, the initial established natural ratios between the ash yield from bed samples, the content of total sulfur and some of its part in the combustible mass of fuel have been preserved.

Cleaning of coals of the second aggregate of mine seams and the reduction of ash yield (in most cases below 10%) predetermined the artificial proximity of the entire aggregate in terms of the content of mineral (conditionally non-combustible) impurities. As a result of actual elimination of the influence of ash yield from clean samples for most of the mine seams according to equation (5), calculated values $S_н^п$ were obtained, which were largely directly related to criterion ($S_t^d - S_г$). This predetermined their high correlation interdependence (Fig. 2 *b*).

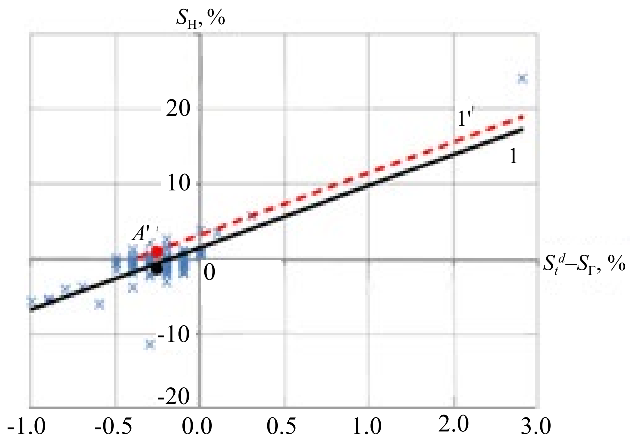
The main difference between the coals of the second and third mine seam aggregates is the values of ash yield from clean and bed samples of coals. For a detailed understanding of the effect of ash yield from clean and raw coal samples on calculated values $S_н$ four aggregates of mine seams of varying degrees of cleaning were additionally considered (Fig. 4).



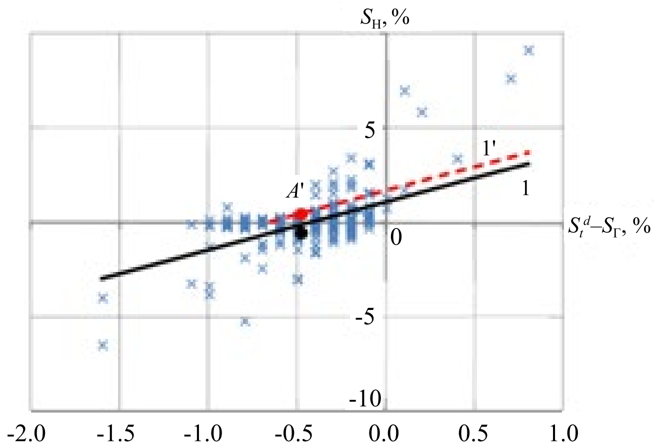
a)



b)



c)



d)

Fig. 4. Dependence of calculated values of sulfur content ($S_Н$) in conditionally non-combustible part of fuel on criterion ($S_t^d – S_Г$) [2, 3]

According to the ash yield from clean samples, mine seams were divided into two groups: less than 10% and more than 10% (Fig. 3). The corresponding aggregates were considered — fourth (Fig. 4 *a*) and fifth (Fig. 4 *b*).

The majority of mine seams (1181% or 87.4%), according to the ash yield of less than 10% of clean samples, were attributed to the fourth aggregate. In the fifth aggregate of mine seams with an ash yield of more than 10%, calculated values $S_Н$ for 171 mine seams were considered, which amounted to 12.6% of the total number of mine seams (1352), the coals of which were cleaned.

Close directly proportional correlation dependencies of calculated values $S_Н$ on $S_t^d – S_Г$ criterion were obtained for both aggregates of mine seams after processing. The correlation coefficients are 0.95 and 0.92, respectively. The regression coefficients of these dependencies (Fig. 4 *a, b*) were 13.84 and 7.50, respectively. The almost twofold difference between the empirical regression coefficients indicates significant differences between the coals of the fourth and fifth aggregates. It can be explained by:

– quantitative and qualitative composition of mineral impurities in bed samples;

– different processing efficiency.

The influence of these factors requires a separate detailed study [11].

Similar aggregates of mine seams were formed by the ash yield from bed (raw) samples of less than and more than 10%. For the sixth aggregate of 149 mine seams, the dependence of $S_н$ on $S_t^d - S_г$ criterion was established when ash yield from raw (bed) samples was less than 10% (Fig. 4 *c*). In the seventh aggregate of 326 mine seams, similar dependencies of calculated values of $S_н$ on $(S_t^d - S_г)$ criterion at an ash yield of more than 10% were considered (Fig. 4 *d*).

The obtained directly proportional empirical dependences for the sixth and seventh aggregates of mine seams with different ash yields from raw (bed) samples differ significantly. The differences are due to both the closeness of correlations and the regression coefficients of empirical equations.

The ash yield of less than 10% from raw (bed) samples indicates a low ash content of coals of the sixth aggregate of mine seams. In this case, the correlation is quite high ($r = 0.79$). For the more ashy coals of the seventh aggregate of mine seams, the correlation is much weaker ($r = 0.56$).

The regression coefficients of the empirical equations of the sixth and seventh aggregates of mine seams differ by more than three times. They are respectively equal to 8.27 (Fig. 4 *c*) and 2.53 (Fig. 4 *d*).

The revealed significant differences between the empirical dependencies of the sixth and seventh aggregates of mine seams in terms of the closeness of correlations and regression coefficients indicate different features of the conditions for accumulation of sulfur in the mineral (conditionally non-combustible) part of fuel for coals with different ash yield levels.

Low ash yield (less than 10%) indicates an insignificant content of mineral impurities. A fairly high correlation coefficient ($r = 0.79$) is recorded between the calculated sulfur content in the conditionally non-combustible part and criterion $(S_t^d - S_г)$ (Fig. 4 *c*). This means that sulfur was formed simultaneously in mineral impurities and in organic matter at different stages of coal formation. The absence of such a close correlation for high-ash coals indicates different conditions for the formation of sulfur content in mineral impurities and in the organic mass of the seventh aggregate of mine seams (Fig. 4 *d*).

Discussion and Conclusion. According to empirical equations (Fig. 4), the aggregates of mine seams were considered in pairs, which, other things being equal, differed in two factors (Table 3):

− whether or not the coals were cleaned;

− ash yield from cleaned or raw coals was less than or more than 10%.

Processing significantly changes the relationship between:

− organic matter and mineral impurities;

− combustible and conditionally non-combustible parts of the fuel.

For this reason, the first, second, fourth and fifth aggregates of mine seams and the corresponding empirical equations do not reflect the true natural sulfur content in non-combustible parts of fossil coals. They should not be used to predict the hazardous properties of mine seams during mining operations.

Sulfur content in conditionally non-combustible mass of raw samples for the third and seventh aggregates is underestimated due to the presence of a high ash yield and the use of an alternative standard method for determining the total sulfur content. The scope of application of the empirical equations corresponding to these aggregates is limited to coal mines with low-ash coals and an insignificant content of calcium compounds in mineral impurities.

The most reliable results of determining the calculated sulfur content in a conditionally non-combustible mass were obtained for the sixth aggregate of mine seams. Practical application of the corresponding empirical equation is recommended when predicting the hazardous properties of mine seams with an ash yield of less than 10%.

It is possible to improve the proposed method for determining sulfur in mineral impurities and expand its scope of application. To do this, it is necessary to establish the following ratios:

− sulfur content in organic and combustible mass of coals;

− mineral impurities and ash yield (with the determination of its chemical composition).

The results of such studies can be used to improve standards for safe mining operations, taking into account the sulfur content in both organic matter and mineral impurities of fossil coals.

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Received 29.11.2023
Revised 18.12.2023
Accepted 29.12.2023

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Claimed contributorship:
NV Pronskaya, EN Filatieva: formulation of the basic concept, goals and objectives of the study.
MV Filatiev: academic advising, analysis of the research results, formulation of the conclusions.
NV Shashlo: calculations, preparation of the text and design of the article.

Conflict of interest statement: the authors do not have any conflict of interest.

All authors have read and approved the final manuscript.

Поступила в редакцию 29.11.2023
Поступила после рецензирования 18.12.2023
Принята к публикации 29.12.2023

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Заявленный вклад соавторов:

Н.В. Пронская, Э.Н. Филатьева — формирование основной концепции, цели и задачи исследования.

М.В. Филатьев — научное руководство, анализ результатов исследований, формулирование выводов.

Н.В. Шашло — проведение расчетов, подготовка текста и оформление статьи.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

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UDC 628.853:697.934
https://doi.org/10.23947/2541-9129-2024-8-1-73-81

Original article

EDN: IUHJOZ

Optimization of the Transmission Ratio by Fuel Consumption

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Abstract

Introduction. The issues of ensuring optimal fuel consumption modes are the subject of constant research in the field of vehicle operation. Works in the field of reducing fuel consumption in most cases are devoted to the study of the design of power units, transmission or aerodynamic features of the body of cars. At the same time, the issues of determining the optimal laws of control of unsteady movement from the point of view of the synthesis of algorithms for controlling the movement of a car have not been considered. To optimize the transmission ratio of cars with unsteady movement, the authors of the work carried out analytical calculations to simplify the synthesis of motion control algorithms, which in turn allowed reducing fuel consumption. The aim of the work was to determine the optimal transmission ratio, which allowed solving the problem of synthesizing vehicle control to reduce fuel consumption.

Materials and Methods. The synthesis of algorithms for controlling the movement of a car considered in the work was based on the application of the needle variation of L.S. Pontryagin to invariant features of the real movement. An analytical method was used to estimate energy efficiency of vehicle performance, which was based on determination of optimal transmission ratio of motor vehicles taking into account minimum fuel consumption. The presented method took into account the amount of torque transmitted from the engine crankshaft to the transmission elements, which, depending on the engine power, was realized in the form of traction force on the wheels of the car.

Results. The law of optimal change in the transmission gear ratio during acceleration of the car in a minimum time was built. The problem of determining the optimal transmission ratio of the vehicle in the case of driving the vehicle at a constant speed and constant fuel supply and in the case of accelerating the vehicle to a given speed at a constant fuel supply, when the condition $\varepsilon = \text{const}$ was met, was solved. The result of the considered case of applying the optimal law of change in the transmission gear ratio was the minimization of fuel consumption under restrictions on acceleration (traction force) and speed of the car.

Discussion and Conclusion. The use by the authors of the analytical method for determining the transmission ratio of a car, as well as the use of this method in practical calculations for a car with given characteristics, showed the possibility of solving the problem of synthesizing vehicle control using a mathematical apparatus. This was confirmed by the built graphical dependence based on the results of the calculations. The considered cases of movement made it possible to determine the analytical dependencies of the optimal transmission ratio and the speed of the car. The initial data obtained by analytical relationships are applicable for cars with a mixed control mode.

Keywords: transmission ratio, fuel consumption, energy efficiency

Acknowledgements. The authors would like to thank the Editorial board and the reviewers for their attentive attitude to the article and for the specified comments that improved the quality of the article.

For citation. Kosenko EE, Marchenko JuV, Marchenko EV, Popov SI, Izyumov AI. Optimization of the Transmission Ratio by Fuel Consumption. *Safety of Technogenic and Natural Systems.* 2024;8(1):73–81. https://doi.org/10.23947/2541-9129-2024-8-1-73-81

Научная статья

Оптимизация передаточного числа трансмиссии по расходу топлива

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Аннотация

Введение. Вопросы обеспечения оптимальных режимов расхода топлива являются предметом постоянного исследования в области эксплуатации автотранспортных средств. Работы в области снижения расхода топлива в большинстве случаев посвящены исследованию конструкции силовых установок, трансмиссии или аэродинамических особенностей кузова автомобилей. Вместе с тем вопросы определения оптимальных законов управления неустановившимся движением с точки зрения синтеза алгоритмов управления движением автомобиля не рассматривались. Для оптимизации передаточного числа автомобилей при неустановившимся движении авторами работы проведены аналитические расчеты, позволяющие упростить синтез алгоритмов управления движением, что позволяет снизить расход топлива. Целью работы являлось определение оптимального передаточного числа, позволяющего решить задачу синтеза управления транспортным средством для снижения расхода топлива.

Материалы и методы. Рассматриваемый в работе синтез алгоритмов управления движением автомобиля основан на применении к инвариантным признакам действительного движения игольчатой вариации Л.С. Понтрягина. Использован аналитический метод оценки энергетической эффективности эксплуатационных характеристик автомобиля, в основе которого лежит определение оптимального передаточного числа трансмиссии автотранспортных средств с учетом наименьшего расхода топлива. Представленный метод учитывает величину крутящего момента, передаваемого от коленчатого вала двигателя на элементы трансмиссии, который, в зависимости от мощности двигателя, реализуется в виде силы тяги на колесах автомобиля.

Результаты исследования. Построен закон оптимального изменения передаточного числа трансмиссии при разгоне автомобиля за минимальное время. Решена задача определения оптимального передаточного числа трансмиссии автомобиля в случае движения автомобиля с постоянной скоростью и постоянной подачей топлива, а также при разгоне автомобиля до заданной скорости при постоянной подаче топлива, когда соблюдается условие ε = const. Результатом рассмотренного случая применения оптимального закона изменения передаточного числа трансмиссии является минимизация расхода топлива при ограничениях на ускорение (силу тяги) и скорость движения автомобиля.

Обсуждение и заключения. Применение авторами аналитического метода для определения передаточного числа трансмиссии автомобиля, а также использование данного метода в практических расчетах для автомобиля с заданными характеристиками показывает возможность решения задачи синтеза управления транспортным средством с применением математического аппарата. Это подтверждается построенной графической зависимостью по результатам проведенных расчётов. Рассмотренные случаи движения позволили определить аналитические зависимости оптимального передаточного числа и скорости автомобиля. Исходные данные, полученные по аналитическим зависимостям, применимы для автомобилей со смешанным режимом управления.

Ключевые слова: передаточное число трансмиссии, расход топлива, энергетическая эффективность

Благодарности. Авторы выражают благодарность редакции и рецензентам за внимательное отношение к статье и указанные замечания, устранение которых позволило повысить ее качество.

Для цитирования. Косенко Е.Е., Марченко Ю.В., Марченко Э.В., Попов С.И., Изюмов А.И. Оптимизация передаточного числа трансмиссии по расходу топлива. *Безопасность техногенных и природных систем.* 2024;8(1):73–81. https://doi.org/10.23947/2541-9129-2024-8-1-73-81

Introduction. Vehicle control mode is a combination of alternating acceleration, braking, as well as the need for various maneuvering when driving motor transport, taking into account its movement in urban areas. Such control leads to increased fuel consumption. Reducing fuel consumption in such conditions is usually associated with the need to increase the time for maneuvers [1]. This makes it necessary to search for optimal laws for controlling the unsteady movement of the car. In [2], energy characteristics of vehicle movement are determined primarily by the amount of torque transmitted from the engine crankshaft and the thrust force realized on the propellers, which depend on the engine power and the value of the gear ratios. The need to determine the optimal values of the transmission ratios of the vehicle is due to a decrease in the values of fuel characteristics [3], as well as a decrease in the amount of energy that is spent when maneuvering the car in case of unsteady movement. Gear ratios are determined in accordance with the specified characteristic of the engine and depend on the speed of movement of the vehicle, which has variable values [4].

When considering the approaches used to solve optimization problems, their diversity should be mentioned. Most of these approaches use methods of optimal control and calculus of variations. The authors in [5] used the maximum principle of L.S. Pontryagin with the definition of analytical dependencies for hybrid cars. A similar approach is considered in [6]. Based on this approach, it is proposed to construct the law of optimal change in the transmission ratio during acceleration of the car in the shortest time, as well as to determine fuel efficiency in the driving cycle [7]. The analysis of the conducted research has shown a significant theoretical groundwork in the field of determining the optimal gear ratio under various operating modes of the car. At the same time, it should be said that the optimal law of changing the transmission ratio should be determined taking into account the minimization of fuel consumption with restrictions on acceleration (traction) and the speed of the car. The authors of the presented work propose to apply an optimization method to determine the optimal laws of control of unsteady motion (from the point of view of the synthesis of control algorithms), which is based on the application of L.S. Pontryagin's needle variation to invariant signs of actual motion. The proposed approach has not been considered by the authors of previous studies.

The aim of the work is to determine the optimal gear ratio, which allows solving the problem of synthesizing vehicle control to optimize fuel consumption.

Materials and Methods. When calculating the instantaneous fuel consumption of a car, we used the following dependence:

$$G_T = q_N K_\omega K_N N_e, \tag{1}$$

where q_N — indicator of specific fuel consumption corresponding to the maximum value $N_e = N_{max}$; K_ω — value of the coefficient determined taking into account the speed mode of the engine; K_N — value of the coefficient determined taking into account the degree of engine load; N_e — engine power at the current time.

Coefficients K_ω and K_N were determined taking into account empirical dependencies, K_ω was determined taking into account the speed mode of the engine. Let us define it by formula:

$$K_\omega = a_\omega - b_\omega \cdot \frac{\omega_e}{\omega_N} + c_\omega \cdot \left(\frac{\omega_e}{\omega_N}\right)^2, \tag{2}$$

where $a_\omega = 1.27$; $b_\omega = 0.94$; $c_\omega = 0.67$; ω_e — current value of angular velocity of the crankshaft; ω_N — angular velocity of rotation of the crankshaft corresponding to the maximum engine power N_{max}.

Value ω_e is related to the gear ratio of transmission i and speed of the car $\dot{x}$ by dependence:

$$\omega_e = (i \cdot \dot{x}) / r_к . \tag{3}$$

Then formula (2) will take the form:

$$K_\omega = a_\omega - \frac{b_\omega}{\omega_N r_к}(i \cdot \dot{x}) + \frac{c_\omega}{(\omega_N r_к)^2}(i \cdot \dot{x})^2 . \tag{4}$$

Coefficient K_N depends on the degree of engine loading ε. Value ε was determined by the ratio of engine power at the current time, regardless of the mode of movement of the vehicle. We took into account: current value of the angular velocity of the crankshaft ω_e, engine power N_{ec} at the time of full fuel supply and the same value of the angular velocity of the crankshaft ω_e:

$$\varepsilon = \frac{N_e}{N_{ec}}. \tag{5}$$

Value of the current power of the engine N_e was determined by the differential equation of the movement of the car along the x axis, having the form [5]:

$$\frac{\delta}{g}\ddot{x} = \frac{N_e \eta_T}{mg\dot{x}} - \psi - k\dot{x}^2. \tag{6}$$

Here δ — value of the coefficient determined taking into account the power input, taking into account the increment of the kinetic energy of the rotating masses of the engine, transmission and wheels during acceleration of the car; η_T — efficiency of transmission; m — gross weight of the car; $\psi = f\,cos\alpha + sin\alpha$ — coefficient of resistance to movement; k — coefficient of air shape, which determines the strength of air resistance.

Coefficient δ in the presented work was determined by the following dependence $\delta = 1 + \gamma i^2$, in which value γ depended on the design parameters of the car and varied within $\gamma = 0.001–0.003$. Then, from equation (6), an expression can be obtained for the current value of engine power:

$$N_e = \frac{mg\dot{x}}{\eta_T}\left[\frac{1+\varepsilon i^2}{g}\ddot{x} + \psi(t) + k\dot{x}^2\right]. \tag{7}$$

Value of engine power N_{ec} at the time of maximum supply of the fuel mixture was determined using a well-known dependence (Leiderman formula) for the external characteristics of the engine, having the form:

$$N_{ec} = N_{max}\frac{\omega_e}{\omega_N}\left[A + B\frac{\omega_e}{\omega_N} - C\left(\frac{\omega_e}{\omega_N}\right)^2\right]. \tag{8}$$

Empirical coefficients *A, B, C*, depending on the engine parameters, can be determined, for example, by the dependencies given in [5]. After transformations taking into account (3), expression (8) takes the form

$$N_{ec} = F(ai\dot{x} + bi^2\dot{x}^2 - ci^3\dot{x}^3), \tag{9}$$

where coefficients *a, b* and *c* were determined by formulas:

$$F = \frac{N_{max}}{\omega_N r_k};\ a = A;\ b = \frac{B}{\omega_N r_k};\ c = \frac{C}{(\omega_N r_k)^2}.$$

Empirical dependence for coefficient K_N has the form:

$$K_N = a_N + b_N \cdot \varepsilon - c_N \cdot \varepsilon^2 - d_N \cdot \varepsilon^3, \tag{10}$$

where constants $a_N = 3.27$; $b_N = -8.22$; $c_N = -9.13$; $d_N = 3.18$ for gasoline engines; $a_N = 1.20$; $b_N = 0.14$; $c_N = 1.80$; $d_N = -1.46$ for diesel engines.

Degree of engine loading ε depending on (10), taking into account (5), (7) and (9), was determined by formula:

$$\varepsilon = \frac{\dfrac{mg\omega_N r_k}{N_{max}\eta_T}\left[\dfrac{1+\gamma i^2}{g}\ddot{x} + \psi(t) + k\dot{x}^2\right]}{ai + bi^2\dot{x} - ci^3\dot{x}^2}. \tag{11}$$

As an objective function, we used the amount of fuel consumption during time $t_к$, during which the car was moving along trajectory $x(t) \le x_к$ with variable speed $\dot{x} = f(t)$. The optimization problem was solved in accordance with the following algorithm: a law was established according to which the change in the transmission ratio was determined $i(\dot{x})$, and the corresponding trajectory $x(t)$ taking into account that the target functional took a minimum value:

$$J = \int_0^{t_K} G_T\dot{x}dt \to min, \tag{12}$$

gear ratio, current speed and power satisfied the constraints:

$$i \ge i_0,\ \dot{x} \le \dot{x}_{max},\ N_e \le N_{max}, \tag{13}$$

where i_0 — transmission ratio of the main gear.

Results. The calculation results were used for the case of a continuous change in the transmission ratio. Then, neglecting the inertia of rotating masses (at $\gamma = 0$), optimal value i_{opt}, if it existed, was found from condition:

$$\frac{\partial(G_T\dot{x})}{\partial i} = \left(\frac{\partial K_\omega}{\partial i} + \frac{\partial K_N}{\partial i}\frac{K_\omega}{K_N}\right)\dot{x} + K_\omega\frac{\partial\dot{x}}{\partial i} = 0. \tag{14}$$

Resulting expression (15) was used as the results of the study for two limiting cases.

The first case was the movement of the car with constant speed $\dot{x} = const$ and constant fuel supply, when ε and K_N = const. Therefore, the second term in equation (14) was zero, which allowed us to obtain a simple formula for determining the optimal transmission ratio:

$$i_{opt} = \frac{b_\omega\omega_N r_к}{2c_\omega\dot{x}}. \tag{15}$$

When minimizing the acceleration time to a given speed, the optimal transmission ratio was determined by formula [5]:

$$i_{opt}^p = \frac{B\omega_N r_к}{3C\dot{x}}\left(1 + \sqrt{1 + \frac{3AC}{B^2}}\right). \tag{16}$$

The second case was the acceleration of the car to a set speed with constant fuel supply, when the condition ε = const was met. In this case, the value of coefficient K_N = const and the optimal transmission ratio were determined by the formula from the solution of equation:

$$\frac{\partial K_\omega}{\partial i}\dot{x} + K_\omega \frac{\partial \dot{x}}{\partial i} = 0.$$

After the transformations, taking into account expression (4) for K_ω we get:

$$\left[-\frac{b_\omega}{\omega_N r_\kappa}\dot{x} + 2\frac{c_\omega}{(\omega_N r_\kappa)^2} i\cdot\dot{x}^2\right]\dot{x} + \left[a_\omega - \frac{b_\omega}{\omega_N r_\kappa}(i\cdot\dot{x}) + \frac{c_\omega}{(\omega_N r_\kappa)^2}(i\cdot\dot{x})^2\right]\frac{\partial\dot{x}}{\partial i} = 0. \quad (17)$$

Derivative $\frac{\partial \dot{x}}{\partial i}$ in equation (17) was determined from the condition ε = const using expression (11). At the same time, we neglected, as before, the inertia of rotating masses (γ = 0) and the force of air resistance $\left(k\dot{x}^2 \approx 0\right)$. Then we established the relationship between the speed of the car and the transmission ratio (at ε = const) from solving the following equation:

$$ci^3\dot{x}^2 - bi^2\dot{x} - ai + \frac{z(t)}{\varepsilon d} = 0,$$

where the notation was introduced:

$$d = \frac{N_{max}\eta_{\text{T}}}{mg\omega_N r_k},\ z(t) = \left[\frac{\ddot{x}}{g} + \psi(t)\right].$$

The resulting equation with respect to velocity had a solution if its discriminant was greater than or equal to zero.

$$D = b^2 i^4 + 4aci^4 - \frac{4ci^3}{\varepsilon d} z(t) \geq 0.$$

Then the condition must be met for the transmission ratio:

$$i_* \geq \frac{z(t)}{\varepsilon d(B^2/4C + A)}. \quad (18)$$

The speed value corresponding to this condition was determined by formula:

$$\dot{x}_* = \frac{B\omega_N r_k}{2Ci_*}\left\{1 + \sqrt{1 + \frac{4C}{B^2}\left[A - \frac{z(t)}{\varepsilon d i_*}\right]}\right\}. \quad (19)$$

When accelerating the car, the maximum (minimum) value of the transmission ratio i_{min} was determined from condition (18), which allowed us to obtain a fairly simple expression for derivative $\frac{\partial \dot{x}}{\partial i}$ extend it to the entire trajectory of movement:

$$\frac{\partial \dot{x}}{\partial i} = -\frac{b}{2ci_{min}^2} = -\frac{B}{2Ci_{min}^2}\omega_N r_k. \quad (20)$$

Substituting the obtained expressions into equation (17), after the transformations, we obtained the equation for the optimal value of the transmission ratio:

$$\left[-\frac{b_\omega}{\omega_N r_\kappa}\dot{x} + 2\frac{c_\omega}{(\omega_N r_\kappa)^2} i\cdot\dot{x}^2\right]\dot{x} + \left[a_\omega - \frac{b_\omega}{\omega_N r_\kappa}(i\cdot\dot{x}) + \frac{c_\omega}{(\omega_N r_\kappa)^2}(i\cdot\dot{x})^2\right]\frac{\partial\dot{x}}{\partial i} = 0,$$

$$\left[-\frac{Bb_\omega}{2Ci_*}\beta + \frac{c_\omega B^2}{2C^2}\beta\right]\frac{B\omega_N r_k}{2Ci_*}\beta - \left[a_\omega - \frac{b_\omega B}{2C}\beta + c_\omega\left(\frac{B}{2C}\beta\right)^2\right]\frac{B}{2Ci_{min}^2}\omega_N r_k = 0,$$

$$\left[-\frac{b_\omega}{i_*} + \frac{2c_\omega B}{C}\right]\frac{\omega_N r_k}{i_*} - \left[\frac{2Ca_\omega}{B\beta^2} - \frac{b_\omega}{\beta} + c_\omega\left(\frac{B}{2C}\right)\right]\frac{\omega_N r_k}{i_{min}^2} = 0,$$

$$\left[-\frac{b_\omega}{i_*} + \frac{2c_\omega B}{C}\right]\frac{1}{i_*}\omega_N r_k - \frac{R}{i_{min}^2}\omega_N r_k = 0,$$

$$-b_\omega + \frac{2c_\omega B}{C} i_* \omega_N r_k - \frac{R i_*^2}{i_{min}^2}\omega_N r_k = 0,$$

$$\frac{Ri_*^2}{i_{min}^2} - \frac{2c_\omega B}{C} i_* \omega_N r_k + b_\omega \omega_N r_k = 0 \,,$$

$$i_{*opt} = i_{min}^2 \left[\frac{c_\omega B}{RC} \mp \sqrt{\left(\frac{c_\omega B}{RC}\right)^2 \omega_N r_k - \frac{b_\omega}{i_{min}^2 R} \omega_N r_k} \right],$$

$$R = \left[\frac{2Ca_\omega}{B\beta^2} - \frac{b_\omega}{\beta} \omega_N r_k + c_\omega \left(\frac{B}{2C}\right) \omega_N r_k \right],$$

$$i_{min} = \frac{z(t)}{\varepsilon d(B^2 / 4C + A)} \omega_N r_k \,.$$

For example, the calculation of fuel consumption for a car with the following characteristics was carried out: total weight of the car $m = 1800$ kg; coefficients of external characteristics of the engine $A = 0.64$; $B = 1.36$; $C = 1.0$; maximum engine power $N_{max} = 100$ kW; angular rotation speed of the crankshaft corresponding to the maximum engine power $\omega_N = 576$ s^{-1}; wheel radius $r_k = 0.34$ m; efficiency of transmission $\eta_{mp} = 0.85$; transmission ratio of the main gear $i_0 = 3.4$ transmission ratios of the gear box $i_5 = 1.0$; $i_4 = 1.5$; $i_3 = 2.2$; $i_2 = 3.2$; $i_1 = 4.8$; coefficient of rotating masses $\delta = 1.0$; coefficient of resistance to movement $\psi = 0.12$.

The given example of calculating fuel consumption for a car with specified characteristics clearly showed the solution to the problem of synthesizing vehicle control. Acceleration graphs of a vehicle with a step-by-step gearbox, illustrating the solution for the optimal law of gear ratio change, are shown in Figure 1. For comparison, a graph for acceleration of a vehicle with a step-by-step gearbox is presented, which was built according to the obtained analytical dependence.

At the first stage of acceleration to speed $\dot{x}_{\min}$ the curves coincide. In this case $\dot{x}_{\min} = 6.14$ m/s or 22.1 km/h.

$$V_i(t) = \frac{V_{i1} \dfrac{V_{0i} - V_{i2}}{V_{0i} - V_{i1}} exp\left[t\sqrt{b_i^2 + 4a_i c_i} \right] - V_{i2}}{\dfrac{V_{0i} - V_{i2}}{V_{0i} - V_{i1}} exp\left[t\sqrt{b_i^2 + 4a_i c_i} \right]}, \tag{21}$$

$$a_i = \frac{A\phi_{\partial max} - \psi}{\delta} G; \; b_i = \frac{\beta_i \phi_{\partial max}}{\delta} G. \tag{22}$$

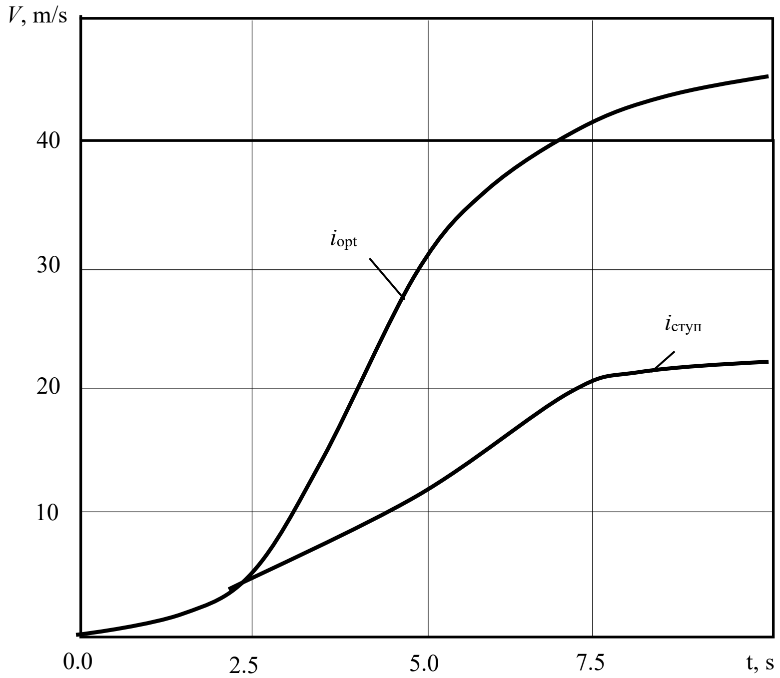

Fig. 1. Acceleration graphs of a car with a step-by-step gearbox
(dry rolled road α = 100; f = 0.025; ψ = 0.118):
i_{opt} — optimal transmission ratio;
i_{cm} — transmission

$$c_i = \frac{\gamma_i \phi_{\text{д}max}}{\delta} G;\ V_{i1,2} = \frac{b_i \pm \sqrt{b_i^2 + 4a_i c_i}}{2c_i}, \quad (23)$$

where $\varphi_{\partial max}$ — engine power factor; V_{0i} — initial speed of the machine in i-th gear; $i = \overline{1.3}$ — index indicating the gear number; $V_i(t)$ — speed of the car in i-th gear.

Discussion and Conclusion. The use of an analytical method by the authors in determining the transmission ratio, as well as its use in practical calculations for a car with specific characteristics, demonstrates the potential for solving the problem of vehicle control synthesis using a mathematical approach.

The goal set by the authors of this work — to determine the optimal gear ratio that allows them to solve the problem of vehicle control synthesis in order to reduce fuel consumption — has been achieved. As a result of the research conducted, analytical dependencies were obtained for two limiting cases of car motion.

The calculations carried out by the authors for the first case showed the optimal value of the transmission ratio, which was determined in accordance with formulas (15) and (16). The value of the transmission ratio is inversely proportional to the speed of the car. The speed value determined for the optimal transmission ratio will be less than the gear ratio determined by acceleration time. The formation of an empirical dependence in the second case with variable fuel supply $K_N = f(t)$ and the optimal transmission ratio were determined as a result of the numerical solution of equation (14).

The significance of the research is to simplify the solution to the problem of synthesizing control of unsteady vehicle movement, which is clearly demonstrated by the obtained graphical dependencies. A similar outcome can be achieved by applying the combined maximum principle.

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Received 29.11.2023
Revised 25.12.2023
Accepted 09.01.2024

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Claimed contributorship:
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SI Popov: calculations.
EV Marchenko: preparation of the text.
AI Izyumov: formulation of conclusions.

Conflict of interest statement: the authors do not have any conflict of interest.

All authors have read and approved the final manuscript.

Поступила в редакцию 29.11.2023
Поступила после рецензирования 25.12.2023
Принята к публикации 09.01.2024

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С.И. Попов — проведение расчетов.
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А.И. Изюмов — формирование выводов.

*Конфликт интересов: а*вторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

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UDC 621.793
https://doi.org/10.23947/2541-9129-2024-8-1-82-87

Original article

Content and Dispersion of Ferroalloys in the Coating During Microarc Alloying of Steel

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Abstract

Introduction. The main disadvantage of traditional processes of diffusion surface hardening of steel products is its long duration. Therefore, the problem of intensification of such processes is relevant. To solve it, the use of high-energy effects on the material is proposed, which allows us to obtain a hardened surface layer from a coating composed of ferroalloy powders containing alloying elements. There is no data in the literature on the required content and dispersion of such powders in the composition of the coating. The aim of this study was to select the particle size of ferroalloys and their concentration in the coating to achieve the most effective hardening of the processed product.

Materials and Methods. For experimental studies, cylindrical samples made of steel 20 with a diameter of 12 mm and a length of 35 mm were used. On the surface of these samples, an alloying coating containing ferroalloy powders and an electrically conductive gel as a binder was applied. After that, the samples were immersed vertically for half their length into a metal container, which was then filled with carbon powder with a particle size of 0.4–0.6 mm. Then an electric current of 2.5 to 3.0 A was passed in the circuit power source — container — carbon powder — sample. The duration of the process was 2–8 minutes.

Results. The calculated estimation of the electrical conductivity of coal powder was performed, and the thermophysical parameters of microarc heating of steel were calculated. These include the power released by electric current on the surface of the steel product, the density of the heat flux, and the energy of a single microarc discharge. The expressions for calculating the particle size of ferroalloy powder were obtained, as well as the experimental dependencies of the diffusion layer thickness on the particle size of ferroalloys and their content in the coating.

Discussion and Conclusion. The results of this study have allowed us to determine the size range of ferroalloys and their content in the coating. This information is essential for optimizing the alloying process and ensuring the most efficient surface hardening treatment for steel products. The data collected will be used to develop improved technological processes for the surface hardening process, leading to improved product quality and performance.

Keywords: chemical-thermal treatment, microarc energy, diffusion saturation of steel

Acknowledgements. The authors would like to thank the Editorial board and the reviewers for their attentive attitude to the article and for the valuable comments that improved the quality of the article.

For citation. Stepanov MS, Dombrovskii YuM. Content and Dispersion of Ferroalloys in the Coating During Microarc Alloying of Steel. *Safety of Technogenic and Natural Systems.* 2024;8(1):82–87. https://doi.org/10.23947/2541-9129-2024-8-1-82-87

Научная статья

Содержание и дисперсность ферросплавов в обмазке при микродуговом легировании стали

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Аннотация
Введение. Основным недостатком традиционных процессов диффузионного поверхностного упрочнения стальных изделий является большая продолжительность, поэтому проблема интенсификации таких процессов является актуальной. Для ее решения предложено применение высокоэнергетического воздействия на материал, позволяющего получить упрочненный поверхностный слой из обмазки, в состав которой входят порошки ферросплавов, содержащие легирующие элементы. В литературе отсутствуют данные о необходимом содержании и дисперсности таких порошков в составе обмазки. Цель исследования — выбор размера частиц ферросплавов и их концентрации в обмазке для достижения максимально эффективного упрочнения обрабатываемого изделия.
Материалы и методы. Для экспериментальных исследований использовали цилиндрические образцы из стали 20 диаметром 12 мм и длиной 35 мм, на поверхность которых наносили легирующую обмазку, содержащую порошки ферросплавов и электропроводный гель в качестве связующего. После этого образцы погружали вертикально на половину длины в металлический контейнер, который далее заполняли угольным порошком с размером частиц 0,4–0,6 мм. Затем пропускали электрический ток величиной от 2,5 до 3,0 А в цепи источник питания — контейнер — угольный порошок — образец. Продолжительность процесса составляла 2–8 мин.
Результаты исследования. Выполнена расчетная оценка электрической проводимости угольного порошка, рассчитаны теплофизические параметры микродугового нагрева стали: мощность, выделяемая электрическим током на поверхности стального изделия, плотность теплового потока, энергия единичного микродугового разряда. Получены выражения для расчета размера частиц порошка ферросплавов, а также экспериментальные зависимости толщины диффузионного слоя от размера частиц ферросплавов и их содержания в обмазке.
Обсуждение и заключение. Результаты исследования позволили определить диапазон размеров частиц ферросплавов и их содержание в обмазке, позволяющие обеспечить наиболее эффективное легирование поверхности обрабатываемых изделий. Полученные данные будут использованы при разработке технологических процессов поверхностного упрочнения стальных изделий.

Ключевые слова: химико-термическая обработка, энергия микродуги, диффузионное насыщение стали

Благодарности. Авторы выражают благодарность редакции и рецензентам за внимательное отношение к статье и ценные замечания, которые позволили повысить ее качество.

Для цитирования. Степанов М.С., Домбровский Ю.М. Содержание и дисперсность ферросплавов в обмазке при микродуговом легировании стали. *Безопасность техногенных и природных систем.* 2024;8(1):82–87. https://doi.org/10.23947/2541-9129-2024-8-1-82-87

Introduction. The duration of various processes of chemical-thermal treatment (CTT) of steel can reach 8–10 hours [1, 2]. Therefore, methods of their intensification based on the application of high-energy effects on the material using plasma heating [3], electro-chemical-thermal treatment [4], combined heating methods [5] laser treatment [6], microarc oxidation [7], and heating in an electrolyte [8] were previously proposed. However, these methods are difficult to apply in practice and therefore have not been widely used. To intensify the CTT processes, it is advisable to use microarc surface alloying, which allows you to achieve a significant (tenfold) acceleration of diffusion saturation process, and does not require the use of complex equipment. A special feature of this method is the immersion of the processed product with a coating applied to its surface in carbon powder. Then an electric current is passed through them. The intensification of the saturation process is achieved due to the formation of diffusant ions and their subsequent accelerated diffusion into the material under the influence of electric and temperature fields. In previous studies, positive results have been achieved using this method for diffusion saturation with chromium, molybdenum, vanadium [9], and tungsten [10]. For complex saturation, a coating was pre-applied to the surface of the processed product, which included a ferroalloy powder containing a diffusant. These studies made it possible to determine the structure and phase composition of the coatings obtained, but the task of achieving the maximum hardening efficiency, which requires determining the optimal particle sizes of ferroalloy and its content in the coating, was not set in previous studies.

The aim of the study was to determine the conditions for the most effective hardening of steel products by microarc alloying due to the choice of particle sizes of ferroalloy powders and their concentration in the coating used.

Materials and Methods. For experimental studies, samples of steel 20 containing 0.2 wt. % C with a diameter of 12 mm were used, on the surface of which a coating prepared on the basis of an electrically conductive gel with the addition of ferroalloy powders was applied. The samples were immersed vertically for half their length in a metal container with a diameter of 35 mm, which was then filled with coal powder with a particle size of 0.4–0.6 mm. Then an electric current of 2.5 to 3.0 A was passed through the sample for 2–8 minutes.

To prepare the coating, powders of ferrochrome, ferromolybdenum, ferrovanadium, ferrotungsten with a particle size of 0.40–0.50 microns and a binder in a volume ratio of 1:1 were used.

The samples were polished according to the standard procedure, followed by etching with Rzheshotarsky reagent. The microstructure of the diffusion layer was studied using a Neophot–21 microscope.

To measure the bulk density of coal powder, the methodology according to GOST 3258-2013 was used. The powder was dispersed by particle size using a set of sieves according to GOST 33 029-2014.

Results. The bulk density of coal powder, i.e. the mass of a unit volume of freely poured powder, was determined experimentally, the values obtained are shown in Figure 1.

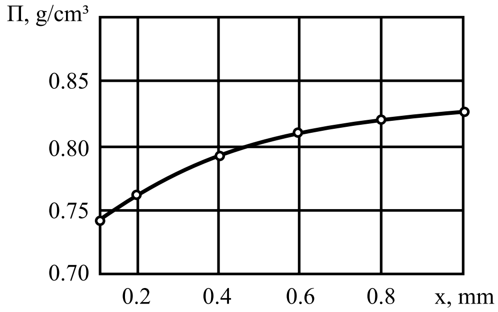

Fig. 1. Dependence of bulk density П of coal powder on size X of its particles

In the size range from 0.4 to 0.6 mm, the average bulk density could be assumed to be 0.81 g/cm^3. The obtained value made it possible to determine the volumetric density of coal powder as the ratio of bulk density to the density of coal, the value of which was borrowed from reference literature [11] and assumed to be 1.6 g/cm^3, from where the volumetric density was assumed to be 0.81/1.6=0.51. The obtained value approximately corresponded to the packing density of a simple cubic lattice (0.52). Therefore, according to [12], it could be assumed that the total resistance of the powder medium was the sum of the resistances of successive layers consisting of parallel chains of the contact resistance RK between the particles and the resistance RM of the particles themselves (Fig. 2).

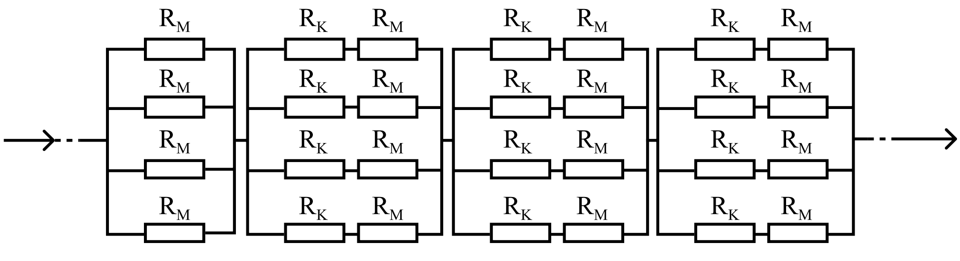

Fig. 2. Electrical contacts of carbon particles in the powder medium:
R_K — resistance of interparticle contacts;
R_M — resistance of a single carbon particle

Calculation according to Figure 2 allowed us to estimate the total electrical resistance R of the powder medium:

$$R = \sum_{m=0}^{n} \frac{(R_K + R_M)d^2}{2\pi H(r + dj)}, \tag{1}$$

where m — number of layers of carbon particles; r — radius of the sample; d — diameter of the particles; H — depth of immersion of the sample; R_K — resistance of interparticle contact; R_M — resistance of a single carbon particle. The following values were used for calculations: $d = 0.5 \cdot 10^{-3}$ m, $H = 1.5 \cdot 10^{-2}$ m, r = 6 mm, R_K = 6 kOhm, R_M = 0. Value R was assumed to be 15.5 Ohm. The obtained value allowed us to calculate: electric current power $P = I^2R$, energy of a single microarc discharge Q_0, surface current density f, heat flux density q. Value Q_0 was defined as the ratio of the current power to the total number of microarcs that simultaneously affected the heated surface for 1 second. According to the video recording, value M was assumed to be 22,500. Table 1 provides the calculation results.

Table 1

Values of thermophysical parameters of microarc heating

I, A	$f\,10^{-2}$, A/cm^2	$P\cdot 10^2$, W	$q\ 10^5$, W/m^2	$Q_0\,10^{-3}$, J
2.5	45	0.97	1.71	4.3
2.75	49	1.17	2.07	5.2
3.0	53	1.39	2.47	6.2

Next, the maximum size d_{max} of a ferroalloy particle was calculated, for the vaporization of which the energy of one microarc was sufficient.

The required amount of heat Q, taking into account specific heat of sublimation λ, can be written as: $Q = \lambda m$, where m — mass of the particle.

For a spherical particle with density ρ:

$$m = \rho V = \frac{1}{6}\rho\pi d^3 .$$

Therefore, the desired condition has the form:

$$\lambda\rho\pi d^3 / 6 \le Q_0 .$$

The maximum particle diameter required to fulfill this inequality:

$$d_{max} = \sqrt[3]{\frac{6Q_0}{\lambda\pi\rho}} . \quad (2)$$

Calculated d_{max} values are shown in Table 2.

Table 2

Calculation results

Ferroalloy		Fe+Cr	Fe+Mo	Fe+V	Fe+W
d_{max}, mm	0.45 A/cm^2	0.045	0.043	0.044	0.038
	0.49 A/cm^2	0.048	0.046	0.047	0.040
	0.53 A/cm^2	0.050	0.048	0.050	0.042

Thus, it was established that the maximum particle size of ferroalloys used in the coating composition should not exceed 38 microns.

The thickness of the diffusion layer was experimentally determined depending on the volume fraction of ferrochrome particles in the coating and its thickness. To do this, ferrochrome powder FKh010A with a particle size of 40–50 microns was added to the binder in the amount necessary to obtain its volume content in the range of 10–50%

Figure 3 provides the results. It can be seen that the maximum coating thickness was formed at a volume concentration of ferrochrome particles in the coating of 50% and its thickness of 0.5 mm. Thus, the maximum intensification of the diffusion saturation process was achieved under the condition of the highest content of ferroalloy particles in the coating, and the ferroalloy particles adjacent to the saturated surface must be exposed to microarcs.

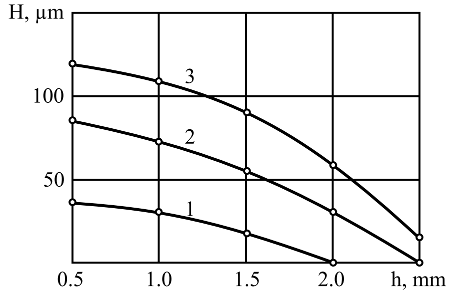

Fig. 3. Dependence of depth H of the hardened layer on thickness h of the coating layer for different contents of ferrochrome powder (vol. %) in the coating: 1 — 10; 2 — 30; 3 — 50

Discussion and Conclusion. Calculated assessment of electrical conductivity of coal powder used for microarc alloying of steel products made it possible to establish the influence of the magnitude of electric current in the circuit on thermophysical parameters of the process: the density of the heat flux on the heated surface, the power released on the heated surface, the energy of a single microarc discharge occurring between the heated product and the surrounding powder medium during the flow of electric current. The results obtained made it possible to determine the diameter of ferroalloy particles used for microarc alloying, their volume fraction in the coating, which ensure the achievement of the greatest intensification of microarc alloying process. The research results will be used in the development of technological processes for surface hardening of steel products by microarc surface alloying.

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Received 15.12.2023
Revised 11.01.2024
Accepted 16.01.2024

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Claimed contributorship:

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YuM Dombrovskii: experimental studies, determination of technological parameters of the microarc surface alloying process, analysis of the results.

Conflict of interest statement: the authors do not have any conflict of interest.

All authors have read and approved the final manuscript.

Поступила в редакцию 15.12.2023
Поступила после рецензирования 11.01.2024
Принята к публикации 16.01.2024

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Заявленный вклад соавторов:

М.С. Степанов — расчеты электрических параметров порошковой среды и теплофизических параметров микродугового нагрева, анализ полученных результатов.

Ю.М. Домбровский — экспериментальные исследования, определение технологических параметров процесса микродугового поверхностного легирования, анализ полученных результатов.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи

CHEMICAL TECHNOLOGIES, MATERIALS SCIENCES, METALLURGY
ХИМИЧЕСКИЕ ТЕХНОЛОГИИ, НАУКИ О МАТЕРИАЛАХ, МЕТАЛЛУРГИЯ

UDC 669.1:66.0
https://doi.org/10.23947/2541-9129-2024-8-1-88-96

Original article

EDN: OWXWVI

Stimulation of the Bainite Transformation Scenario by an External Magnetic Field

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Abstract
Introduction. It makes practical sense to change the properties of steels with a bainite structure, as with bainite transformation under the influence of a magnetic field, it is possible to improve the ductility of the steel while maintaining or even increasing its strength. Scientific research in this area has focused on the influence of the magnetic field on thermodynamics and on the change in the phase transformation scenario. However, there is no detailed description in open sources of the effect of a magnetic field on the structure and properties of the products of intermediate bainite transformation. The aim of the work is to study the peculiarities of the influence of an external magnetic field on the scenario and kinetics of phase transformation of steel.
Materials and Methods. The study was conducted using samples made of 65G steel. Their chemical composition was monitored using a Magellan Q8 optical emission spectrometer. Heat treatment (resistive heating) was carried out in an IMASH 20–75 installation for high-temperature research. The heating temperature was approximately 1000 degrees 1000°C, and the holding time was 10 minutes. The sample was cooled down using water-cooled electrical contacts. An external magnetic field with a strength of 400 kA/m and 800 kA/m was created by an electromagnet integrated into the vacuum chamber of the installation.
Results. The experiments confirmed the potential for altering the transformation pathway from pearlite into bainite in the presence of an external magnetic field of up to 1 MA/m. Images of the microstructure and surface relief of samples after cooling in a magnetic field were obtained. Kinetic changes and dependencies of the volumetric transformation rates on the duration of isothermal exposure were analyzed. It has been found that exposure to a constant magnetic field of 1.6 MA/m increased the volumetric transformation rate by 1.808 times (for 65G steel) and by 1.687 times (for 45Kh steel).
Discussion and Conclusion. The results of observations of changes in the surface relief during cooling in the absence of a magnetic field, and in magnetic fields of various strengths, were recorded. This has allowed us to draw the conclusion that the external magnetic field stimulates the bainitic transformation instead of the original pearlitic one. Microstructural changes can be explained by the influence of the magnetic field on the initial phase magnetic state.

Keywords: bainite transformation magnetic stimulation, pearlite transformation, improvement of steel properties, microstructural changes in steels, vacuum etching, magnetostrictive deformations

For citation. Dolgachev YuV, Pustovoit VN, Nefedov DV. Stimulation of the Bainite Transformation Scenario by an External Magnetic Field. *Safety of Technogenic and Natural Systems.* 2024;8(1):88–96. https://doi.org/10.23947/2541-9129-2024-8-1-88-96

Научная статья

Стимуляция бейнитного сценария превращения внешним магнитным полем

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Аннотация

Введение. Изменение свойств сталей с бейнитной структурой имеет практический смысл, т. к. при бейнитном превращении под воздействием магнитного поля возможно улучшение пластичности стали при сохранении или повышении ее прочностных показателей. Научные изыскания в этой сфере касались вопросов влияния магнитного поля на термодинамику и смену сценария фазового превращения. Однако в открытых источниках нет детального описания воздействия магнитного поля на структуру и свойства продуктов промежуточного бейнитного превращения. Цель работы — исследование особенности влияния внешнего магнитного поля на сценарий и кинетику фазового превращения стали.

Материалы и методы. Исследование проводилось на образцах из стали 65Г. Их химический состав контролировали при помощи оптико-эмиссионного спектрометра Magellan Q8. Термическую обработку (резистивный нагрев) проводили в установке для высокотемпературных исследований «ИМАШ 20–75». Температура нагрева — около 1000 °С, время выдержки — 10 минут. Образец охлаждали при помощи водоохлаждаемых электроконтактов. Внешнее магнитное поле напряженностью 400 кА/м и 800 кА/м создавалось электромагнитом, интегрированным в вакуумную камеру установки.

Результаты исследования. Эксперименты подтвердили возможность смены сценария превращения с перлитного на бейнитный при воздействии внешним магнитным полем до 1 МА/м. Получены изображения микроструктуры и поверхностного рельефа образцов после охлаждения в магнитном поле. Проанализированы кинетические изменения и зависимости объемных скоростей превращения от времени изотермической выдержки. Установлено, что действие постоянного магнитного поля напряженностью 1,6 МА/м увеличивает объемную скорость превращения в 1,808 раза (для стали 65Г) и в 1,687 раза (для стали 45Х).

Обсуждение и заключение. Зафиксированы результаты наблюдений за изменением поверхностного рельефа при охлаждении без магнитного поля и в магнитных полях различной напряженности. Это позволило сделать вывод о стимуляции внешним магнитным полем бейнитного превращения вместо исходного перлитного. Микроструктурные изменения объясняются влиянием поля на магнитное состояние исходной фазы.

Ключевые слова: магнитное стимулирование бейнитного превращения, перлитное превращение, улучшение свойств сталей, микроструктурные изменения сталей, вакуумное травление, магнитострикционные деформации

Для цитирования. Долгачев Ю.В., Пустовойт В.Н., Нефедов Д.В. Стимуляция бейнитного сценария превращения внешним магнитным полем. *Безопасность техногенных и природных систем.* 2023;8(1):88–96. https://doi.org/10.23947/2541-9129-2024-8-1-88-96

Introduction. As it is known, the magnetic field affects thermodynamics [1], in particular, the equilibrium temperature of phase transitions [2]. A significant shift in critical temperatures can be achieved only when using sufficiently strong (pulsed) magnetic fields [3], which is associated with certain technical difficulties when implemented in production conditions. The experiments indicate the appearance of α-phase in structural and tool steels under the action of fields with strength of 1.6–2.4 MA/m [1]. These processes take place at temperatures that are much higher than equilibrium and do not fit into the shift assumed by thermodynamic estimates [4]. The influence of an external magnetic field during the heat treatment of steel is expressed in an increase in the rate [5] and dispersion of transformation products [6]. It is known from [7] that during intermediate (bainitic) transformation under the influence of a magnetic field with strength of up to 2 MA/m, structural changes allow for a greater margin of plasticity while maintaining or slightly increasing strength parameters.

The regions with a short-range magnetic order in the γ-phase undergo magnetostriction under the action of an external magnetic field. This is due to the magnetic inhomogeneity of austenite [8] and causes a change in the field of elastic forces of the lattice, and the energy of formation of the critical nucleus of the α-phase decreases. The external magnetic field increases the number and size of ferromagnetic clusters [1]. As a result, the number of nucleation centers multiplicatively increases during cooling in a magnetic field.

It is shown in [9] how the short-range magnetic order in austenite affects the change of the phase transformation scenario. It is known from [10] that the magnetic state of γ-phase determines the transformation of ferromagnetic α-phase into one or another product. It can be ferrite, perlite, bainite or martensite.

The aim of the presented work is to experimentally verify the possibility of changing the pearlite transformation scenario to a bainite one when exposed to an external magnetic field up to 1 MA/m. In addition, it is necessary to evaluate the change in the kinetics of bainite transformation when the field is applied.

Materials and Methods. Samples of one melting made of 65G steel were used. Their chemical composition was monitored using a Magellan Q8 optical emission spectrometer (Table 1).

Table 1

Average content of elements in the samples

Steel grade	Mass fraction, %							
	C	Si	Mn	Cr	S	P	Cu	Ni
65G	0.65	0.20	0.97	0.21	0.009	0.0012	0.08	0.13

Polished samples were placed in a vacuum chamber of an IMASH 20–75 high-temperature research facility. This equipment provided vacuum in the working chamber of $1.3 \cdot 10^{-5} \div 6.6 \cdot 10^{-6}$ Pa. This made it possible to implement the vacuum etching method. The structure was revealed as a result of evaporation in a vacuum at high temperature under the influence of surface tension. Upon cooling during phase transformations accompanied by shear processes, a corresponding relief appeared on the surface of the sample.

The samples were subjected to resistive heating to ~ 1000°C for 10 minutes and cooled with heat removal to water-cooled copper electrical contacts at a rate of ~28÷32 °C/s. In accordance with the diagram of the isothermal decomposition of austenite of 65G steel, the obtained cooling rate corresponded to the intersection of the nose of the area of the beginning of the pearlite transformation. The high heating temperature contributed to the growth of the austenitic grain and vacuum etching of its boundaries, which was required for video recording of surface relief changes during phase transformation.

To measure the temperature, thermal junctions were welded in the middle of the sample. During cooling, the processes occurring on the surface were recorded using an Eakins digital eyepiece. The obtained data on the microstructure of the surface relief and inside the sample were processed to determine the volume fraction of the structural components. For this purpose, SIAMS 800 analytical software was used in 16÷25 fields of vision.

External magnetic field was created by an electromagnet integrated into the vacuum chamber of the installation [11]. The experiments involved fields with a strength of 400 kA/m and 800 kA/m. Samples without a field were processed in the same way, but with an electromagnet removed from the vacuum chamber.

Results. With the bainitic or martensitic shear character of the transformation, a relief should appear on the surface of the polished sample. If this did not happen, we were talking about a pearlitic transformation. Under experimental conditions, the cooling rate was insufficient for quenching 65G steel with martensite. One could expect competition between pearlite and bainite transformations depending on the presence or absence of an external magnetic field during the cooling process.

Figure 1 shows screenshots of video frames of changes in the surface relief observed during the transformation of supercooled austenite at various points in time (τ). Each line in Figure 1 corresponds to the specified strength of the external magnetic field (H).

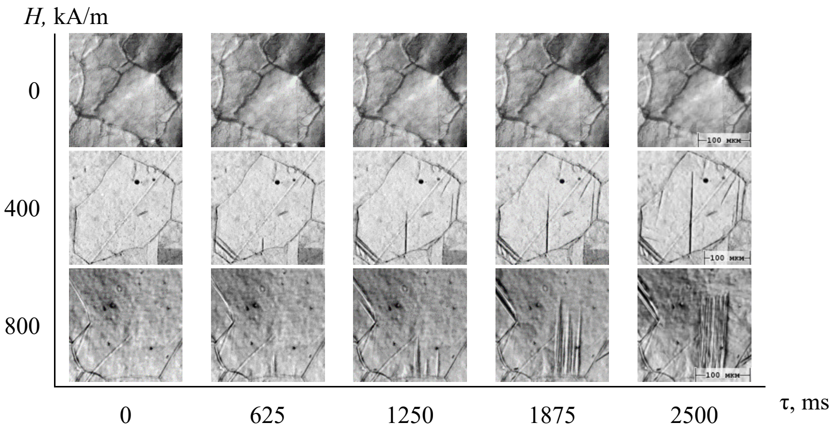


Fig. 1. Change in surface relief during cooling depending on strength of the external magnetic field (H, kA/m) and transformation time (τ, ms)

Figure 2 shows the microstructures of the surface relief and inside the samples after various processing modes.

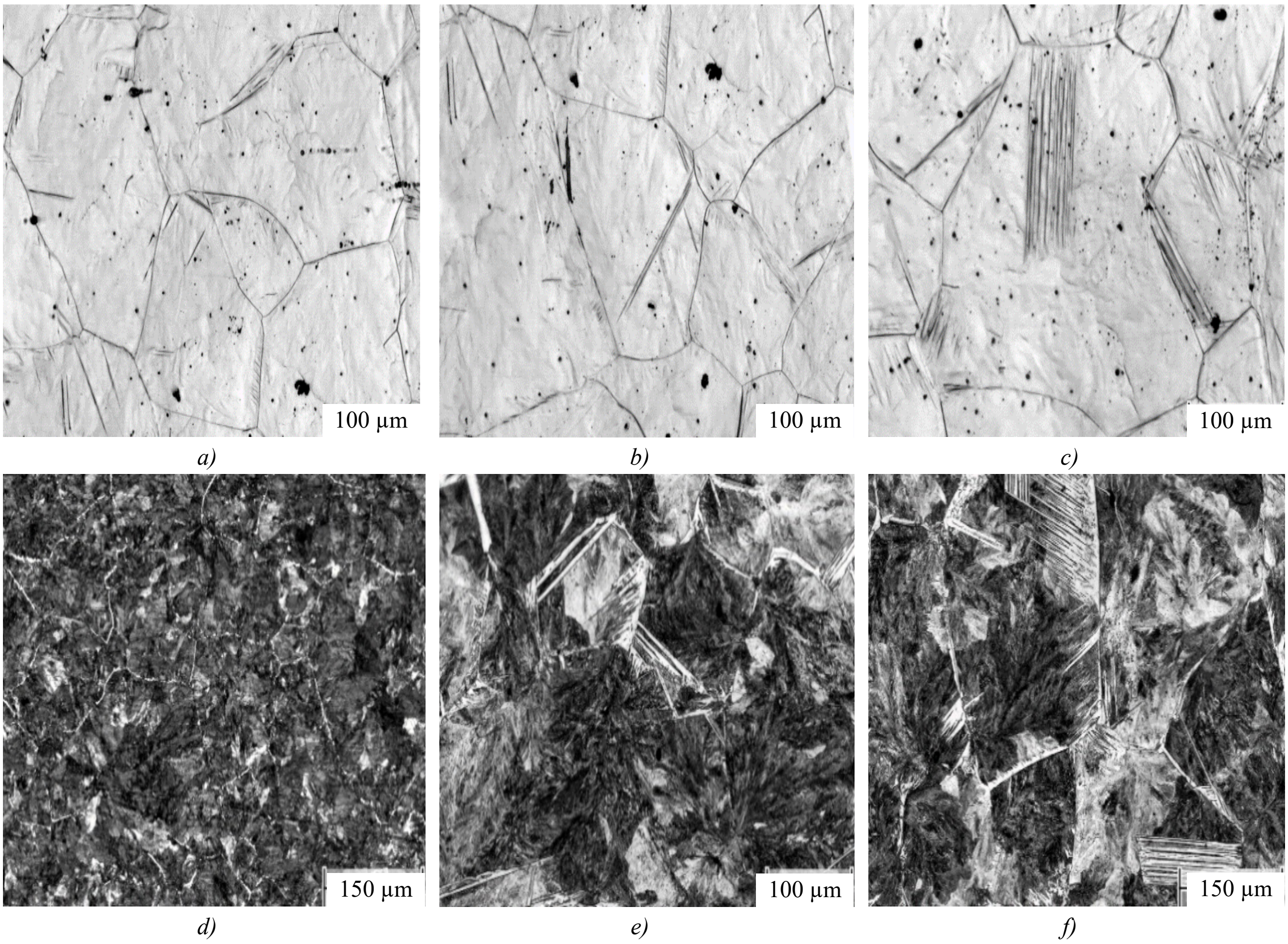


Fig. 2. Microstructure of the surface relief (*a, b, c*) and inside t he sample (*d, e, f*) after processing:
a, d — without a field; *b, e* — in a magnetic field with a strength of 400 kA/m;
e, f — in a magnetic field with a voltage of 800 kA/m

When processing without a field, changes in the surface relief were observed only in individual small formations (1st line of Fig. 1 and Fig. 2 *a*). On the video recording of austenite grain cooling, the propagation of the wave process over the surface was slightly noticeable. Apparently, this was a reflection of phase transformation. Microstructural analysis of the inner layers of the sample showed the presence of an overwhelming amount (98%) of the pearlitic structure (Fig. 2 *d*).

With the imposition of an external magnetic field, the surface relief was formed by nascent and growing bainite needles (the 2nd line of Fig. 1 and Fig. 2 *b*). These crystals could not be classified as martensitic because of their slow growth (Fig. 1). With increasing field strength, the intensity of shear transformation on the surface increased (Line 3 of Fig. 1 and Fig. 2 *c*), a batch bainite was formed.

Under the action of a magnetic field with a strength of 400 kA/m, the volume fraction of bainite increased three-fold — up to 6% (Fig. 2 *e*) compared with treatment without a field. In a magnetic field with a strength of 800 kAm, the volume fraction of bainite was already 8÷10%. This allowed us to conclude that it stimulated the change of the scenario of transformation from pearlite to bainite during processing in an external magnetic field.

If the initial phase (austenite) was kept as long as possible during cooling, then the short-range magnetic order (magnetic inhomogeneity), which increased in it with a decrease in temperature, would lead to an athermal martensitic transformation scenario to its critical extent. This was known from [9]. It was shown in [1] that the superposition of an external magnetic field during cooling of austenite led to additional, forced magnetic stratification of austenite due to an increase in the number, size and time of stable existence of ferromagnetic clusters. Under the conditions of the current experiment, artificially enhanced by an external field, the short-range magnetic order in the γ-phase promoted the bainite transformation instead of the pearlite one, which was natural for these cooling conditions without superposition of the field.

Under the influence of a magnetic field, the kinetics of the bainite transformation changed significantly. This was evidenced by the increase in the bainite reaction noted during the experiment with an increase in the magnetic field strength. In addition, [7] considered the imposition of an external magnetic field with a strength of 1.6 MA/m during isothermal exposure of various steels. The results of this work also confirmed the above statement about the kinetics of transformation.

To clarify the mechanism of the influence of an external magnetic field on the kinetics of an intermediate transformation, the following factors were taken into account:

– specifics of the growth of bainite crystals, which depended on the rate of removal of carbon atoms from the γ/α boundary;

– structural stresses arising during transformation due to changes in the specific volume of the transforming phases.

This approach was due to the fact that relaxation processes at the interface were strongly inhibited at low temperatures [12]. In such a situation, the stress gradient caused the drift of carbon atoms in spite of the concentration heterogeneity. This played a decisive role in the rate of growth of the lower bainite. The movement of C atoms led to a decrease in its concentration in the volumes of the γ-phase along the growth front of the bainite plates. As a result, a concentration gradient-controlled diffusion flow occurred. It was directed towards the growing crystal and reduced its growth rate. Dependencies describing these processes were found in the works of L.N. Alexandrov and B.Ya. Lyubov [13].

Magnetostrictive deformations occurred under the influence of an external magnetic field. Their elastic energy could make a certain contribution to the energy of interaction of diffusing atoms with the field of structural stresses. An increase in carbon drift and an increase in the growth rate of α-phase crystals should be expected. The rate of growth by the drift mechanism in accordance with the calculations of L.N. Alexandrov and B.Ya. Lyubov is described by the dependence:

$$V = \frac{2PD}{R_{кр} kT\left(1-\left(\frac{C_{н.ф}}{C_0}\right)^{\frac{4}{7}}\right)}. \quad (1)$$

Here D — carbon diffusion coefficient in austenite; $R_{кр}$ — radius of the critical nucleus under the supercooling; $C_{н.ф}$ and C_0 — carbon concentration in the α-phase and the initial austenite respectively. P characterizes the energy of interaction of diffusing atoms with the field of structural stresses caused by dilation of ε with a change in volume during the transformation process, and is found from the ratio:

$$P = \frac{8}{9}\pi r_a^3 \omega \frac{4\mu\varepsilon m}{(3-4v)(1-m)}, \quad (2)$$

where r_a — radius of the carbon atom; ω — parameter characterizing the dependence of the lattice constant on the concentration of atoms of the dissolved element in solid solutions; E — Young's modulus; ν — Poisson's ratio; $\mu = (E / 2) \cdot (1 - v)$ — Lame coefficient (shear modulus in the direction [100]); $m = (a - b) \cdot (a + b)$, where a and b — dimensions of the semi-axes of the crystal in the form of an ellipsoid of rotation.

The calculation according to formula (1) was carried out for carbon steel at: $C_0 = 0.7$; $m = 0.9$; $v = 0.3$; $\mu \approx 73.5$ hPa; $D = 0.0999\, exp\left(\frac{-131300\,\text{J/mol}}{RT}\right)\frac{\text{cm}^2}{\text{c}}$; $\varepsilon = 0.01$; $\omega = 0.02$. Value $R_{кр}$ was determined from the ratio $R_{кр} = 2\sigma / \Delta F_0$. Surface tension at the coherent boundary $\sigma = 0.2$ J/m^2; ΔF_0 at $T = 600$ K was 315 MJ/m^3. Value $C_{н.ф} = 0.4$ was determined as the concentration corresponding to the temperature of the beginning of the martensitic transformation (600 K). The growth rate of α-phase crystals found in this way was $\sim 8 \cdot 10^{-6}$ cm/s, i.e. it was a value of the same order as $V_{ср} \sim 10^{-6}$ cm/s, obtained experimentally for 65G steel when videotaping isothermal relief formation.

When the magnetic field was turned on, the measurement of the growth rate gave the same results, i.e. the effect of magnetostrictive stresses on the intensification of drift was not experimentally detected.

Let us suppose the elastic displacement was equal to the true magnetostriction of the paraprocess $\lambda \approx 0.5 \cdot 10^{-4}$ [14]. In this case, at $H = 1.6$ MA/m and $t = 400$°C the stresses from magnetostriction were $\sigma_\lambda = E_\lambda \approx 10$ MPa. They made a very small contribution to the energy of interaction of diffusing atoms with the field of structural stresses. This was explained by the fact that the magnitude of magnetostriction was two to three orders of magnitude less than the magnitude of dilation (0.01 ÷ 0.07 [15]) at a shear γ→α transition. For this reason, the estimation of the contribution of magnetostriction according to formula (1) gave a vanishingly small difference in the values of the growth rate during processing without a field and in a magnetic field.

The acceleration of the bainite formation process can actually be estimated using the A.N. Kolmogorov equation [16], which establishes a relationship between the degree of transformation, the rate of nucleation and the growth of the centers of a new phase. The change in the volumetric rate of transformation in a magnetic field due to a decrease in the formation of a ferromagnetic nucleus of critical size [1] can be found by formula:

$$\frac{\upsilon_H}{\upsilon_0} = exp\left[\frac{w}{kt}\left[1-\left(1+\frac{\Delta f^*}{\Delta f}\right)^{-4}\right]\right], \quad (3)$$

where υ — volumetric rate of transformation (indices *0* and *H*, respectively, indicate the processing conditions without a field and in an external magnetic field); *W* — energy of formation of an equilibrium nucleus; *I* — magnetization; *H* — magnetic field strength; Δf — specific "chemical" driving force; Δf^* — free energy of formation of one ferromagnetic cluster [1].

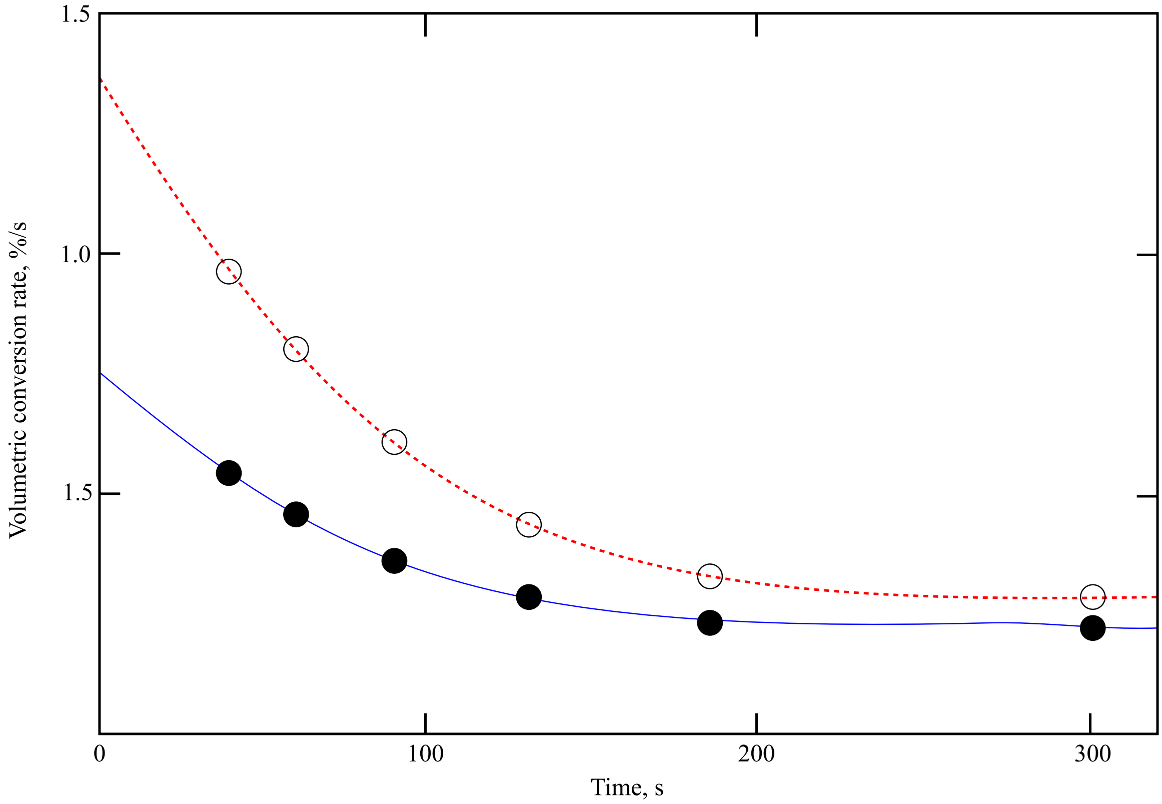
According to the classical theory of L. Kaufman and M. Cohen [17], the nucleation energy of the centers of new phases is equal to:

$$W = \frac{952,7 \cdot \theta^2 \sigma^2}{\left(\Delta f + \Delta f^*\right)^4}. \quad (4)$$

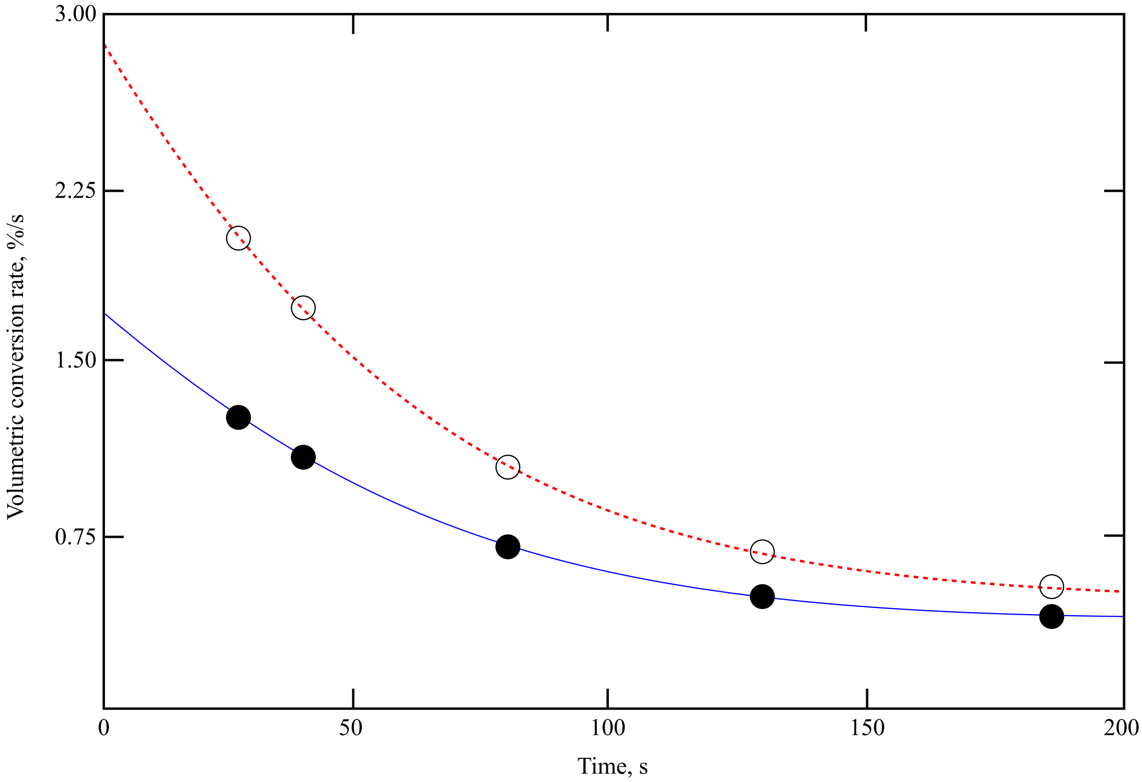
Here Δf^* — process of formation of ferromagnetically ordered clusters in austenite; θ — parameter that takes into account the influence of elastic deformation energy; σ — surface tension. It is known from [17] that $\theta^2\sigma^3 = 9.92 \cdot 10^{10}$ J^5/m^{12}.

Calculations were performed for temperatures of 543 K (65G steel) and 628 K (45Kh steel) at a magnetic field strength of $H = 1.6$ MA/m. Energy of formation of the equilibrium nucleus *W* was determined at a specific chemical driving force $\Delta f = 150$ MJ/m^3 taking into account the field strength and the average size of the ferromagnetic cluster ~ 1.8 nm [1], for which value $\Delta f^* = 0.63$ MJ/m^3 was obtained. Calculation by formula (3) gave for the bainitic transformation in 65G steel $\upsilon_H/\upsilon_0 = 1.804$, and in 45 Kh steel $\upsilon_H/\upsilon_0 = 1.665$.

Dependencies of the volumetric conversion rate (Fig. 3) were obtained using experimental data [7] on the degree of bainitic transformation in 65G and 45Kh steels at different times of isothermal exposure without a field and in a magnetic field with a strength of 1.6 MA/m.



a)



b)

Fig. 3. Dependencies of volumetric conversion rate (vertical axis, %/ s) on time of isothermal exposure: *a* — for 65G steel at a temperature of 375°C; *б* — for 45Kh steel at a temperature of 320°C. The blue curve reflects processing data without a field, the red one — in a magnetic field. Experimental points are marked on each line

Figure 3 allows us to consider the ratio of the volumetric conversion rate during processing in the field to processing without the field υ_H/υ_0 at the very beginning of the bainite reaction (extrapolated value in τ = 1 s). For 65G steel, it turns out to be 1.808, for 45Kh steel — 1.687. This is close to the theoretical estimates given above: 1.804 for 65G steel and 1.665 for 45Kh steel. In the process of transformation, the speeds change. If we consider the very first experimental points on the graphs, then:

– for 65G steel at τ = 40 s υ_H/υ = 1.75;

– for 45Kh steel at τ = 28 s υ_H/υ = 1.629.

As the isothermal exposure time increases, the volume velocities become less correlated with the calculated values.

Conclusion. It has been experimentally established that by using an external magnetic field, it is possible to change the transformation scenario from pearlite to bainite. This is explained by an increase in the degree of short-range magnetic order in austenite as a result of an increase in the number and size of ferromagnetic clusters in the gamma phase under the influence of a magnetic field. With an increase in its voltage, the magnetic heterogeneity of austenite increases. As a result, the rate of bainite transformation increases. The calculated values of the increase in the volumetric rate of transformation under the action of an external magnetic field are in good agreement with experimental data for the initial rates of bainite transformation.

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Received 28.12.2023
Revised 25.01.2024
Accepted 29.01.2024

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Conflict of interest statement: the authors do not have any conflict of interest.

All authors have read and approved the final manuscript.

Поступила в редакцию 28.11.2023
Поступила после рецензирования 25.12.2023
Принята к публикации 29.12.2023

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Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.