Vol. 8, no. 3, 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. 3, 2024

The journal is created in order to highlight the results of research and real achievements on topical issues of Mechanical Engineering, Technosphere Safety, Modern Metallurgy and Materials Science. The journal highlights the problems of the development of fundamental research and engineering developments in a number of important areas of technical sciences. One of the main activities of the journal is integration into the international information space.

The Journal Publishes Articles in the Following Fields of Science:

Ground Transport and Technological Means and Complexes (Engineering Sciences)
Machines, Aggregates and Technological Processes (Engineering Sciences)
Metallurgical Science and Heat Treatment of Metals and Alloys (Engineering Sciences)
Powder Metallurgy and Composite Materials (Engineering Sciences)
Materials Science (Engineering Sciences)
Fire Safety (Engineering Sciences)
Environmental Safety (Engineering Sciences)
Occupational Safety (Engineering Sciences)

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	30.08.2024

Безопасность техногенных и природных систем

Рецензируемый научно-практический журнал (издается с 2017 года)

eISSN 2541-9129
DOI: 10.23947/2541-9129

Том 8, № 3, 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:

2.5.11 – Наземные транспортно-технологические средства и комплексы (технические науки)
2.5.21 – Машины, агрегаты и технологические процессы (технические науки)
2.6.1 – Металловедение и термическая обработка металлов и сплавов (технические науки)
2.6.5 – Порошковая металлургия и композиционные материалы (технические науки)
2.6.17 – Материаловедение (технические науки)
2.10.1 – Пожарная безопасность (технические науки)
2.10.2 – Экологическая безопасность (технические науки)
2.10.3 – Безопасность труда (технические науки)

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	30.08.2024

Contents

Содержание

ANNIVERSARY OF THE SCIENTIST
ЮБИЛЕЙ УЧЕНОГО

Besarion Chokhoevich Meskhi, scientist, engineer, teacher, leader, is 65

Besarion Chokhoevich Meskhi — Doctor of Engineering Science, Professor, Corresponding Member of the Russian Academy of Education, Deputy of the Legislative Assembly of the Rostov Region, Rector of Don State Technical University, Member of the Presidium of the Southern Scientific Centre of the Russian Academy of Sciences, Head of the Rostov Scientific Center of the Southern Branch of the Russian Academy of Education, Chairman of the Council of Rectors of the Rostov Region, Editor-in-Chief of peer-reviewed scientific and practical journals "Safety of Technogenic and Natural Systems" and "Science Almanac of Black Sea Region Countries" included in the list of the Higher Attestation Commission of the Russian Federation.

Besarion Chokhoevich began his career as an electrical engineer after graduating from the Rostov Institute of Agricultural Engineering in 1985, earning a degree in Automation of Agricultural Production. From his first year of study, he demonstrated his dedication to his education by actively participating in social activities and combining his studies with work in the research department. After receiving his diploma, Besarion Chokhoevich Meskhi dedicated his life to his alma mater, working his way up through the ranks from senior laboratory assistant to engineer and senior engineer in the Department of Automation of Agricultural Production, and eventually becoming the head. Since 1990, he worked as a vice-rector for administrative and economic affairs, then since 2002 as a vice-rector for administrative and economic work and capital construction. In 2007, the staff of the university (84.3%) elected Besarion Chokhoevich Meskhi as the rector of Don State Technical University. Since then, three more times — in 2012, 2017, and 2022 — the university staff has re-elected Besarion Ch. Meskhi to the position of rector, demonstrating their respect and trust for his leadership and commitment to the chosen path of university development. During this time, Besarion Ch. Meskhi also headed the Department of Life Safety and Environmental Protection from 2007 to 2018. In 2021, he was elected a Corresponding Member of the Russian Academy of Education.

Besarion Ch. Meskhi is a renowned expert in the field of technological and industrial safety. He defended his candidate dissertation in 1999 and his doctoral dissertation in 2004, both in the specialty of Occupational Safety (Technical Sciences). He is the leader of the scientific school "Theory and Methods of Integrated Occupational Safety in Machine-Building Industries and Technological Equipment in Design". His scientific and technical solutions have formed the scientific and methodological basis for improving safety in the machine-building industry and have been implemented at major companies in the region, including LLC KZ Rostselmash, LLC Novocherkassk Electric Locomotive Plant, and PJSC Rostvertol.

Besarion Ch. Meskhi holds 39 patents for his inventions and has authored more than 700 scientific papers and publications. Among these, 158 articles have been published in journals indexed in scientometric databases such as Scopus and Web of Science. Additionally, 77 of his articles have been published in journals included in the list of the Higher Attestation Commission. His Hirsch index, based on the Scopus database, is 22.

Currently, Besarion Ch. Meskhi is actively involved in multilevel work on training highly qualified personnel. With extensive experience in managing scientific projects, Professor Meskhi chairs DSTU dissertation council 24.2.297.05, which oversees the defense of candidate and doctoral dissertations in the specialties "Occupational safety" and "Machines, aggregates and technological processes". Under his guidance, 3 doctoral dissertations and 10 candidate dissertations have been successfully defended.

The Rector of Don State Technical University places great emphasis on the systematic development of engineering education, both within the university and through interuniversity partnerships. Within the university, modern teaching formats and effective educational platforms are being introduced. These include the Institute of Advanced Technologies "School X" and the Institute of End-to-End Technologies "T-University", as well as an advanced engineering school, the Institute of Advanced Mechanical Engineering "Rostselmash". Additionally, the university is actively pursuing interuniversity collaborations through the establishment of joint experimental sites for engineering education with leading universities across the country.

For his outstanding achievements in his professional career, Besarion Ch. Meskhi was awarded medals of the Order “For Merit to the Fatherland” of the I and II degrees, the Order of Friendship, the Badge of Honor of Higher Professional Education of the Russian Federation, the Medal of St. Sergius of Radonezh of the I degree of the Russian Orthodox Church, the Badge of the Ministry of Emergency Situations of Russia “For Merits”, Gratitude and Diploma of ehe President of the Russian Federation to the Commemorative Medal “XXVII World Summer Universiade 2013 in Kazan”, the Badge of Honor “For Service to the city of Rostov-on-Don”, the Medal of the Order “For Service to the Rostov region”, the Order “For Service to the Rostov region”. In 2009, Besarion Ch. Meskhi received the award of the Government of the Russian Federation in the field of education.

The Editorial Team of the journal “Safety of Technogenic and Natural Systems” heartily congratulates Besarion Ch. Meskhi on his anniversary and wishes him good health, happiness, and continued success in his organizational, scientific, and educational endeavors.

TECHNOSPHERE SAFETY
ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ

UDC 539.3
https://doi.org/10.23947/2541-9129-2024-8-3-9-18

Original Theoretical Research

Relationship between Changes in the Frequency of Thunderstorms, the Number of Forest Fires in the Territory of Yugra, and Air Temperature and Solar Activity during Climate Warming

EDN: KQQSVJ

Aleksandr V. Kholoptsev
Siberian Fire and Rescue Academy of the State Fire Service of the Ministry of Emergency Situations of Russia, Zheleznogorsk, Russian Federation
✉ knd@sibpsa.ru

Abstract

Introduction. Improving methods for modeling and forecasting changes in the number of forest fires, as well as the frequency of thunderstorms that cause them, is a significant challenge for environmental safety, emergency preparedness, and climatology. This is particularly relevant for regions with a forest landscape, such as the Khanty-Mansi Autonomous Okrug (Yugra). Domestic and foreign researchers have found that variations in seasonal average air temperatures and solar activity are effective predictors for modeling these processes in many regions. However, the connections between these processes and these factors in Yugra remain understudied, hindering our ability to determine the usefulness of including them in predictive models. The aim of the study is to test the hypothesis that there are significant statistical relationships between changes in the frequency of thunderstorms, the number of forest fires in the territory of Yugra, and variations in average air temperatures near the surface of the atmosphere during the thunderstorm season. The study aims to investigate whether these relationships are significant and increasing during periods of climate warming, as well as to assess the impact of solar activity on these relationships. To achieve this goal, we have analyzed the significance of correlation between the changes in the frequency of thunderstorms over the territory of Ugra and synchronous variations in the number of forest fires occurring here, as well as synchronous and ahead of time variations in the average seasonal air temperatures and solar activity in the period of climate warming.

Materials and Methods. The study used observational data on average daily air temperatures, dates of thunderstorms over representative hydrometeorological stations of the studied area, information on changes in average annual solar radiation with a wavelength of 10.7 cm, and information on forest fires and related emergencies in Yugra. The data were obtained from international and Russian climate data banks and systems, as well as official reports from relevant ministries and agencies. The method of assessing the strength of links between processes was multiple correlation analysis. The statistical significance of identified links was assessed using the Student's t-test.

Results. As a result of the study, it was established that the hypothesis put forward was valid. There was the correlation between the changes in the frequency of thunderstorms and the number of forest fires in the territory of Yugra with variations in average air temperatures and solar activity during the thunderstorm season. This trend was significant and increasing. We proved that the correlation of interannual changes in the number of forest fires that occurred in the XXI century in the territory of Yugra per year with synchronous variations in the frequency of thunderstorms over it was significant and intensified. The conditions were identified under which statistical relationships between changes in the frequency of thunderstorms here, as well as variations in average monthly air temperatures and solar activity, were significant and are increasing now. Therefore, when these conditions were met, it was advisable to take into account the factors under consideration during modeling and forecasting of the process under study.

Discussion and Conclusion. The results obtained fully confirm the existing ideas about the impact of climate change and solar activity on the frequency of thunderstorms in the atmosphere, as well as the features of current climate change in Western Siberia. These connections can be used to predict changes in thunderstorm frequency and forest fire risk, and these predictions should be taken into account when planning activities within the unified state emergency management system.

Keywords: Khanty-Mansi Autonomous Okrug, forest fires, thunderstorms, solar activity, mean air temperatures, correlation, modern period

Acknowledgements. The author would like to thank the Editorial team of the Journal and anonymous reviewers for their competent expertise and valuable recommendations for improving the quality of the article.

For citation. Kholoptsev AV. Relationship between Changes in the Frequency of Thunderstorms, the Number of Forest Fires in the Territory of Yugra, and Air Temperature and Solar Activity during Climate Warming. *Safety of Technogenic and Natural Systems.* 2024;8(3):9–18. https://doi.org/10.23947/2541-9129-2024-8-3-9-18

Оригинальное теоретическое исследование

Связь изменений повторяемости гроз и количества лесных пожаров на территории Югры с температурой воздуха и солнечной активностью при потеплении климата

А.В. Холопцев
Сибирская пожарно-спасательная академия ГПС МЧС России, г. Железногорск, Российская Федерация
knd@sibpsa.ru

Аннотация

Введение. Совершенствование методик моделирования и прогнозирования изменений количества лесных пожаров, а также повторяемости гроз, их вызывающих, является актуальной проблемой экологической безопасности, безопасности при чрезвычайных ситуациях, а также климатологии. Наибольший интерес ее решение представляет для регионов лесной ландшафтной зоны, одним из которых в России является Ханты-Мансийский автономный округ (Югра). Отечественными и зарубежными учеными установлено, что во многих регионах к числу эффективных предикторов моделей изучаемых процессов относятся вариации среднесезонных температур воздуха над исследуемыми территориями, а также солнечная активность. Вместе с тем связи таких процессов с названными факторами в Югре изучены недостаточно, что не позволяет оценить целесообразность их учета. Целью данной работы является проверка гипотезы о том, что статистические связи изменений повторяемости гроз и количества лесных пожаров на территории Югры с синхронными или опережающими их по времени вариациями средних за грозоопасный сезон температур воздуха в приземном слое атмосферы и солнечной активностью являются значимыми и усиливаются. Задачи, которые были решены для достижения поставленной цели, состоят в оценке значимости корреляции между изменениями повторяемости гроз над территорией Югры и синхронными вариациями количества возникающих здесь лесных пожаров, а также синхронными и опережающими по времени вариациями среднесезонных температур воздуха и солнечной активности в период потепления климата.

Материалы и методы. Фактический материал исследования составили данные наблюдений о среднесуточных температурах воздуха и датах, в которые происходили грозы над репрезентативными гидрометеорологическими станциями изучаемого района, информация об изменениях среднегодового потока солнечного радиоизлучения с длиной волны 10,7 см, сведения о количестве зарегистрированных лесных пожаров и чрезвычайных ситуаций, ими обусловленных, на территории Югры, представленные в международных и российских климатических банках данных и информационных системах, а также в официальных докладах профильных министерств и ведомств. Методом оценки силы связей между рассматриваемыми процессами явился множественный корреляционный анализ, а оценка статистической значимости выявленных связей выполнена с использования критерия Стьюдента.

Результаты исследования. В результате исследования впервые установлено, что выдвинутая гипотеза о том, что связи изменений повторяемости гроз и количества лесных пожаров на территории Югры с вариациями средних за грозоопасный сезон температур воздуха и солнечной активностью являются значимыми и усиливаются, является справедливой. Доказано, что корреляция межгодовых изменений количества лесных пожаров, возникавших в XXI веке на территории Югры за год, с синхронными вариациями повторяемости над ней гроз была значимой и усиливалась. Выявлены условия, при которых статистические связи между изменениями здесь повторяемости гроз, а также вариациями среднемесячных температур воздуха и солнечной активностью значимы и в настоящее время усиливаются. Следовательно, при выполнении этих условий учет рассматриваемых факторов в ходе моделирования и прогнозирования изучаемого процесса целесообразен.

Обсуждение и заключение. Полученные результаты в полной мере соответствуют существующим представлениям о влиянии потепления климата и солнечной активности на изменения повторяемости гроз в земной атмосфере, а также об особенностях современных изменений климата Западной Сибири. Выявленные связи могут быть использованы при прогнозировании изменений повторяемостей гроз и лесных пожаров, результаты которого целесообразно учитывать при планировании деятельности соответствующих функциональных подсистем единой государственной системы предупреждения и ликвидации чрезвычайных ситуаций.

Ключевые слова: Ханты-Мансийский автономный округ, лесные пожары, грозы, солнечная активность, средние температуры воздуха, корреляция, современный период

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

Для цитирования. Холощев А.В. Связь изменений повторяемости гроз и количества лесных пожаров на территории Югры с температурой воздуха и солнечной активностью при потеплении климата. *Безопасность техногенных и природных систем*. 2024;8(3):9–18. https://doi.org/10.23947/2541-9129-2024-8-3-9-18

Introduction. According to Russian [1] and foreign researchers [2], thunderstorms that pass over certain areas are a cause of landscape fires in various parts of the world, causing significant damage to ecosystems. Therefore, the improvement of methods for modeling and forecasting changes in the frequency of thunderstorms is an urgent problem of environmental safety. The regions with significant forest resources are the most interested in solving this problem, as landscape fires, which occur predominantly in forests, cause the most damage to the environment, population and economy.

In Russia, one of these regions is the Khanty-Mansi Autonomous Okrug (Yugra). Its territory is located on the West Siberian lowland and is characterized by almost monotonous taiga landscapes[1], as a result of which the Khanty-Mansi hydrometeorological station (HMS) (61.01ºN, 69.06ºE) can be considered representative for it

52% of the Yugra's area is covered by forests, and the fires that occur there annually cause significant damage to the region's forest resources [3]. A notable feature of this territory is that approximately 30% of all forest fires are caused by thunderstorms[2].

Figure 1 shows the territories of Yugra that belong to the control zone. These territories are relatively small, and most of them are occupied by the area of forest aviation activities. Therefore, the data from the Information System for Remote Monitoring of the Federal Forestry Agency (ISDM-Rosleskhoz)[3] is quite reliable regarding the number of forest fires (NFF) that occurred on this territory in a given year.

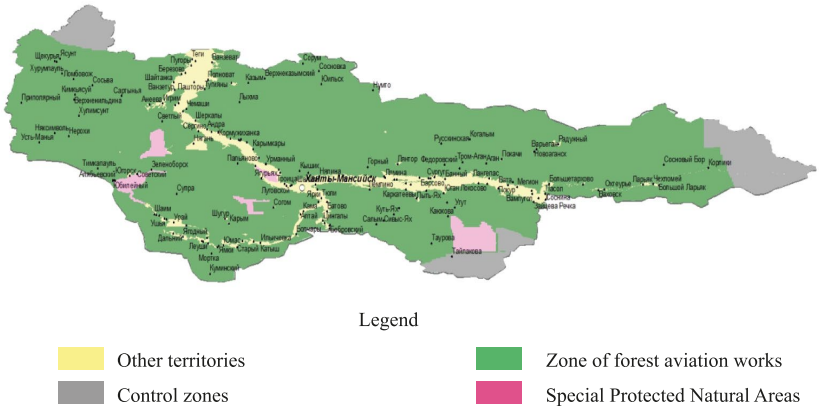


Fig. 1. Sections of control zones on the territory of Yugra [4]

In the territory of Yugra, the risk of forest fires is increased due to its status as the major oil-producing region of Russia. Oil production takes place at 406 oil fields, including the Samotlor, Priobskoye, Fyodorovskoye, and Mamontovskoye fields, which have unique reserves [4].

The works of Baranovskii N.V. [5], Ivanov V.A. and others [6] are basis for the existing ideas about modeling changes in the frequency of thunderstorms (FT), as well as NFF over Siberia. They show that the processes under consideration may depend on numerous factors, some of them are not observable, therefore it is advisable to consider them as random processes, in modeling which the multiple regression method is effective [7].

The mentioned method is also applicable in forecasting. The latter is possible if the factors of the studied processes, which were significant in the past, will remain significant in the future, for which the forecast is being developed. The future is not predetermined, however, the feasibility of this condition is more likely if the statistical relationships under consideration have been strengthened in the past [8].

[1] Makunina GS. *The West Siberian Plain.* The Great Russian Encyclopedia (2004–2017). URL: https://old.bigenc.ru/geography/text/4138680 (accessed: 19.03.2024). (In Russ.)
[2] *Information System of Remote Monitoring of the Federal Forestry Agency.* URL: https://pushkino.aviales.ru/main_pages/index.shtml (accessed: 19.03.2024). (In Russ.)
[3] *Information System of Remote Monitoring of the Federal Forestry Agency.* URL: https://pushkino.aviales.ru/main_pages/index.shtml (accessed: 19.03.2024). (In Russ.)
[4] *The Layout of the Control Zone on the Territory of the Khanty-Mansi Autonomous Okrug.*URL: https://aviales.ru/default.aspx?textpage=229 (accessed: 06.05.2024). (In Russ.)

It is obvious that the forecast of the studied process, built taking into account such a factor, may correspond to a scenario in which the main patterns that determine their dynamics will not change in the future.

In the studies of many authors, for example, Baranovskii N.V. [5], Ivanova G.A. et al. [9], Kopeikin M.A. et al. [10], it was found that the number of significant factors of FT and NFF in certain territories of Siberia may include synchronous variations in the average seasonal temperatures of the air above them and solar activity.

The relationship between changes in FT and average air temperatures (AAT) at the Earth's surface during the thunderstorm season is causal, since thunderstorms are formed during thermal convection in Cb thunderstorms [11], and the intensity of the latter is higher the higher the average air temperature in the cloud layer [12].

The relationship between changes in FT and solar activity is also causal, since due to the Forbush effect [13], the latter significantly affects variations in the flow of galactic and extragalactic cosmic rays entering the Earth's atmosphere and participating in the ionization of air in thunderclouds. The higher the solar activity, the lower the intensity of air ionization in thunderclouds, and the frequency of thunderstorms is decreased [14].

The connections of solar activity and changes in AAT with variations in NFF have been revealed only statistically. Nevertheless, in the twentieth century they were significant for several decades [15]. Since both of these factors of the studied processes were significant in the twentieth century, they are usually taken into account in modeling. The question of whether it is advisable to take these factors into account when forecasting the studied processes has not been adequately addressed. It has been found that quasi-biennial modes are present in the variability spectra of FT and AAT, which leads to a statistical relationship between their fluctuations with time lags of 2–3 years. The main mode of solar activity is the 11–year cycle, which also suggests a possible correlation between changes in solar activity over time that are shifted by years [16].

Consequently, the connections of changes in NFF and FT with the factors under consideration, which are ahead of them for such a time, are possible because these connections are inherent in these factors themselves. However, the significance of such connections is far from obvious.

The ideas about the importance of the factors under consideration are based on the results of monitoring conducted in the twentieth century. However, climate changes that have occurred on the territory of Yugra in the twenty-first century, as well as various anthropogenic impacts on forest ecosystems in this region, have the potential to disrupt the links between the studied processes and some of their factors [17]. As a result, taking these factors into account when predicting the studied processes may not improve, but, on the contrary, worsen the justifiability of its results.

In the 21st century, monitoring of the studied processes and their factors in the region continues. Nevertheless, the existence of properties between its results that determine the expediency of taking them into account in modeling and forecasting these processes has not been previously verified. As a result, the expediency of their accounting needs to be confirmed. Assessing the correlation between the studied processes and their coincident and overlapping factors, as well as identifying trends in their changes, is not only of theoretical interest, but also of practical significance.

Based on the above, the aim of this study is to verify the hypothesis that there is a significant and increasing statistical relationship between changes in NFF and FT for the territory of Yugra with synchronous or time-ahead variations of AAT in the atmosphere and solar activity during the modern period.

To achieve this goal, an assessment was conducted of the significance of the correlation between FT over the territory of Yugra and synchronous changes in NFF, synchronous variations in AAT and solar activity. Additionally, time-ahead variations in AAT and solar activity were considered for the period of modern climate warming.

Materials and Methods. The information provided in the database on weather changes in various parts of the world[5] from 1961 to 2023 was used as factual material for the average daily temperatures above the reference HMS and the dates of thunderstorms occurred here.

The FT value was determined as the ratio of the number of days belonging to the thunderstorm season (May–September) of the studied year, in which thunderstorms occurred above the representative HMS, to its total duration (15 days).

The AAT value was calculated as the average value of the average daily temperatures of the surface layer of the atmosphere above the same HMS for the period from May 1 to September 30 of each year.

Information about the NFF in the territory of Yugra for the period from 2000 to 2023, which was also considered as factual material, was obtained from ISDM-Rosleskhoz[6].

[5] *Global Climate Data.* URL: https://en.tutiempo.net/climate (accessed: 13.05.2024).

[6] *Information System of Remote Monitoring of the Federal Forestry Agency.* URL: https://pushkino.aviales.ru/main_pages/index.shtml (accessed: 12.10.2023). (In Russ.)

As an actual material on solar activity, information from the database of changes in global climate indices[7], on changes in the average annual flux of solar radio emission with a wavelength of 10.7 cm (SA index), measurements of which were possible under any weather conditions and were most accurate, was used.

The value of their correlation coefficient was considered as a characteristic of the strength of the connection between the studied processes.

Taking into account the length of the considered NFF time series, the values of their correlation coefficient with synchronous FT series and the SA index were estimated in a sliding window of 11 years in solving the first problem.

The method of solving the second problem involved calculating the values of the correlation coefficient of the FT and AAT series, as well as the FT and the SA index in a sliding window of 11, 22 and 44 years for the period from 1961 to 2023.

When solving the third problem, the values of the correlation coefficient of the FT series, as well as the AAT series and the SA index series, which are 1–3 years ahead of it in time, were calculated.

When calculating the correlation coefficient values, the linear trends present in the compared segments of the time series corresponding to each sliding window have been previously compensated for.

The correlation coefficient value was considered significant if the reliability of such a statistical conclusion, estimated by the Student's t-test (taking into account the number of degrees of freedom of the series), was at least 0.95.

As a characteristic of the trend in the changes of the correlation coefficient in the studied series, we calculated the angular coefficient of the linear trend (ACLT) for the time series formed by the values of this coefficient within a sliding window of certain duration.

The revealed trend with a confidence of 0.95 was considered significant if:

$$N \cdot |A| > 1{,}65 \cdot CKO,$$

where $|A|$ — modulus of the angular coefficient of the linear trend in the time series being considered, which is determined from a series with length N; CKO — standard deviation of the members of this series from the corresponding trend.

The latter was true if the deviations of the members of the studied series from the corresponding trend followed the normal distribution. However, due to the small length of the series, it was not possible to verify the validity of this assumption using the Pearson's criterion. Therefore, the results should be considered to be of a qualitative nature.

Results. In accordance with the described methodology, when solving the first task, time series of the number of thunderstorms that occurred during the thunderstorm season (and actually over the year) over the representative GMS and NFF in the territory of Yugra were formed.

The corresponding time dependencies of these indicators are presented in Figure 2.

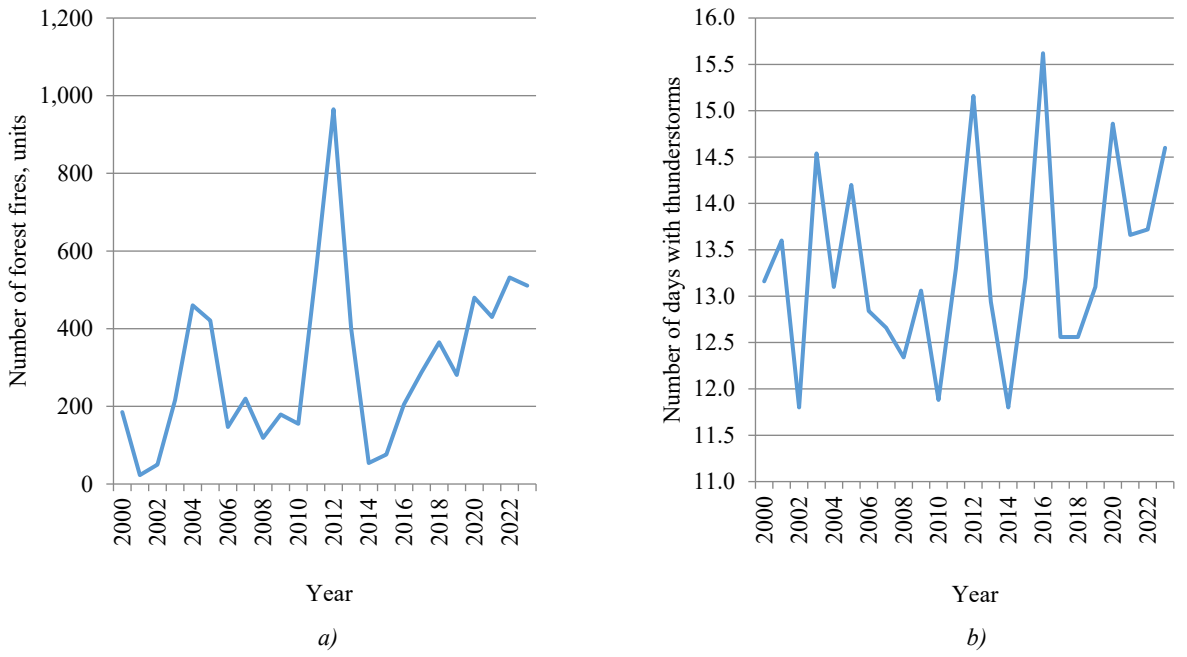


Fig. 2. Dependencies on the time of the number of events that occurred during the year over the Khanty-Mansi hydrometeorological station: *a* — number of forest fires; *b* — number of days with thunderstorms

[7] *Correlation of the Average Monthly Values of Climatic Time Series.* URL: https://psl.noaa.gov/data/correlation/solar.data (accessed: 13.05.2024). (In Russ.)

In Figure 2 it can be seen that both dependencies represented complex oscillations in which the periods of the most powerful short-period modes practically coincided. At the same time, in the period up to 2011, the maxima of the dependence of the number of thunderstorms on the time did not coincide with similar extremes of the same dependence of the NFF.

Since 2012, almost all the extremes of the same name of the dependencies under consideration coincided. Therefore, their correlation has clearly increased. The latter was confirmed by calculations.

The correlation coefficient of the series under consideration for the period from 2000 to 2023 was 0.484, which (with the number of degrees of freedom of the series 23) exceeded the threshold level of 0.44, corresponding to the reliability of the conclusion of 0.95. Consequently, the correlation of the time series of FT and NFF for the territory of Yugra was significant in the 21st century (the latter was quite expected, since, as noted above, about 30% of forest fires here caused thunderstorms). The correlation between the NFF and AAT series over the same period was also significant, which confirmed the validity of the conclusion [9] about the significance of the influence of Russian climate warming on forest fire.

Similarly, it was found that in the period from 2000 to 2023, the correlation of the time series of the NFF, as well as the series of the SA index, was not significant. The latter was quite understandable, since the periods of the most powerful modes of the spectra of interannual changes in the NFF and the SA index differed by 3–4 times.

An analysis of the relationships between the time series of the NFF in the territory of Yugra with the time-ahead series of the SA, AAT and FT indexes above the representative point showed that the correlation between them, estimated in a sliding window of 11 years, was not significant and became weaker over time. Therefore, when modeling changes in NFF over the territory of Yugra, it was advisable to take into account variations in the SA, AAT and FT indexes. However, it was ineffective to forecast these changes using the same predictors that are 1–3 years ahead of the studied process.

As a result of solving the second problem, the values of the correlation coefficient of synchronous segments of the FT and AAT series, as well as the FT and the SA indexes were calculated corresponding to sliding windows of 11, 22 and 44 years.

Taking into account these values, the dependencies of the coefficient of these series on the year of the beginning of the corresponding sliding window were constructed (Fig. 3).

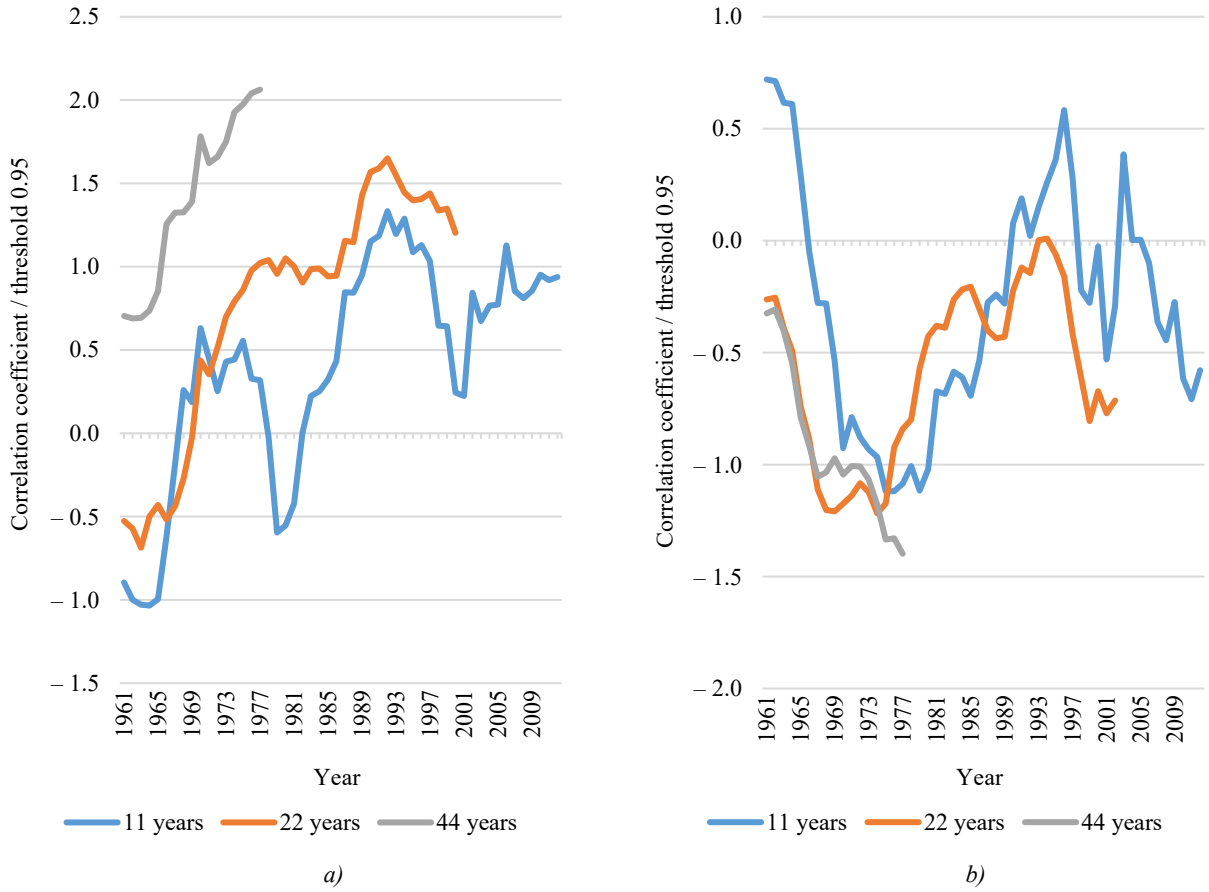


Fig. 3. Dependencies of sliding windows of 11, 22 and 44 years on the year of the beginning, their corresponding ratios to the threshold of significance of the coefficient of synchronous correlation of changes in FT over Khanty-Mansi HMS, as well as variations: *a* — AAT; *b* — SA index

The data in Figure 3 *a* demonstrate that the dependencies on the year of the start of the sliding windows with lengths of 22 and 44 years, as well as their corresponding ratios to the significance threshold of the correlation coefficient for changes in greenhouse gas emissions over the Khanty-Mansi region, and synchronous variations in AAT, were described by increasing functions on average. The values of these indicators for the windows corresponding to the modern period (2000–2023 and 1978–2023) were greater than 1 (indicating significance). Therefore, a scenario in which AAT remains a significant FT factor in the near future was more likely than an alternative scenario.

The dependence under consideration, which corresponded to a sliding window of 11 terms, was oscillatory in nature. For the window corresponding to the modern period (2012–2023), the value of the correlation coefficient of the FT and AAT series did not reach the level of significance. The reliability of the statistical conclusion about their significance was at least 0.94.

The obtained result confirmed the expediency of taking into account AAT variations when modeling FT changes over the territory of Yugra occurring in the 21st century.

Figure 3 *b* demonstrates that the dependencies of the ratio of the correlation coefficient of FT changes over the Khanty-Mansi HMS, as well as synchronous variations of the SA index to the threshold of significance for sliding windows of 11 and 22 years, also represented complex fluctuations. The values of this indicator for modern periods were significantly less than 1 (the correlation is not significant).

For a sliding window with a length of 44 years, the studied dependence was monotonous, and for the period 1978–2023, the correlation of the studied processes was negative and significant (the reliability of such a conclusion exceeds 0.95). Therefore, when modeling FT changes over such long periods of time, including the modern period, it was also advisable to take into account variations in the SA index.

When solving the third problem, it was established that the same conclusion was valid for the problems of forecasting changes in FT, in which the series of the SA index were used as predictors of multiple regression models.

As confirmation of this, Figure 4 shows the dependence of the correlation coefficient of FT changes over the Khanty-Mansi HMS on the year of the beginning of the 44-year sliding window, as well as the variations of the SA and AAT indexes that were 1–3 years ahead of them in time.

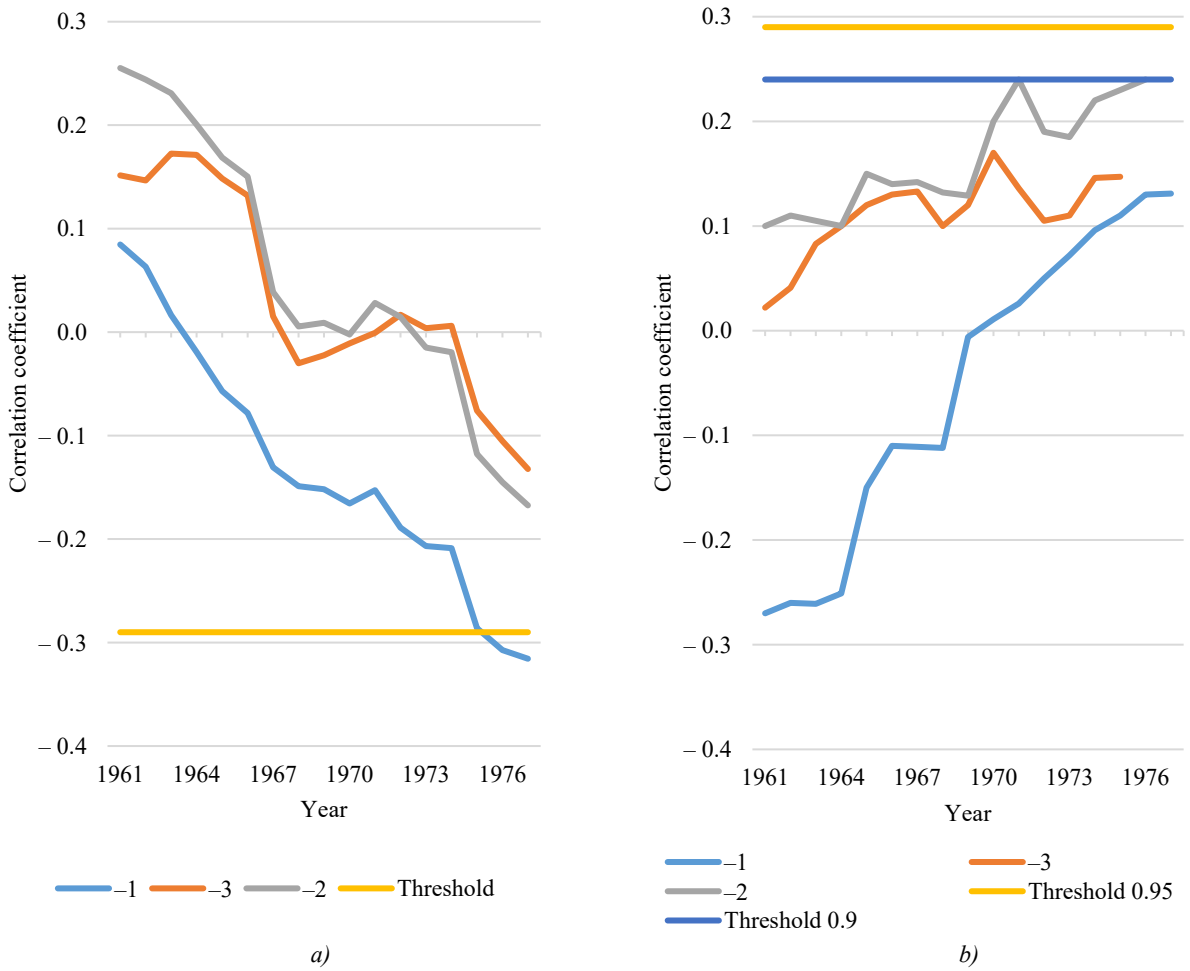


Fig. 4. Dependencies on the year of the beginning of the sliding window with a length of 44 years, the correlation coefficient of FT changes over the Khanty-Mansi HMS, as well as variations that are 1–3 years ahead of them in time: *a* — SA index; *b* — AAT

According to the data in Figure 4 *a*, it can be seen that during the period of modern climate warming, the correlation of 44-year-long segments of the FT time series over the representative HMS, as well as segments of the SA index series that were 1 year ahead of them in time, intensified and was significant in the period 1975–2023.

If the SA index series were ahead of the FT series for a longer time, their correlation also increased over the same period, but did not reach the selected significance level.

As follows from the data in Figure 4 *a*, the probability that the correlation of the FT series and the SA index would remain significant over time periods that also included the near future. It was higher than the probability of an alternative scenario. Therefore, taking into account changes in this factor when forecasting FT over the territory of Yugra for the coming year would help to increase the justifiability of its results.

The data in Figure 4 *b* indicate that the values of the correlation coefficient of FT changes over the same HMS over a time interval of 44 years, as well as AAT variations that were 1–3 years ahead of them, have increased over the period of modern climate warming. It follows that a scenario in which they would become larger in the future was more likely than an alternative scenario. At the same time, the reliability of the conclusion about the significance of the considered links in the period 1978–2023 reached only 0.9 (assuming that a number of AAT is 2 years ahead of a number of FT).

Similar studies performed for comparable shorter time periods showed that the time dependence of the correlation coefficient of changes in FT over the same HMS, as well as 1–3 years ahead of them, variations in the SA and AAT indexes were oscillatory (the trends of these processes were alternating). For the segments of the FT series, including 2023, the values of their correlation coefficient with the time-leading series of the factors under consideration were significantly less (modulo) than the threshold of significant correlation. Consequently, there were no grounds to believe that taking into account such short time series of the factors under consideration when predicting FT changes over the Khanty-Mansi HMS, which were 1–3 years late in relation to them, would lead to positive results.

Thus, it has been established that the hypothesis put forward regarding the synchronous connections of changes in NFF for the territory of Yugra with variations in FT and AAT was valid. It was also valid for synchronous connections of changes in FT with variations in AAT and the SA index. The hypothesis under consideration was also valid in relation to the relationships of FT changes, as well as variations in the SA index that were 1 year ahead of them.

In addition, it is shown that at present, the relationship of changes in the time intervals of 44 years of FT over the territory of Yugra, as well as the variations of the SA and AAT indexes ahead of them, are increasing, as a result of which such relationships may become significant in the future with other values of these advances.

The results obtained fully correspond to existing ideas about the influence of climate warming and solar activity on changes in the frequency of thunderstorms in the Earth's atmosphere [1], including those published by Rosgidromet[8], as well as about the features of modern climate changes in Western Siberia [3].

Discussion and Conclusion. The statistical links between changes in NFF and FT, as well as NFF and AAT in the territory of Yugra in the 21st century are not only significant, but also significantly enhanced. Therefore, it is advisable to take into account the results of monitoring of AAT and FT when modeling forest fires in the territories belonging to the control zone, as well as when managing the activities of its fire-fighting units (according to Federal Laws 69–FZ and 123–FZ).

The correlation of FT changes over the territory of Yugra, as well as time-matching variations of AAT over time periods ending in 2023 is significant and increases provided that their length is at least 11 years. For such a factor as variations in the SA index, it is significant and increases only if the length of the corresponding segments is at least 44 years.

The correlation of FT changes over the territory of Yugra with variations of the SA index that are 1 year ahead of them in time is significant and increases, provided that it is estimated for time periods of at least 44 years. With large values of such advances, the relationship between these processes also increases, but it has not reached the level of significance by 2023.

Thus, it has been established that the revealed features of statistical relationships between changes in the period of modern climate warming, the number of forest fires and the frequency of thunderstorms over the territory of the Khanty-Mansi Autonomous Okrug (Yugra), as well as with variations in seasonal average air temperatures and solar activity, correspond to existing ideas about the reasons for the existence of these relationships.

In the 21st century, synchronous relationships between changes in the number of forest fires that occurred per year in the territory of the studied region and variations in the frequency of thunderstorms over it are significant and increasing. This suggests that part of the total number of forest fires formed here due to the action of lightning discharges will increase in the future.

[8] *The Third Assessment Report on Climate Change and Its Consequences on the Territory of the Russian Federation. General Summary.* Saint-Petersburg: Naukoemkie tekhnologii; 2022. 124 p. URL: https://www.meteorf.gov.ru/upload/pdf_download/compressed.pdf (accessed: 14.05.2024). (In Russ.)

It is advisable to take into account the relationship of changes in the average seasonal air temperatures in the studied region during the thunderstorm period with synchronous variations in the frequency of thunderstorms during the same season and the number of forest fires when modeling these processes, since it has been established that with climate warming they intensified and are significant for the modern period.

It is advisable to take into account the relationship of changes in solar activity with synchronous, as well as 1–year delayed variations in the frequency of thunderstorms over the territory under consideration when forecasting the latter, since they increased over the same period and for the modern period the reliability of the conclusion about their significance exceeds 0.95.

References

1. Ivanov VA, Ponomarev EI, Ivanova GA, Mal'kanova AV. Lightning and Forest Fires in Current Climatic Conditions of Central Siberia. *Meteorologiya i Gidrologiya.* 2023;7:102–113. (In Russ.)

2. Pérez-Invernón FJ, Huntrieser H, Soler S, Gordillo-Vázquez FJ, Pineda N, Navarro-González J, et al. Lightning-Ignited Wildfires and Long-Continuing-Current Lightning in the Mediterranean Basin: Preferential Meteorological Conditions. *Atmospheric Chemistry and Physics*. 2021;21(23):17529–17557. https://doi.org/10.5194/acp-2021-125

3. Kuplevatskiy SV, Shabalina NN. Forest Fires in the Ural Federal District and Their Impact on the Environment. *Forests of Russia and Economy in Them.* 2020;4(75):4–12. https://doi.org/10.51318/FRET.2020.36.84.001 (In Russ.)

4. Kuzmenkov SG, Isaev VI, Bulatov VI, Ayupov RSh, Eginbaeva NO, Kuzmin YuA, et al. Development of Yugra Oil and Gas Complex, Hard-to-Extract Reserves. *Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering.* 2018;329(11):103–113. https://doi.org/10.18799/24131830/2018/11/214 (In Russ.)

5. Baranovskii NV. *Forecasting of Forest Fire Danger in Conditions of Thunderstorm Activity.* Novosibirsk: Publishing House of the Siberian Branch of the Russian Academy of Sciences; 2019. 235 p. (In Russ.)

6. Ivanov VA, Ivanov AV, Ponomarev EI. The Nature of Fires from Thunderstorms in the Forests of Siberia. In: *Proceedings of the VIII All-Russian Scientific and Practical Conference "Monitoring, Modeling and Forecasting of Natural Hazards and Emergencies".* Zheleznogorsk: Siberian Fire and Rescue Academy of the State Fire Service; 2018. P. 9–11. (In Russ.)

7. Dreiper N, Smit G. *Applied Regression Analysis.* Moscow: Dialektika; 2017. 912 p. (In Russ.)

8. Kholoptsev AV, Nikiforova MP. *Solar Activity and Forecasts of Physical and Geographical Processes.* Saarbrucken: Lap Lambert Academic Publishing; 2013; 340 p. (In Russ.)

9. Ivanova GA, Ivanov VA, Musokhranova AV, Onuchin AA. Forest Fires and the Causes of Their Occurrence in Central Siberia. *Sibirskij Lesnoj Zurnal.* 2023;6:6–16. https://doi.org/10.15372/SJFS20230602 (In Russ.)

10. Kopeykin MA, Koptev SV, Tretyakov SV. Impact of Solar Activity on Forest Fires in Arkhangelsk Region. *Forestry Bulletin.* 2021;25(3):73–81. https://doi.org/10.18698/2542-1468-2021-3-73-81 (In Russ.)

11. James RJ, Nkechinyere IE. The Mechanism of Thunderstorms and its Environmental Effects (A Review). *Asian Journal of Basic Science & Research.* 2022;4(3):55–60. http://doi.org/10.38177/AJBSR.2022.4308

12. Danilova NYe, Semyonova YuA, Smerek YuL, Zakinyan RG. Influence Under-Cloudy Convections on Development of a Cloudy Convection. *Science. Innovations. Technologies.* 2018;4:131–150. https://doi.org/10.37495/2308-4758-2018-4-131-150 (In Russ.)

13. Vasilev MS. *Causal Relationships of Forest Fires and Abiotic Factors in the Territory of Yakutia.* Thesis for a Candidate Degree in Geography. Moscow; 2022. 220 p. (In Russ.)

14. Ermakov VI, Stozhkov YuI. *Physics of Thunderclouds.* Moscow: Lebedev Physical Institute of the Russian Academy of Sciences; 2004. 38 p. URL: https://preprints.lebedev.ru/wp-content/uploads/2011/12/2004_2.pdf (accessed: 14.05.2023). (In Russ.)

15. Tartakovsky VA, Cheredko NN. Sun Effect on Surface Temperature in the Northern Hemisphere. *Optika Atmosfery i Okeana.* 2017;30(12):1059–1064. http://doi.org/10.15372/AOO20171209 (In Russ.)

16. Petukhov EI. Solar Activity in the Past and in Our Time. *Mezhdunarodnyi zhurnal gumanitarnykh i estestvennykh nauk.* 2023;2–2(77):121–124. https://doi.org/10.24412/2500-1000-2023-2-2-121-124 (In Russ.)

17. Kuznetsova EA, Sokolov SN, Kushanova AU, Prasina YuA. Dynamic Features of the Weather and Climate Regime in the City of Khanty-Mansiysk. *Advances in current natural sciences*. 2021;6:82–87. https://doi.org/10.17513/use.37645 (In Russ.)

About the Author:

Aleksandr V. Kholoptsev, Dr. Sci. (Geogr.), Professor of the Department of Control and Supervisory Activity, Siberian Fire and Rescue Academy of the State Fire and Rescue Service of the Ministry of Emergency Situations of Russia (1, Severnaya St., Zheleznogorsk, 662970, Russian Federation), SPIN-code: 2419-5410, ORCID, ScopusID, kndp@sibsa.ru

Conflict of Interest Statement: **the author does not have any conflict of interest.**

The author has read and approved the final manuscript.

Об авторе:

Александр Вадимович Холопцев, доктор географических наук, профессор кафедры контрольно-надзорной деятельности Сибирской пожарно-спасательной академии ГПС МЧС России (662970, Российская Федерация, г. Железногорск, ул. Северная, 1), SPIN-код: 2419-5410, ORCID, ScopusID, kndp@sibsa.ru

Конфликт интересов: **автор заявляет об отсутствии конфликта интересов.**

Автор прочитал и одобрил окончательный вариант рукописи.

Received / Поступила в редакцию 20.05.2024
Revised / Поступила после рецензирования 07.06.2024
Accepted / Принята к публикации 14.06.2024

TECHNOSPHERE SAFETY
ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ

UDC 504.05/06
https://doi.org/10.23947/2541-9129-2024-8-3-19-28

Original Empirical Research

Improving the Environmental Safety of Construction Industry Enterprises through the Use of Modern Dust Suppression Technologies

Vadim I. Bespalov ✉, **Oksana S. Gurova**
Don State Technical University, Rostov-on-Don, Russian Federation
✉ izos-rgsu@mail.ru

EDN: JDCNLX

Abstract

Introduction. In the modern world, special attention is paid to the quality of atmospheric air. One of the major contributors to air pollution is the release of harmful substances, including solid particles from industrial activities. These particles can accumulate in high concentrations, making it difficult for even the most efficient (up to 95.0%) cleaning devices to keep up. That is why the development and improvement of highly efficient air purification devices from dust are very relevant. In this regard, as a scientific problem, the authors highlighted the need to improve engineering means of air purification from dust by separating the dispersed phase (dust particles) and the dispersion medium (air), which ultimately will lead to an increase in cleaning efficiency. The aim of this study is to improve the environmental safety of industrial sites of construction industry enterprises and adjacent residential areas by using highly effective means of air purification.

To achieve this goal, we have developed a physics and power-engineering concept and created a block diagram of a physical model for reducing air pollution from construction dust. We have also developed a highly efficient and economical device for hydrodynamic purification of ventilation air from poorly wetted clumping dust. The experiments were conducted to identify the real range of values of the efficiency of air purification from dust.

Materials and Methods. The research is based on methods of physical modeling, mathematical description, and statistical analysis of experimental data.

Results. As a result of the research, it was found that:

– the basis for the development of a highly efficient and economical air purification device from various types of construction dust could be based on the physics and power-engineering scientific concept proposed by the authors, describing the processes of pollution and reduction of air pollution;

– step-by-step consideration of the process of air pollution could be the basis for scientific justification and description of the process of air pollution reduction in the construction industry;

– based on the analysis of the process of the reduction of air pollution by various types of construction dust, it was possible to develop a block diagram of a physical model of this process;

– the study of the behavior and properties of dust aerosol and external force influences directed at it made it possible to outline the main directions, technologies and engineering means to increase the efficiency of the cleaning process and develop a highly efficient and economical device that implemented this process;

– to study the range of changes in the values of the efficiency of air purification from dust, a number of experimental studies were conducted in laboratory conditions.

Discussion and Conclusion. The studies conducted allowed us to determine that an increase in air purification efficiency from dust with a SiO_2 content of 20–70% was achieved in the device through a series of design modifications that enhanced wetting, bonding, and removal of particulate matter from the air. Simultaneously, high levels of integrated efficiency (96.5–98.7%) ensured the compliance with regulatory environmental standards for atmospheric surface air quality.

Keywords: environmental safety, dust suppression, air purification device, efficiency improvement

Acknowledgements. The authors would like to thank Head of the Industrial Safety Department, Dr. Sci. (Engeneering), Professor S.L. Pushenko for his assistance in organizing laboratory experiments.

For citation. Bespalov VI, Gurova OS. Improving the Environmental Safety of Construction Industry Enterprises through the Use of Modern Dust Suppression Technologies. *Safety of Technogenic and Natural Systems.* 2024;8(3):19–28. https://doi.org/10.23947/2541-9129-2024-8-3-19-28

Оригинальное эмпирическое исследование

Повышение экологической безопасности предприятий стройиндустрии на основе современной технологии пылеподавления

В.И. Беспалов ✉, **О.С. Гурова**
Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация
✉ izos-rgsu@mail.ru

Аннотация

Введение. В современном мире особое внимание уделяется качеству атмосферного воздуха. Одним из основных факторов негативного воздействия на атмосферу является выброс загрязняющих веществ, среди которых наиболее массово наблюдаются твердые (пылевые) частицы от промышленных источников. При высоких концентрациях пыли устройства очистки, даже обладая высокой эффективностью (до 95,0 %), не справляются с нагрузкой. Именно поэтому разработка и совершенствование высокоэффективных устройств очистки воздуха от пыли являются весьма актуальными. В связи с этим в качестве научной проблемы авторами выделена необходимость совершенствования инженерных средств очистки воздуха от пыли за счет разделения дисперсной фазы (пылевых частиц) и дисперсионной среды (воздуха), что в конечном счете приведет к повышению эффективности очистки. Целью данного исследования явилось повышение экологической безопасности территорий промышленных площадок предприятий стройиндустрии и прилегающих селитебных зон на основе применения упомянутых высокоэффективных средств очистки воздуха от пыли.

Для достижения поставленной цели авторами решены следующие задачи: применена физико-энергетическая концепция и разработана блок-схема физической модели процесса снижения загрязнения воздушной среды различными видами строительной пыли, разработано высокоэффективное и экономичное устройство гидродинамической очистки вентиляционного воздуха от плохо смачиваемой слипающейся пыли, проведены экспериментальные исследования для выявления реального диапазона значений эффективности очистки воздуха от пыли.

Материалы и методы. В основу исследований авторами положены методы физического моделирования, математического описания и статистической обработки экспериментальных данных.

Результаты исследования. В результате исследований установлено, что:

– в основу разработки высокоэффективного и экономичного устройства очистки воздуха от различных видов строительной пыли может быть положена предложенная авторами физико-энергетическая научная концепция, описывающая процессы загрязнения и снижения загрязнения воздушной среды;

– поэтапное рассмотрение процесса загрязнения воздушной среды может быть основой научного обоснования и описания процесса снижения загрязнения воздушной среды предприятий строительной индустрии;

– на основании выполненного анализа процесса снижения загрязнения воздушной среды различными видами строительной пыли возможна разработка блок-схемы физической модели этого процесса;

– изучение особенностей поведения и свойств пылевого аэрозоля и направленных на него внешних силовых воздействий дает возможность наметить основные направления, технологии и инженерные средства повышения эффективности процесса очистки и разработать высокоэффективное и экономичное устройство, реализующее этот процесс;

– для исследования диапазона изменения значений эффективности очистки воздуха от пыли проведен ряд экспериментальных исследований в лабораторных условиях.

Обсуждение и заключение. Выполненные исследования позволили установить, что повышение эффективности очистки воздуха от пыли с содержанием от 20 до 70 % SiO_2 обеспечивается в устройстве за счет ряда конструктивных изменений, приводящих к интенсификации смачивания, связывания и удаления из воздуха пылевых частиц. При этом высокие значения (96,5–98,7 %) интегральной эффективности обеспечивают нормативные экологические требования к качеству воздуха приземного слоя атмосферы.

Ключевые слова: экологическая безопасность, пылеподавление, устройство очистки воздуха, повышение эффективности

Благодарности. Авторы благодарят доктора технических наук, профессора, заведующего кафедрой «Производственная безопасность» С.Л. Пушенко за содействие в организации лабораторных экспериментов.

Для цитирования. Беспалов В.И., Гурова О.С. Повышение экологической безопасности предприятий стройиндустрии на основе современной технологии пылеподавления. *Безопасность природных и техногенных систем.* 2024;8(3):19–28. https://doi.org/10.23947/2541-9129-2024-8-3-19-28

Introduction. Currently, dry construction mixes are in high demand among various construction-related consumers. In particular, the production of highly dispersed binding materials such as gypsum, cement, tile adhesive, and facade adhesive occupies a special place [1, 2]. During the preparatory stage of production, raw materials such as clinker are sieved and crushed (ground) in accordance with standards. General manufacturing process of any dry building material includes filling with crushed raw materials, mixing different ingredients, and packaging the mixture. However, the specific technologies may vary depending on the recipe for the mixture, the initial product, the number and type of ingredients used, and the corresponding equipment.

From the perspective of ensuring the required environmental standards for dust particle content in the air at industrial sites of companies producing building materials and binders, the areas where the most intense dust formation occurs are during the crushing of raw materials [3]. It is during this process that the main types of construction dust are formed, including cement, gypsum, and sand, with SiO_2 content ranging from 20% to 70%, and with particle sizes primarily of PM2.5 and PM10. With subsequent release, this dust leads to an excess of MPC in the air of the working areas of construction industry enterprises and maximum single MPC (average daily MPC) in the air of the surface layer of the atmosphere of both at the industrial sites and in adjacent residential areas. The negative effects of this dust include its potential to enter the human body via the respiratory system, gastrointestinal tract, skin, and mucous membranes, causing various health problems. At the same time, it is the smallest particles, with sizes of PM2.5 and PM10 that pose the greatest danger [1, 4].

As a result, for the main types of industrial dust listed above, there is an excess of the corresponding MPC values by 5–25 times. This ranges from 10 to 300 milligrams per cubic meter (mg/m³) without the use of engineering dust suppression measures. This state of the air environment has a negative impact on employees of enterprises and the population in adjacent territories [5–7]. It should be noted that while the use of modern dust suppression devices, such as dust collection devices (exhaust hoods, umbrellas, etc.) effectively meet sanitary and hygiene requirements by removing dust from industrial premises, it also creates high concentrations of dust that even advanced air purification systems with high efficiency (up to 95.0%) cannot completely eliminate. Thus they do not ensure the compliance with environmental regulations. This is a scientific problem related to improving engineering methods for removing dust from air emitted into the atmosphere, with the aim of increasing the efficiency of dust removal (over 96.0%). Therefore, the goal of this research is to develop highly effective and modern technologies and tools for dust suppression in order to improve the environmental safety of construction industry sites and adjacent residential areas.

Materials and Methods. The study used an analytical method for studying accumulated experience in the scientific and technical field, as well as methods for constructing a physical model combined with a mathematical description of the resulting characteristics of this process. In addition, methods of statistical processing of the results of laboratory studies obtained by the authors and comparing them with the results of similar studies by other scientists were used.

At the same time, a device was selected as the object of research for purifying the air from dust emitted by construction industries, which is one of the main stages in the dust suppression process. The effectiveness of this process depended on the basic physical and chemical properties of the dispersed phase and the dispersion medium of the dust aerosol, as well as on external factors that could destroy it. The subject of the study was to improve the efficiency of air purification devices in order to ensure environmental safety in industrial sites and adjacent residential areas of construction enterprises.

The most suitable approach for the development of a device for purifying air from dust with a concentration of 20–70% SiO_2 was based on the use of the physical and energy concept [5]. This approach allowed for establishing physical connections between all components of the pollution reduction process, including dust aerosol, cleaning device, and external forces. It also allowed for outlining technologies to improve the efficiency of the cleaning process and developing the design of an effective air purification device for specific conditions and types of dust generated by construction industry enterprises.

Results. The development of a highly efficient and economical air purification device from construction dust was based on the physics and power engineering scientific approach proposed by the authors. This approach allowed us to describe the processes of pollution and air pollution reduction [5–7]. This concept was based on the consideration of the dispersed “pollutant” system, which changed the parameters of its state in the process of air pollution and passed from one quality (dust material) to another (dust aerosol) [5, 8]. Thus, when processing raw materials (construction materials) on technological equipment, the formation of dust particles and the formation of dust material was observed. Then the formed dust material was released into the air of production room and a dust aerosol was formed. And finally, the dust aerosol, spreading in the space of the production room, was released into the air of the surface layer of the atmosphere

of the territories of industrial sites of construction industry enterprises and adjacent residential areas with subsequent dispersion.

At the same time, it should be noted that the stages of dust formation and internal release allowed dust particles to be returned to the initial technological material, which was advantageous from an environmental and economic perspective, but not always feasible in terms of the requirements of technological regulations. Other stages were associated with the aerosol state of dust, where dust particles were suspended in air and could not be easily separated from the aerosol for subsequent return to the technological raw material, or cause significant difficulties.

A step-by-step analysis of the air pollution process formed the basis for a scientific justification and description of how to reduce pollution from the considered types of dust in the air surrounding construction industry facilities. At the same time, there was a clear correlation between the stages of pollution reduction and the stages of atmospheric pollution [8, 9]:

– the first stage: binding of dust particles formed during the processing of raw materials on technological equipment;

– the second stage: detention of unbound dust particles in the area where processed raw materials weare located, including those formed within the internal volume of the production facility;

– the third stage: capture of dust aerosols released into the internal space of the production area in order to prevent the spread of dust particles within a designated limited area. Removal of these particles from the zone and transportation to a cleaning area;

– the fourth stage: purification of air (dispersion medium) from dust particles (dispersed phase) of dust aerosol captured and released into the surface layer of the atmosphere through maximum separation;

– the fifth stage: dispersion of the remaining amount of dust particles after purification, immediately before their release into the surface layer of the atmosphere. This was done by intensively separating dust particles during their release and accelerating gravitational seeding in a pre-selected, strictly limited area on the industrial site. This additional measure helped to reduce the concentration of dust particles in the atmosphere to levels below the MPC maximum single (MPC mean daily).

The main goal of each stage in the pollution reduction process was to decrease the stability and, ultimately, the destruction of the dust aerosol as a dispersed system by using pre-determined parameters of external influences applied to it of various physical natures.

The analysis conducted by the authors has allowed them to examine the process of air pollution reduction, which was implemented in two main cycles [8, 9]:

Cycle I was the reduction of pollution of technological raw materials (technological equipment), which included the development of new or improvement of the existing basic production equipment and the organization of technological processes that excluded the stages of formation and release of pollutants;

Cycle II was the reduction of air pollution, which included the use of additional engineering devices, structures, and devices in the current or projected technological process that localized the spread of dust aerosol and ensure its destruction as a dispersed system.

It should be noted that activities related to the first cycle were often not possible due to violations of requirements for raw materials and technical processes. Therefore, the authors have laid the foundation for further research and development of a second cycle of measures to reduce air pollution.

Thus, the main goal of the second stage of the air pollution reduction process was to eliminate dust aerosol particles by separating them from the air. This was achieved through the consistent implementation of several stages, including dust capture, air purification, and dispersion of the remaining dust in the atmosphere. Let us consider the physical foundations of each of the stages of Cycle II.

As a result of the research, the authors found that the physical essence of the dust capture process consisted in purposeful exposure to the released dust aerosol with pre-prepared parameters, or additional (Д–II.1) dispersed system, or a force field leading to the formation of two dispersed systems [8, 10]:

– residual (О–II.1) dispersed system, which contained a minimum amount of dust particles as a dispersed phase (focused on compliance with the MPC maximum single), and which spatially remained and spread in the internal volume of the production room (air of the working area);

– intermediate (П–II.1), which contained the maximum amount of dust particles trapped and removed from the emission zone, and which had increased stability in the dust aerosol state.

Further research by the authors also made it possible to reveal the physical essence of the air purification process from dust. This process involved the purposeful exposure to solid particles of dust aerosol (intermediate (П–II.1) dispersed system) in the active cleaning zone after capture with pre-prepared parameters or additional (Д-II.2) dispersed system, or a force field leading to the formation of two dispersed systems [8, 10]:

– residual (О–II.2), which contained the maximum amount of dust particles as a dispersed phase and has increased stability after passing into the state of a dust material, accumulated in special dust collectors (accumulators);

– intermediate (П–II.2), which contained a minimum amount of dust particles as a dispersed phase (aiming for compliance with the MPC maximum single or MPC mean daily). It was then released into the surface layer of the atmosphere.

Further research by the authors has also allowed them to reveal the physical nature of forced dispersion of remaining dust particles in the atmospheric surface layer, which occurred when the purification process failed to achieve a concentration of dust at environmentally significant points in the surface atmosphere that corresponded to the MPC maximum single (MPC mean daily). Thus, the physical essence of the process of scattering dust particles consisted in the purposeful effect on solid particles of a dust aerosol (intermediate (П–II.2) dispersed system) in the active dispersion zone after cleaning with pre-prepared parameters, or an additional (Д–II.3) dispersed system, or a force field leading to the formation of two dispersed systems [8, 10]:

– residual (O–II.3), which contained the main amount of emitted dust particles as a dispersed phase, and which in the airspace outside ecologically significant zones was subject to intensive deposition on the underlying surfaces, having increased stability during the transition to the state of dusty material;

– residual (O–II.4), which contained a minimum amount (aiming for compliance with the MPC maximum single or MPC mean daily) dust particles as a dispersed phase, and which remained floating in the surface layer of the atmosphere.

Based on the analysis of the reduction of air pollution caused by various types of construction dust, the authors have developed a block diagram of a physical model of this process, taking into account the two cycles discussed above for the conditions of implementation of technological processes at enterprises of the construction industry (Fig. 1) [8, 11, 12].

A visual representation of the flowchart for the physical model of air pollution reduction allowed us to draw several conclusions. Firstly, despite the numerous advantages, the initial cycle of the pollution reduction process under real-world conditions and the organization of technological processes at construction industry enterprises were overwhelmingly not implemented due to violations of technical regulations.

Secondly, within the framework of Cycle II, the capture stage determined the effectiveness of ensuring sanitary and hygiene standards in the air in work areas of industrial premises. In modern conditions, technological processes at construction industry enterprises were provided with very efficient and economical engineering solutions, such as exhaust hoods, panels, and other structures.

Thirdly, within the framework of Cycle II, the stage of forced dispersion of the remaining dust particles in the surface layer of the atmosphere was auxiliary to the air purification process and was used in very rare cases.

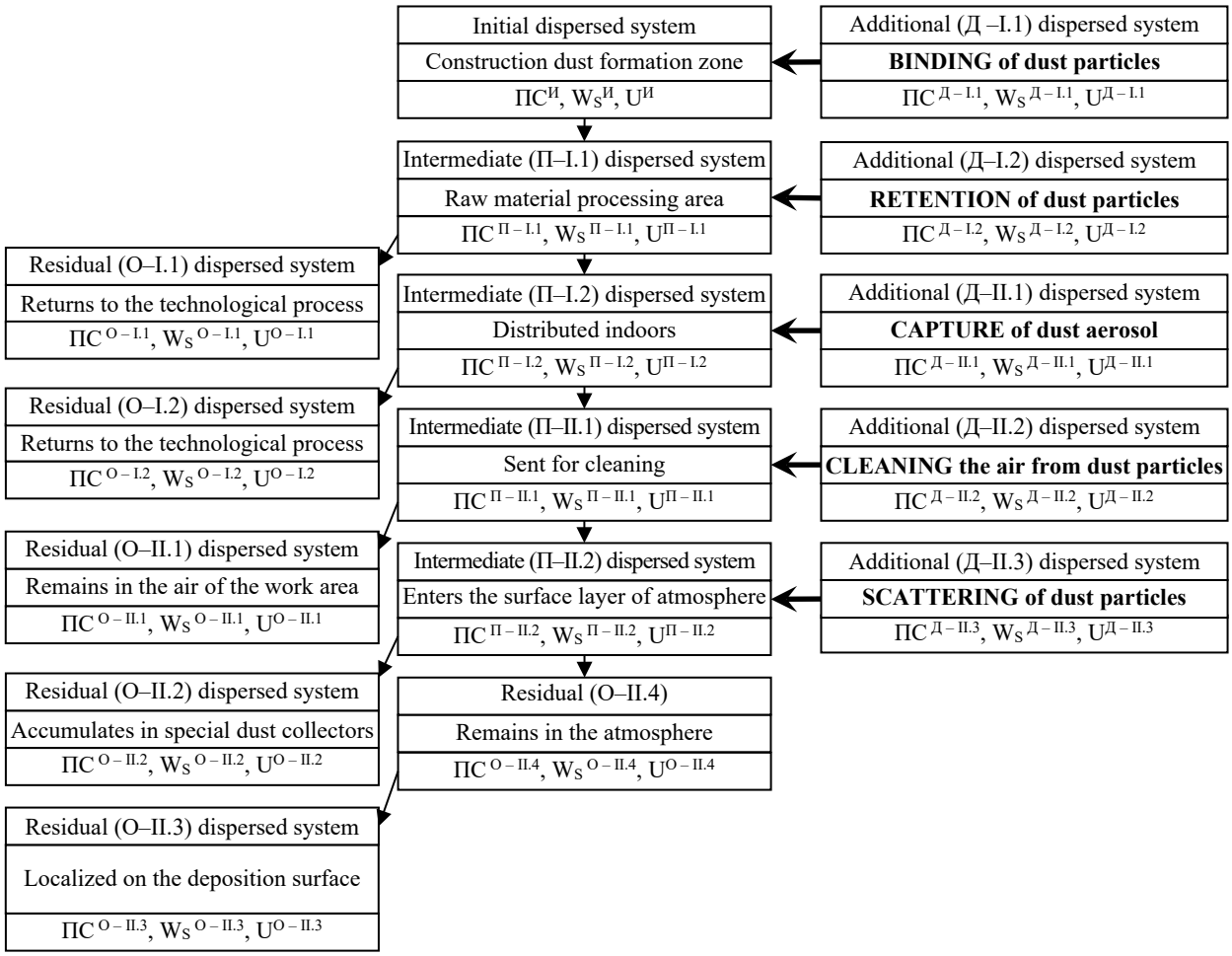
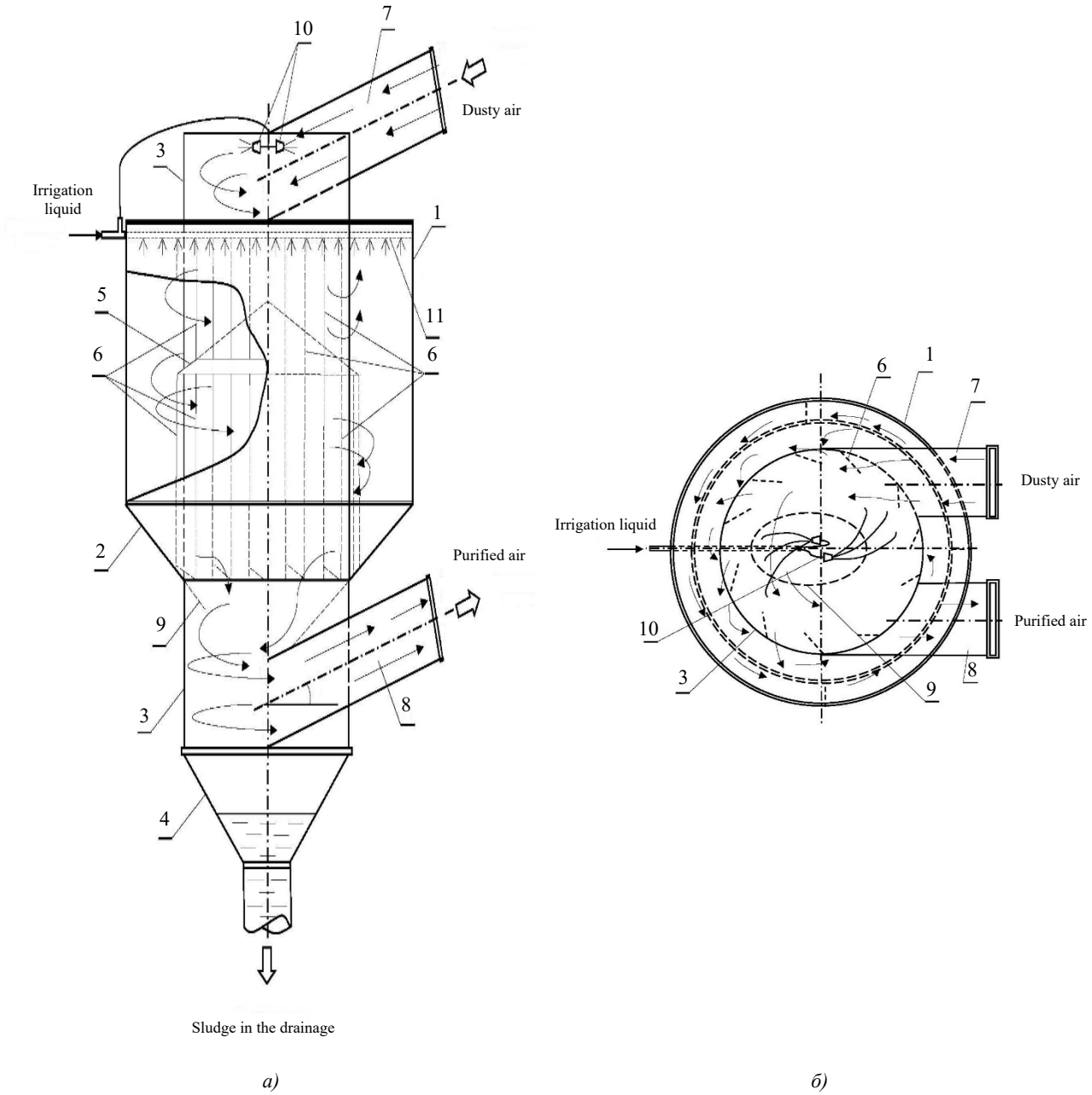


Fig. 1. Physical model of the process of air pollution reduction

Thus, the authors based their practical developments on the stage of air purification from various types of construction dust, for which the possibilities of increasing efficiency were far from exhausted. Improving the efficiency of cleaning agents was possible on the basis of the theoretical research results presented above and, in particular, the flowchart of the physical model for air pollution reduction [13–15].

The study of the behavior and properties of dust aerosol and external dispersed systems or force influences directed at it during the cleaning process allowed the authors to outline the main directions, appropriate technologies and engineering means to increase the efficiency of the cleaning process. One of the brightest representatives of such means was a highly efficient and economical device developed by the authors, designed for hydrodynamic purification of ventilation air (Fig. 2).

The main structural element of the developed device is its cylindrical body (1), which ends in conical section (2). Partially inside and partially outside body (1) there is cylindrical chamber (3) with bottom (4) in the shape of a cone. In this case, chamber (3) is divided by solid hollow bump cone (5) into two parts: the lower and the upper. Slotted air intakes (6) are located on the inner side surfaces of these parts. Inlet tangential inclined branch pipe (7) and outlet tangential branch pipe (8) are connected to the side surfaces of the upper and lower parts of chamber (3). Branch pipe (7) in plan enters body (1) in its upper part “counterclockwise”, and branch pipe (8) — in its lower part “clockwise”. In this case, branch pipes (7) and (8) face the same side.



a) *б)*

Fig. 2. Device for hydrodynamic purification of ventilation air from poorly wetted clumping dust formed at enterprises of the construction industry: *a* — front view; *b* — top view

Slotted air intakes (6) mentioned above are made in the form of rectangular slotted holes. Moreover, in the upper part of chamber (3), the edges of slotted air intakes (6) are bent inside chamber (3), and in the lower part — outwards so that the air flow is captured in both the upper and lower parts.

The lower part of chamber (3) is equipped with cone (9), which is combined with conical section (2), and the base is located along the lower edge of air intakes (6). Hydrodynamic cleaning system in the device includes three stages:

– two nozzles (10), which are tangentially directed along the incoming flow of dusty air;

– annular perforated pipeline (11) installed under the upper wall of body (1) in an annular cavity between the walls of body (1) and chamber (3) with exit holes directed vertically downward;

– a hydrofilter formed by a continuous liquid film flowing from the edges of cone (9).

The principle of operation of the device is as follows. The dusty air flow from the technological equipment enters inlet tangential pipe (7), and then go into the inner cavity of the upper part of chamber (3) and is irrigated with droplets of liquid, which moisten, bind and remove a certain amount of dust particles from the stream (the first stage of purification) and which are formed using nozzles (10). As a result of irrigation, the sludge moves through chamber (3) from top to bottom onto bump cone (5). And the dust and gas-liquid mixture, thanks to air intakes (6) with inward-curved edges and installed solid hollow cone-bump (5), is removed from the upper part of chamber (3) into the annular cavity between it and body (1), falling into a dense annular drip-liquid curtain, which also captures a certain amount of dust particles (the second stage of purification) formed by annular perforated pipe (11).

At the same time, flowing down from the surface of bump cone (5), the sludge forms a dense annular film curtain (the third stage of purification), which moistens and binds a significant part of dust particles. After passing through this curtain, the residual dusty flow is captured by the outward-bent edges of air intake (6) in the lower part of chamber (3) and returns to its inner cavity.

Ultimately, the total sludge flow from the annular cavity between chamber (3) and body (1) flows down conical section (2) of body (1), and then along cone (9), forming another annular film curtain with different film thicknesses (fourth stage of purification), which increases towards the outlet The sludge is discharged from the device through conical bottom (4). Thus, after passing four stages of purification sequentially, the air stream, as free from dust particles as possible, is released into the atmosphere through outlet pipe (8). All the above-described design features of the developed device determine its integral efficiency in cleaning the air from dust.

To investigate the range of variations in the efficiency values, the authors performed a series of experiments in laboratory settings. During these experiments, the overall efficiency of air purification from dust containing from 20 to 70% SiO_2 (sand dust) was measured. The average median diameter of dust particles was 50 μm, and the bulk density of dust material was 1,860 kg/m³. The dust had a weak adhesion with a breaking strength of 200 Pa and an angle of natural inclination of 57°, while the marginal wetting angle was 10°. The researchers changed the design and parameters of bump cone (5) as well as the design and position of slit air intake (6) to study their effects on the efficiency. The results of the research are presented in Tables 1 and 2.

Table 1

Experimental values of integral efficiency $E_{эф}$, %, of air purification from dust containing from 20 to 70% SiO2, depending on the design of bump cone (5) and the location of slit air intakes (6) with other optimal design solutions

Location of the slit air intakes (6) in the upper part of the chamber (3)	Design of the bump cone (5)								
	The edges of the bump cone coincide with the walls of the chamber (3)			The edges of the bump cone protrude beyond the chamber (3)			The edges of the bump cone form a gap with the inner walls of the chamber (3)		
	conic	spherical	ellipsoid	conic	spherical	ellipsoid	conic	spherical	ellipsoid
Along the entire height of the body (1)	86.9	85.7	83.9	98.7	98.5	91.8	85.2	84.8	83.1
On the upper and lower parts of the chamber (3) partially along the height of the body (1)	84.1	83.8	83.5	95.3	94.9	88.6	83.2	82.9	82.6

Table 2

Experimental values of integral efficiency Eэф, %, of air purification from dust containing from 20 to 70% SiO2, depending on the design of slit air intakes

Design of the slit air intakes (6) in the plan		At the top of the camera (3)	
		with the edges bent outward in the direction of flow	with the edges bent inward towards the flow
At the bottom of the camera (3)	With the edges bent outwards	95.8	98.7
	With the edges spread outwards	93.4	97.2

Discussion and Conclusion. The analysis of the experimental results in the laboratory leads to the following conclusions: Based on Table 1, we can see that the maximum value of integral $E_{эф}$, with SiO_2 content between 20 and 70%, is 98.7%. This occurs when slit air intakes (6) are positioned in the upper part of chamber (3), along the entire height of body (1).

According to Table 2, it can be seen that the same maximum value of integral $E_{эф}$ containing from 20 to 70% SiO_2. amounting to 98.7%, is ensured by the fact that in the design of slit air intakes (6) in the plan in the upper part of chamber (3) the edges are bent inward towards the flow, and in the lower part of chamber (3) the edges of slit air intakes (6) are bent outward.

In conclusion, it should be noted that an increase (up to 96.5–98.7%) of $E_{эф}$ containing from 20 to 70% SiO_2 is provided in the proposed device due to a number of design changes leading to an intensification of wetting, binding and removal of dust particles from the air.

For example, the installation of nozzles (10) and annular perforated pipe (11) increases the likelihood of meeting and trapping dust particles by droplets of dispersed liquid. At the same time, the aerodynamic characteristics of the dust and gas-liquid flow during irrigation are maintained constant.

In addition, cylindrical chamber (3) coaxially passed through body (1) of the device helps to maintain a uniform distribution of the swirling air flow when it exits chamber (1) through slit air intakes (6).

The design of bump cone (5) makes it possible to evenly distribute the air coming from the volume of chamber (3), which, in turn, contributes to the formation of a dense curtain in the form of an annular film, which acts as an additional cleaning filter (the third stage of purification) installed in the path of a dust and gas-liquid stream swirled in the annular cavity.

The sequential movement of the dust-air flow into the cavity of the device through all air purification zones from dust is provided by air intakes (6). At the same time, the shape and location of the edges of the slots allow to stabilize the aerodynamics in the cavity of the device.

Moreover, an additional contribution to improving efficiency is made by cone (9), the shape and location of which create an additional annular film curtain with different film thicknesses (the fourth stage of purification). It is created in the path of the air flow due to the runoff of sludge from the edges of the smaller base of cone (9) and increases in thickness towards outlet pipe (8). Also, the design of cone (9) ensures the removal of sludge from the device in the area of removal of purified air with a significant reduction in drop entrainment into outlet pipe (8). At the same time, the slope of outlet pipe (8) helps to reduce drop entrainment.

It should be noted that in order to ensure stable, reliable and all-season operation of the device, it is necessary to use aqueous solutions as an irrigation liquid that do not freeze even at negative ambient temperatures. If water is used, the device must be kept in closed, heated rooms.

In conclusion, it should be noted that the developed air purification device from dust with all the design features described above provides the required integral efficiency, due to high values (96.5–98.7%), which, in turn, complies with regulatory environmental requirements for the air quality of the surface layer of the atmosphere.

Thus, as a result of the research, the final goal was achieved — the possibility of improving the environmental safety of industrial sites of construction industry enterprises and adjacent residential areas was determined by developing and applying highly effective (at least 96.0%) modern technologies and dust suppression tools, which included the device proposed by the authors for cleaning air from dust containing from 20 to 70% SiO_2.

References

1. Pokotilo VE, Strezhnev DO, Tolmacheva LV. Study of Chemical Pollution of the Environment. In: *Achievements of modern science and education. Collection of articles and abstracts of the IV International Interdisciplinary Conference. Stavropol. 2018*. Taganrog: El'Direkt; 2018. P. 59–61. (In Russ.)

2. Andreeva EV, Klado TN. *Atmosphere and Life.* Leningrad: Hydrometeorological Publishing House; 1963. 268 p. (In Russ.)

3. Kulagina TA, Andrunyak IV. *Technological Processes and Polluting Emissions*. Krasnoyarsk: Siberian Federal University; 2019. 206 p. (In Russ.)

4. Malashkina AV. Factors for Assessing the Impact of Industrial Cities on Public Health. In: *Proceedings of the 1st National Scientific and Practical Conference with international participation "Innovations in environmental management and environmental protection".* Saratov: KUBiK Publishing House; 2019. PC. 196–199. (In Russ.)

5. Lysova E., Paramonova O., Samarskaya N., Gyrova O., Tsarevskaya I. Application of Physical and Energetic Approach to Estimation and Selection of Atmospheric Protection Systems for Energetic Devices. *MATEC Web of Conferences.* 2018;170:04013. https://doi.org/10.1051/matecconf/201817004013

6. Momei Qin, Murphy BN, Isaacs KK, McDonald BC, Quanyang Lu, McKeen SA, et al. Criteria Pollutant Impacts of Volatile Chemical Products Informed by Near-Field Modelling. *Nature Sustainability.* 2021;4(2):129–137. https://doi.org/10.1038/s41893-020-00614-1

7. Khalikov IS. Identification of Natural Objects Contamination by Polycyclic Aromatic Hydrocarbons with the Use of Molecular Relations. *Ekologicheskaya khimiya.* 2018;27(2):76–85. (In Russ.)

8. Bespalov V, Gurova O, Samarskaya N, Paramonova O. Classification of Air Pollution Criteria for the Improvement of Methodical Approaches to Ensure the Environmental Safety of Major Cities. *E3S Web of Conferences.* 2019;135:01033. https://doi.org/10.1051/e3sconf/201913501033 (accessed: 04.05.2024).

9. Palliyarayil A, Saini H, Vinayakumar K, Selvarajan P, Vinu A, Kumar NS, et al. Advances in porous material research towards the management of air pollution. *Emergent Materials.* 2021;4:607–643. https://doi.org/10.1007/s42247-020-00151-9

10. Sadunishvili TA, Khatisashvili GA, Gurova OS, Samarskaya NS. *Global Environmental Issues and Biotechnological Approach.* Monograph. Rostov-on-Don: Don State Technical University; 2021. 146 p. (In Russ.)

11. Samarskaya N, Paramonova O, Lysova E. Study of the Air Pollution Reduction Process in the Production of Film-Forming Substances for Quick-Drying Enamels. *IOP Conference Series: Earth and Environmental Science.* 2021;666:042072 http://doi.org/10.1088/1755-1315/666/4/042072

12. Bespalov V, Gurova O. Development of an Integrated Approach to the Selection of Remediation Measures and Environmental Technologies for their Implementation. *E3S Web of Conferences*. 2021;258:08027. https://doi.org/10.1051/e3sconf/202125808027

13. Samarskaya N, Gyrova O. Analysis of the Results of Theoretical Calculations Based on the Methodology for Making a Decision on the Choice of Optimal Technologies for Dedusting with Foam. *AIP Conference Proceedings.* 2022;2503(1):040004. https://doi.org/10.1063/5.0099703

14. Bespalov VI, Gurova OS. Scientific Substantiation of New Concept for Environmental Technologies Choice. *AIP Conference Proceedings.* 2022;2503(1):040005. https://doi.org/10.1063/5.0099700

15. Bespalov VI, Lysova EP, Paramonova ON, Samarskaya NS. Justification of the Scientific Approach Choice for Formation of the Most Effective Ways and Means of Reducing Air Pollution in the Operation of Power Plants. *Engineering journal of Don.* 2018;(3). URL: http://www.ivdon.ru/uploads/article/pdf/IVD_42_Bespalov_Lysova.pdf_c86775c35f.pdf (accessed: 04.05.2024). (In Russ.)

About the Authors:

Vadim I. Bespalov, Dr. Sci. (Eng.), Professor, Head of the Environmental Engineering Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), SPIN-code: 6778-4627, ORCID, ResearcherID, ScopusID, izos-rgsu@mail.ru

Oksana S. Gurova, Dr. Sci. (Eng.), Associate Professor, Professor of the Environmental Engineering Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), SPIN-code: 1852-507, ORCID, ResearcherID, ScopusID, okgurova@yandex.ru

Claimed Contributorship:

VI Bespalov: formulation of the basic concept, goals and objectives of the study, academic advising.

OS Gurova: research results analysis, conclusions correction, graphic design, text revision.

***Conflict of Interest Statement:* the authors do not have any conflict of interest.**

All authors have read and approved the final manuscript.

Об авторах:

Вадим Игоревич Беспалов, доктор технических наук, профессор, заведующий кафедрой инженерной защиты окружающей среды Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), SPIN-код: 6778-4627, ORCID, ResearcherID, ScopusID, izos-rgsu@mail.ru

Оксана Сергеевна Гурова, доктор технических наук, доцент, профессор кафедры инженерной защиты окружающей среды Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), SPIN-код: 1852-507, ORCID, ResearcherID, ScopusID, okgurova@yandex.ru

Заявленный вклад авторов:

В.И. Беспалов: формирование основной концепции, цели и задачи исследования, научное руководство.

О.С. Гурова: анализ результатов исследований, корректировка выводов, графическое оформление, доработка текста.

Конфликт интересов: **авторы заявляют об отсутствии конфликта интересов.**

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 13.06.2024
Revised / Поступила после рецензирования 07.07.2024
Accepted / Принята к публикации 15.07.2024

TECHNOSPHERE SAFETY
ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ

UDC 614.8.084
https://doi.org/10.23947/2541-9129-2024-8-3-29-38

Original Empirical Research

Improving the Injury Prevention System Based on Convergent Digital Management Technologies to Provide Employees with Personal Protective Equipment

EDN: AGDEEN

Viktoriya A. Petrova ✉, **Elena V. Klimova**, **Alexander Yu. Semeykin**, **Oksana N. Tomarovshchenko**
Belgorod State Technological University named after V.G. Shukhov, Belgorod, Russian Federation
✉ lezhand@mail.ru

Abstract

Introduction. The introduction of high-tech equipment and specialized software makes it possible to improve the quality of labor operations without attracting additional labor, which contributes to the rational use of time and resources. As a result of the implementation of this approach, the prevention of possible errors and delays caused by the human factor is achieved. By integrating digital technologies, it is possible not only to simplify management procedures, but also to reduce the level of occupational injuries and incidents by monitoring the compliance with the requirements for the use of personal protective equipment by personnel in real time. This work aims to reduce the level of occupational injuries by improving the micro-trauma prevention system and implementing integrated solutions for accounting for the issuance of personal protective equipment using software tools.

Materials and Methods. The paper examined the existing methods and technologies for accounting and issuing personal protective equipment in order to determine their effectiveness and applicability, taking into account the industry characteristics of enterprises based on the requirements of the legislative and regulatory framework of the Russian Federation. A questionnaire was developed to assess the need to improve the personal protective equipment used among employees of a construction organization in the Belgorod region. The survey of employees was conducted in the form of a checklist, where it was necessary to note the shortcomings and inconsistencies of the occupational health management system (OHMS) in the field of issuing PPE.

Results. The results of analyzing the completed questionnaires from the respondents who participated in the study suggested the importance of transitioning to a digital format for managing and issuing PPE in order to enhance the efficiency and effectiveness of providing employees with necessary personal protective equipment. The patent search conducted revealed the primary flaws in current methods and systems for distributing PPE, addressing which would enhance the reliability of the procedure for equipping personnel with protective equipment, indicating the significance of further research in this field. A model has been developed to improve the system for providing employees of construction companies with personal protective equipment by implementing the StroyKontrol+ software package to automate the accounting and issuance of these resources. This software solution integrated with the existing enterprise information systems and could be customized to meet the specific needs of an organization. The model included the use of monitoring tools to identify the need for replacing personal protective equipment and the creation of accounting documents to help increase safety and protect workers from harmful and dangerous industrial factors.

Discussion and Conclusion. The introduction of the Stroykontrol+ software package has made it possible to reduce the level of micro-trauma among construction workers due to their improper use of PPE, lack of necessary PPE and insufficient knowledge on how to use these tools. In addition, the authors emphasize, it is necessary not only to record applications from employees for certain protective equipment or violations identified, but also to reduce the time response of responsible parties when it comes to replacing defective personal protective equipment.

Keywords: occupational safety, industrial injuries, personal protective equipment, questionnaires, software for accounting and issuing personal protective equipment

Acknowledgements. The authors would like to thank the Editorial team of the Journal and anonymous reviewers for their competent expertise and valuable recommendations for improving the quality of the article.

Funding Information. The research was done within the framework of the Priority 2030 program at the Belgorod State Technological University named after V.G. Shukhov using equipment from the High Technology Center of V.G. Shukhov BSTU.

For citation. Petrova VA, Klimova EV, Semeykin AYu, Tomarovshchenko ON. Improving the Injury Prevention System Based on Convergent Digital Management Technologies to Provide Employees with Personal Protective Equipment. *Safety of Technogenic and Natural Systems.* 2024;8(3):29–38. https://doi.org/10.23947/2541-9129-2024-8-3-29-38

Оригинальное эмпирическое исследование

Совершенствование системы профилактики травматизма на основе конвергентных технологий цифрового управления обеспечением работников средствами индивидуальной защиты

В.А. Петрова ✉, Е.В. Климова, А.Ю. Семейкин, О.Н. Томаровщенко
Белгородский государственный технологический университет имени В.Г. Шухова, г. Белгород, Российская Федерация
✉ lezhand@mail.ru

Аннотация

Введение. Внедрение высокотехнологичного оборудования и специализированных программных средств позволяет повысить качество выполнения трудовых операций без привлечения дополнительного рабочего контингента, что способствует рациональному использованию времени и ресурсов. В результате реализации данного подхода достигается предотвращение возможных ошибок и задержек, связанных с человеческим фактором. Путем интеграции цифровых технологий возможно не только упростить управленческие процедуры, но и снизить уровень производственного травматизма и инцидентность за счет мониторинга соблюдения требований по использованию персоналом средств индивидуальной защиты в режиме реального времени. В данной работе была поставлена цель определить возможности совершенствования системы профилактики микротравматизма путем внедрения комплексных решений по учету выдачи средств индивидуальной защиты с использованием программных средств.

Материалы и методы. В работе использованы базирующиеся на требованиях законодательной и нормативно-правовой базы РФ методы и технологии учета и выдачи средств индивидуальной защиты с целью определения их эффективности и применимости с учетом отраслевых особенностей предприятий. Для оценки потребности в улучшении применяемых средств индивидуальной защиты была разработана анкета. Анкетирование проводилось среди работников строительной организации Белгородской области в форме чек-листа, в котором необходимо было отметить недостатки системы управления охраной труда (СУОТ) в области выдачи средств индивидуальной защиты (СИЗ).

Результаты исследования. Результаты обработки заполненных анкет респондентов, участвующих в исследовании, свидетельствуют о важности перехода к цифровому формату учета и выдачи СИЗ с целью повышения эффективности и оперативности обеспечения работников необходимыми средствами индивидуальной защиты. Проведенный патентный поиск позволил выявить основные недостатки существующих методов и систем выдачи СИЗ, устранение которых позволит повысить надежность процесса обеспечения персонала защитными средствами, что указывает на актуальность дальнейших исследований в данной области. Разработана модель по улучшению системы обеспечения сотрудников строительных организаций средствами индивидуальной защиты путем внедрения программного комплекса «СтройКонтроль+» по автоматизации процессов учета и выдачи этих средств. Данное программное решение предполагает интеграцию с существующими информационными системами предприятия и может быть адаптировано под конкретные потребности и требования организации. Разработанная модель предусматривает использование средств мониторинга для отслеживания необходимости замены средств индивидуальной защиты с последующим формированием отчетной документации, что способствует повышению уровня безопасности и сохранению здоровья работников в условиях воздействия на них вредных и опасных производственных факторов.

Обсуждение и заключение. Внедрение программного комплекса «СтройКонтроль+» позволило сократить уровень микротравмирования работников строительных организаций по причинам неправильного применения ими средств индивидуальной защиты, отсутствия у них необходимых СИЗ, недостаточных знаний в области использования подобных средств. Кроме того, подчеркивают авторы, необходимо не только фиксировать заявки

от работников на получение определенных средств защиты или выявленные нарушения, но и уменьшить период реагирования ответственных лиц на необходимость замены неисправных средств индивидуальной защиты.

Ключевые слова: охрана труда, производственный травматизм, средства индивидуальной защиты, анкетирование, программное обеспечение по учету и выдачи средств индивидуальной защиты

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

Финансирование. Работа выполнена в рамках программы «Приоритет-2030» на базе Белгородского государственного технологического университета имени В.Г. Шухова с использованием оборудования Центра высоких технологий БГТУ имени В.Г. Шухова.

Для цитирования. Петрова В.А., Климова Е.В., Семейкин А.Ю., Томаровщенко О.Н. Совершенствование системы профилактики травматизма на основе конвергентных технологий цифрового управления обеспечением работников средствами индивидуальной защиты. *Безопасность техногенных и природных систем.* 2024;8(3):29–38. https://doi.org/10.23947/2541-9129-2024-8-3-29-38

Introduction. The use of personal protective equipment (PPE) is one of the most reliable ways to ensure safety of health and protect employees from exposure to harmful and dangerous factors. As part of the government's strategy to integrate a risk-based approach into occupational health and safety, a systematic risk assessment process is implemented. This process takes into account the specific characteristics of the workplace, including the potential hazards associated with different types of work, as well as the subsequent development of appropriate safety measures. An important step in this process is the transition to uniform standard norms (USN) for the provision of PPE. This involves replacing the current system of providing PPE based on the type of work performed by an employee with a system that is based on a special assessment of working conditions and occupational risks. Properly selected and effectively used personal protective equipment helps to reduce the risk of occupational diseases and accidents, as well as increase labor productivity and improve employee health [1, 2].

One of the key elements of the strategic personnel safety management system is high-quality employee training. Conducting training sessions aimed at consolidating theoretical knowledge and developing practical skills in the use (application) of personal protective equipment is a determining factor for the effectiveness of measures to prevent occupational injuries, occupational diseases and eliminate their consequences. The legal basis for regulating the use and provision of personal protective equipment to employees in the Russian Federation is a set of regulatory legal acts. In particular, Orders of the Ministry of Labor No. 767N[1] and No. 766N[2] define the criteria and procedures for PPE use. There are also regulations establishing mandatory requirements for PPE quality, certification, and safety guarantees when using PPE [3, 4].

An urgent area of focus in occupational safety management is increasing the level of safety culture in the workplace. This implementation allows for ensuring the effectiveness of personal protective equipment (PPE) use and application processes. To achieve this, a comprehensive approach is required, including training and educating employees on the importance of compliance with safety regulations, actively involving them in the selection and testing of PPE, and regularly analyzing and improving the Occupational Health and Safety Assessment System. As part of this effort, the authors aim to develop methods for reducing industrial micro-trauma occurrences by improving the prevention system for construction organization personnel. This involves introducing integrated solutions that utilize digital technologies to track PPE distribution and usage.

Materials and Methods. The work uses methods and technologies based on the requirements of the legislative and regulatory framework of the Russian Federation for accounting and issuing personal protective equipment in order to determine their effectiveness, taking into account the industry characteristics of enterprises. The evaluation of personal protective equipment used by employees of a construction organization in the Belgorod region was conducted using a questionnaire developed based on the methodology for evaluating PPE effectiveness presented in Federal Law No. 426–FZ[3]. Indicators reflecting the degree of PPE compliance with regulatory requirements were also taken into account (Table 1).

[1] *On Approval of Uniform Standards for the Issuance of Personal Protective Equipment and Flushing Agents.* Order of the Ministry of Labor of the Russian Federation No. 767N dated 29.10.2021. URL: https://www.consultant.ru/document/cons_doc_LAW_405226/ (accessed: 14.05.2024). (In Russ.)
[2] *On Approval of the Rules for Providing Employees with Personal Protective Equipment and Flushing Agents.* Order of the Ministry of Labor of the Russian Federation No. 766N dated 29.10.2021. URL: https://docs.cntd.ru/document/727092798 (accessed: 14.05.2024). (In Russ.)
[3] *On Special Assessment of Working Conditions.* Federal Law of the Russian Federation No. 426-FZ dated 28.12.2013. URL: https://www.consultant.ru/document/cons_doc_LAW_156555/ (accessed: 14.05.2024). (In Russ.)

Table 1

Questionnaire offered to respondents of the Belgorod region construction company

No.	Content of the question	Answer options *	
		Yes	No
1	When applying for your current position, were you provided with personal protective equipment (PPE)?		
2	During the initial issuance of personal protective equipment, were you satisfied with all aspects, such as size, quality, and appearance?		
3	Do the assortment and number of PPE issued correspond to real working conditions?		
4	Are you satisfied with the quality and other technical characteristics of the PPE provided by the organization?		
5	Do the actual terms of PPE use in the enterprise comply with established standards?		
6	Are you familiar with the map of the special assessment of the working conditions of your workplace?		
7	Has an employee's personal record been created, which reflects all PPE issued to you?		
8	Are you satisfied with the results of replacing and updating your personal protective equipment? If not, please provide the reason for your dissatisfaction on the back of this questionnaire.		
9	Do you have enough time to replace unsuitable PPE before the start of your next shift? If not, please specify how long you have waited for the replacement on the back of this questionnaire.		
10	Do you have any suggestions for improving the system of providing personal protective equipment and safety instructions at work? If so, please share them with us on the back of this questionnaire.		

The collection of statistical data was conducted through a survey of employees. The aim was to obtain direct information from those involved in the work process in order to evaluate the current level of protective equipment provision and identify areas that needed improvement. Choosing protective equipment that was comfortable and met individual preferences could increase its acceptance among employees, which was essential for motivating them in the field of occupational health and safety.

In today's technological landscape, there has been a significant increase in the number of computer programs designed to automate and ensure the safety of work processes, as well as increase labor productivity [5, 6]. As an example of the successful market entry and implementation of digital technologies in industrial practice, we can consider specialized distribution systems for personal protective equipment — automatic issuing devices (vending machines), developed by a large holding company — Vostok-Service Group. Vending machine model 540 issues PPE with a short service life; model 34 produces large-sized protective equipment; the machine for accepting PPE for cleaning, model 640, is equipped with a trolley or durable bag that can hold up to 40 pieces of workwear; and storage model 140 is a device for separate disposal of various types of PPE consisting of sections with touch screens. Information kiosk model 740 is a device that allows employees to log into their personal accounts and find information about their personal protective equipment (PPE), the status of their workwear in the laundry, and the expiration dates for their work garments.

The analysis of promising scientific directions in the field of digitalization of accounting processes and personal protective equipment issuance was carried out based on a study of patent and technical information resources [7, 8]. The relevance of developing digital solutions in this area is confirmed by the annual increase in the number of registered utility models and inventions. This can be seen from the data presented on the digital platform of the Federal Service for Intellectual Property. As examples, the following developments can be mentioned: utility model for patent RU165544U1 “Automatic machine for issuing and monitoring personal protective equipment (PPE)”; utility model for patent RU183254U1 “Device for storing and issuing personal protective equipment and tools”; patent for invention RU2742980C1 “Container for collecting and disinfecting used personal protective equipment”.

Vending machines are widely used in enterprises located on construction sites and have all necessary personal protective equipment in abundance. However, integrating these devices with corporate software and electronic accounting for PPE remains a significant challenge. For instance, vending machines provided by Vostok-Service

Group have their own information system connected via the Internet, which may not always work on remote construction sites. The software of these devices can be integrated with enterprise systems (1C or SAP), which would be convenient if such systems are already implemented in the organization. It is better to use cloud-based software on construction sites, as this would allow for real-time tracking of each piece of issued PPE. All employees would receive plastic RFID cards that would allow the system to identify them and record their personal protective equipment. The main advantage of these devices is that, as a supplier, Vostok-Service Group provides all the necessary personal protective equipment at once.

The analysis of patented utility models and inventions has revealed that these machines and containers cannot be synchronized with the information systems of enterprises, which is a significant disadvantage [9, 10].

Currently, in most organizations, the traditional system of providing personal protective equipment is used. Under this system, PPE is purchased in advance and stored in a warehouse. Employees are then given PPE when they need it. However, this method has several drawbacks. It limits the choice of PPE available and provides only a limited number of types. This can slow down the process of introducing new PPE and adapting it to specific working conditions. Additionally, it can take time to deliver new PPE to workplaces, which can further delay the implementation of new safety measures [11, 12].

The material for the study consisted of the results of a survey conducted among employees using a developed questionnaire, as well as statistical data on micro-injuries (micro-traumas) recorded in the company's logs. Based on the survey results, the problems were identified regarding the provision of personal protective equipment and its improper use during work, which was confirmed by data from accounting documentation related to the registration of micro-traumas.

In order to reduce the number of micro-traumas among workers in the construction industry due to improper use of PPE, lack of necessary protective equipment, insufficient knowledge on their use, it was decided to change the process of issuing personal protective equipment to employees by introducing a digital product for smartphones Stroykontrol+ (Fig. 1)

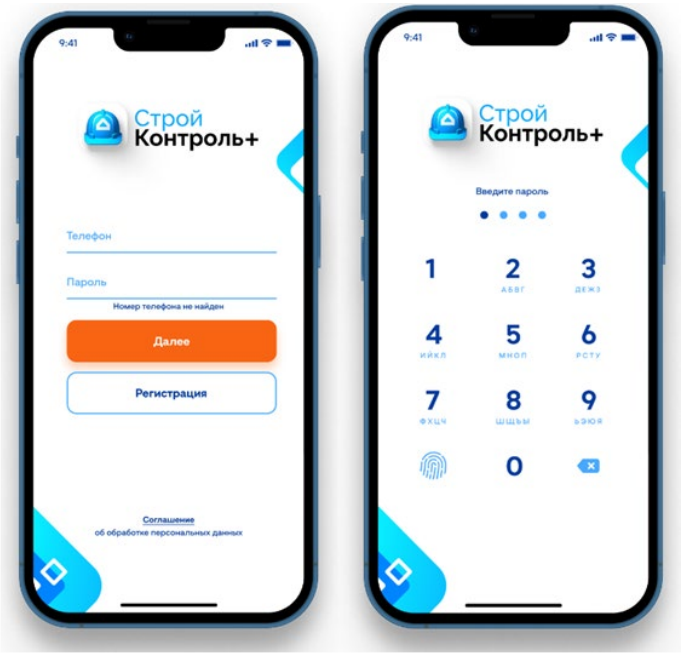


Fig. 1. User registration and authentication module in the Stroykontrol+ application

An employee of the organization needs to install this app on their mobile device. After that, the account will be verified by an occupational health and safety specialist. The account must be linked to the employee's phone number, which minimizes the risks of personal data leakage and digital hacking, and prevents unauthorized persons from using the application. This verification technique is widely used in various digital applications and has demonstrated high efficiency.

The application provides employees with the opportunity to take both mandatory and voluntary tests. To use this feature, you need to familiarize yourself with the program's interface. An important part of this is the built-in chat function, which allows managers and employees to communicate during working hours. This chat is used to quickly resolve production issues and problems. The use of chat communication facilitates the efficient exchange of information about issues and needs that arise during work, as well as allows managers to receive timely notifications about the lack of personal protective equipment on their smartphones, which helps speed up its delivery to the workplace (Fig. 2).

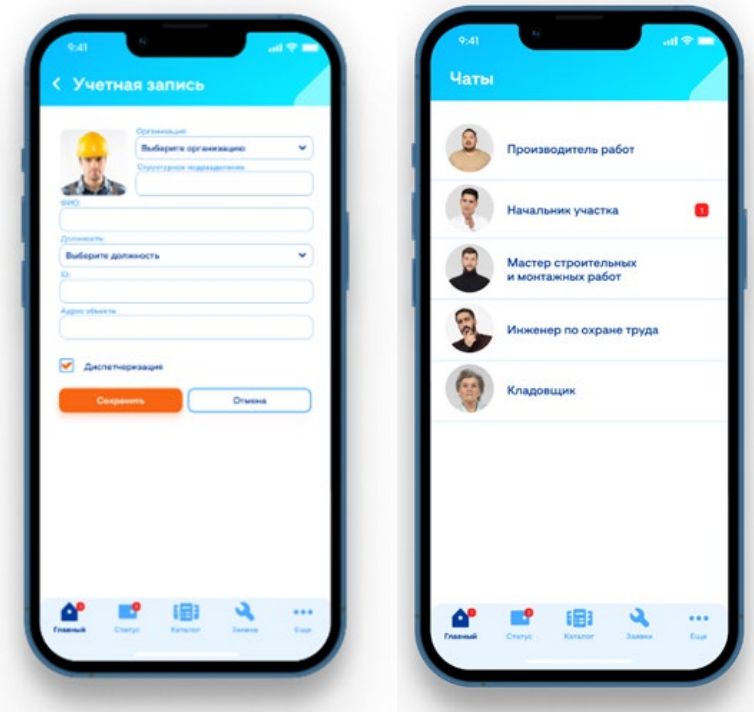


Fig. 2. Personal account design and presentation of the list of dialog channels

The section of the application for notifying managers and other responsible parties about problems with the use of personal protective equipment will be created to address issues related to its replacement due to technical issues. The implementation of this feature will reduce problem-solving time by 35%, as information is processed as soon as possible and decisions are made within a few seconds. This section can be useful for employees due to the convenient way of writing off personal protective equipment (Fig. 3).

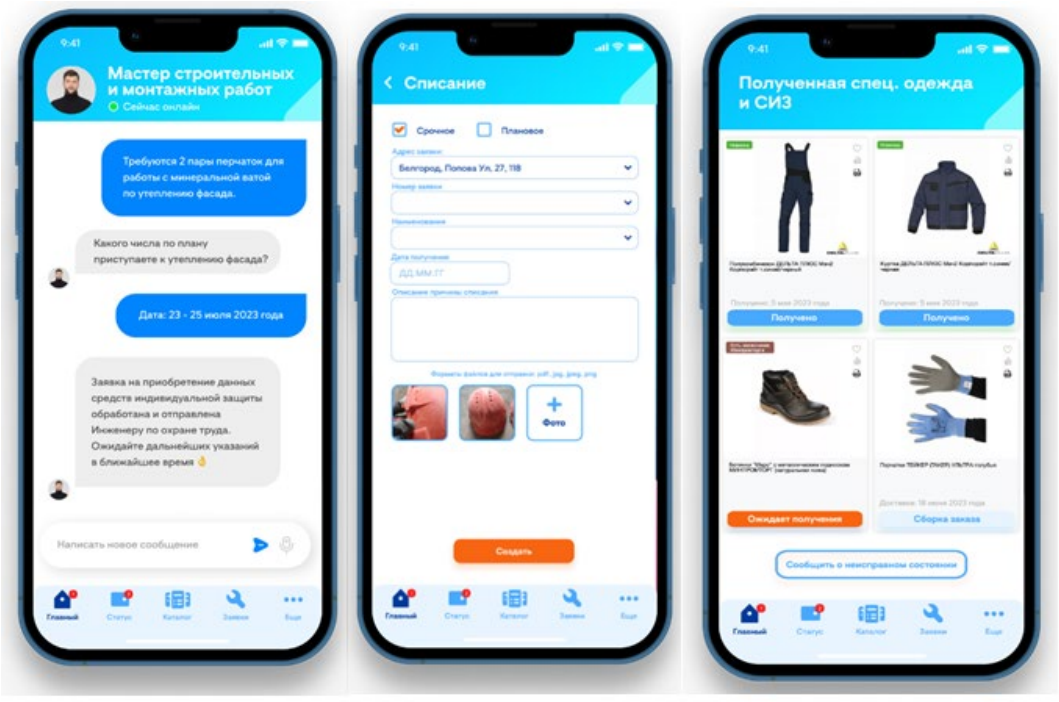


Fig. 3. Design of the screen for operations to obtain and control the availability of PPE

The introduction of a mobile app has significantly improved the process of providing personal protective equipment in the construction industry. It has provided a more convenient and transparent system for monitoring and managing PPE, as well as an effective way for employees to obtain the necessary equipment. The app allows employees to easily access the PPE they need, while also providing an efficient system for employers and authorized personnel to submit and process requests. This helps to increase security levels and reduce time spent on PPE issuance. Additionally, the app keeps a more accurate record of PPE provided and helps prevent problems related to stock shortages. Using mobile

apps like this to improve safety awareness among employees contributes to a stronger overall safety culture in the workplace. The application provides instructions on the proper use of personal protective equipment, as well as educational materials, videos, and guides on safe usage of these products. This helps to reduce the risk of injuries and accidents in the workplace.

Results. An important responsibility of employers is to provide construction workers with personal protective equipment that ensures safety and health in the workplace [13]. The traditional method of providing PPE involves purchasing it from suppliers or stores and then distributing it directly to workers [14]. This is followed by training the workers on how to use the equipment safely to reduce the risk of accidents and potential hazards on the construction site.

The survey was conducted among 300 employees of a construction company in the Belgorod region. The participants included a construction and mechanical foreman, an operator of lifting equipment, a bricklayer, a carpenter, an electric and gas welder, a tower crane operator, a plasterer-painter, a tiler, a welder and others. The average age of the respondents was 40–55 years and they had more than 10 years of work experience. Eighty percent of the participants were male and 85 percent had secondary vocational education. Their work schedule was 5/2, which means an eight-hour working day.

The results of the survey among employees of the construction company in the Belgorod region revealed that 80% of them were provided with necessary personal protective equipment from warehouse managers with mandatory recording and filling out of personal PPE cards.

To obtain admission to independent work, employees undergo introductory training on labor protection and training on labor protection in the workplace [15]. During this training, they are informed about maps of a special assessment of working conditions and an assessment of occupational risks. According to the results of a survey, about 70% of employees expressed dissatisfaction with the results of replacement and renewal of personal protective equipment due to the length of the process. In their notes, the employees mentioned that they had been unable to change unsuitable protective equipment for months. After analyzing the questionnaires of the respondents, several reasons for the delayed replacement of personal protective equipment were identified: the geographical distance between the warehouse and the construction site, the absence of necessary protective equipment, and the presence of intermediaries between the employee and the storekeeper. These factors all contributed to the delay in replacing personal protective equipment. These problems increased the risk of injuries and occupational diseases.

The issue of microtraumatism among workers was primarily due to their failure to use personal protective equipment. This was caused by several factors, including ignorance of the need to use PPE, lack of formal training on its use, improper usage, delayed replacement and updates. This was confirmed by the statistical data collected based on documentation on the recording and accounting of micro-injuries in construction organizations in the Belgorod region for 2022 and 2023 (Fig. 4).

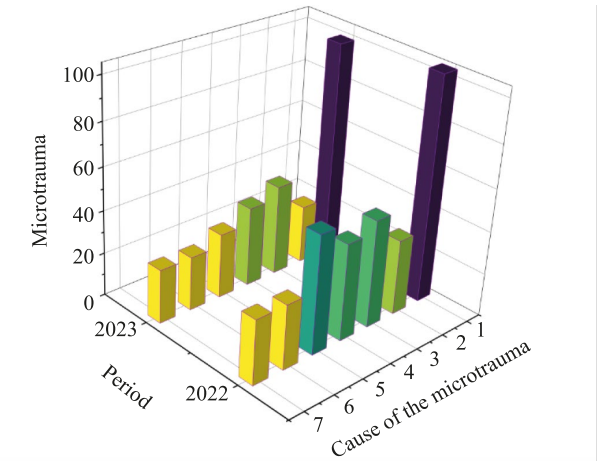


Fig. 4. Distribution of types of micro-traumas among construction workers by the causes of their occurrence in 2022 and 2023: 1 — fatigue, physical overstrain; 2 — ignoring the use of PPE by an employee; 3 — improper use of PPE by an employee; 4 — lack of knowledge about the proper use of PPE among employees; 5 — lack of necessary PPE for employees; 6 — performing work that is not part of official duties; 7 — unsatisfactory condition of floors, including uneven, slippery and sunken surfaces

It was found that there were 350 microtraumas recorded in 2022. After the introduction of the developed digital product Stroykontrol+, there was a decrease in the number of microtraumas in 2023 by 64 cases. This decrease was due to several factors: 1. Ignoring the use of personal protective equipment (PPE) by employees. 2. Improper use of PPE by employees. 3. Lack of knowledge among employees on the correct use and application of PPE. 4. Absence of necessary PPE for some employees.

Discussion and Conclusion. As part of the construction activities in the Belgorod region, different approaches are used to provide personnel with personal protective equipment. This includes both the traditional PPE distribution system and a hybrid model that eliminates the need for a warehouse and transfers the supply and storage functions to a technical engineer.

The distribution of PPE is done as necessary, taking into account the level of completion of work. One of the most common problems faced by construction companies is the lack of sufficient PPE, which can be attributed to several factors: inefficient planning and inventory management due to a lack of systematic analysis of PPE needs, as well as imperfections in ordering and receiving goods.

As a result of inadequate adaptation, non-compliance with needs, and lack of control over PPE use, untimely updating, traditional systems for their issuance cannot ensure effective employee safety. To minimize the risk of occupational injuries, it is essential to implement a continuous analysis and update system for PPE. The optimal solution is to develop and implement a digital platform based on a mobile app with advanced features and an intuitive interface. This platform should integrate key aspects of digital construction in Russia, including the introduction of building information modeling (BIM) technology and automation/robotization of production.

Thanks to the introduction of the digital product Stroykontrol+, which automates the accounting of PPE distribution, the process of providing personal protective equipment to employees has been improved. This has led to improvements in the indicators presented in Table 2.

Table 2

Effectiveness evaluation of the Stroykontrol+ application implementation

Performance indicators for the implementation of digital solutions	2022 Distribution of PPE according to the traditional method	2023 Distribution of PPE using the Stroykontrol+ application
Number of microtraumatic injuries caused by: – improper use of personal protective equipment (PPE) by personnel; – insufficient qualifications of employees in the field of application of personal protective equipment; – lack of necessary PPE for employees	350 50 45 55	286 42 37 30
Number of correct answers when checking the knowledge of employees during testing according to the training program for the use (application) of personal protective equipment	65–72%	85–99%
Average time to replace defective PPE from application to receipt	30 days	10 days
Average response time for responsible parties to address identified comments or issues related to the use of PPE by employees	10 days	2 days

For the methodological content of the Stroykontrol+ digital product, training materials have been developed to work with personnel, including instructions on the use of PPE, illustrated memos on the rules for using protective equipment, and test tasks to test knowledge.

In the future, it is planned to improve the PPE issuance system by integrating with data on dynamic assessment of occupational risks and special assessment of working conditions. This will help to improve the efficiency of our occupational safety management system.

References

1. Timofeeva NV, Krasil'nikova AM. Development of the Interface of the Information Support System for the Process of Accounting for Personal Protective Equipment of Employees of the Enterprise. *Tendentsii razvitiya nauki i obrazovaniya.* 2021;(80–2):163–169. https://doicode.ru/doifile/lj/80/lj12_2021_p2.pdf (In Russ.)

2. Stikanova VE, Zhuravleva SV. Development of Recommendations for Improving the System of Providing Employees with Personal Protective Equipment. In: *Materials of the II All-Russian (national) scientific and practical conference "Engineering tasks: problems and solutions".* Arkhangelsk: Northern (Arctic) Federal University named after M.V. Lomonosov; 2021. P. 231–234. (In Russ.)

3. Trubetskov AD, Makhonko MN, Shkrobova NV, Shelekhova TV. Problems of Using Personal Protective Equipment in Modern Conditions. *Russian Journal of Occupational Health and Industrial Ecology.* 2023;63(5): 336–343. https://doi.org/10.31089/1026-9428-2023-63-5-336-343 (In Russ.)

4. Tom Ka Man Wong, Siu Shing Man, Alan Hoi Shou Chan. Critical Factors for the Use or Non-Use of Personal Protective Equipment amongst Construction Workers. *Safety Science.* 2020;126:104663. https://doi.org/10.1016/j.ssci.2020.104663

5. Dementieva AI, Buzikova OM. Digitalization of the System for Occupational Safety and Health of Workers: Structure, Priorities, Regulations, Management, Personal Protection Means. In: *Collection of articles of the XXII International scientific and practical conference "Ecology and life safety".* Penza: Penza State Agrarian University; 2022. P. 87–91. (In Russ.)

6. Nath ND, Behzadan AH, Paal SG. Deep Learning for Site Safety: Real-Time Detection of Personal Protective Equipment. *Automation in Construction.* 2020;112:103085. https://doi.org/10.1016/j.autcon.2020.103085

7. Zijian Wang, Yimin Wu, Lichao Yang, Arjun Thirunavukarasu, Colin Evison, Yifan Zhao. Fast Personal Protective Equipment Detection for Real Construction Sites Using Deep Learning Approaches. *Sensors.* 2021;21(10):3478. https://doi.org/10.3390/s21103478

8. Edamenko AS, Yastrebinskaya AV. Hazard Analysis and Accident Risk Assessment at Petroleum Product Storage Facilities. *Technosphere Security Technologies.* 2023;3(101):60–73. https://doi.org/10.25257/TTS.2023.3.101.60-73 (In Russ.)

9. Zhdanov VV. Data Transmission Process for the Automated Distribution of Personal Protective Equipment. *National Development. Science and Education.* 2023;10(22):29–30. (In Russ.)

10. Bakhonina EI, Nasibullina VA, Gaybadullin FF, Fedosova EA. Review of Legislation Regulating the Procedure for Issuing Personal Protective Equipment. *Eurasian Law Journal.* 2023;9(184):239–240. (In Russ.)

11. Vlasova KA, Korepanov AV. Development of an Automated Accounting System for the PPE of Elecond JSC. In: *Proceedings of the All-Russian Scientific and Technical Conference "Information Technologies in Science, Industry and Education".* Izhevsk: Kalashnikov Izhevsk State Technical University; 2022. P. 94–101. (In Russ.)

12. Bystrov EN, Kharlamova AV. Provision of Personal Protective Equipment for Employees of Transport Enterprises. *Proceedings of Petersburg Transport University.* 2023;20(2):396–403. https://doi.org/10.20295/1815-588X-2023-2-396-403 (In Russ.)

13. Egorova LG, Sukhodoev VA. Algorithmic Support for Automation of the Complex of Registration of Standard Norms for the Issuance of Personal Protective Equipment at an Industrial Enterprise. In: *Collection of scientific papers. AB OVO... (From the very beginning...).* Magnitogorsk: Magnitogorsk State Technical University named after G.I. Nosov; 2021;6:4–9. (In Russ.)

14. Bakhonina EI, Matuzov GL, Karimova VA. Features of Providing PPE Workers in the Russian Federation and Foreign Countries. *Life Safety.* 2022;6(258):11–16. (In Russ.)

15. Bogdanov AS. Practical Features of the Implementation of a Risk-Based Approach in the Occupational Safety Management System. *Occupational Health and Safety in Logging and Woodworking Industries.* 2023;6:4–8. https://doi.org/10.33920/pro-05-2306-01 (In Russ.)

About the Authors:

Viktoriya A. Petrova, Postgraduate Student of the Life Safety Department, Belgorod State Technological University named after V.G. Shukhov (46, Kostyukova Str., Belgorod, 308012, Russian Federation), SPIN-code: 2361-2396, ORCID, ResearcherID, ScopusID, lezhand@mail.ru

Elena V. Klimova, Cand. Sci. (Eng.), Associate Professor, Head of the Life Safety Department, Belgorod State Technological University named after V.G. Shukhov (46, Kostyukova Str., Belgorod, 308012, Russian Federation), SPIN-code: 7194-0598, ORCID, ScopusID, lena_1109@mail.ru

Alexander Yu. Semeykin, Cand. Sci. (Eng.), Associate Professor of the Life Safety Department, Belgorod State Technological University named after V.G. Shukhov (46, Kostyukova Str., Belgorod, 308012, Russian Federation), SPIN-code: 4768-3762, ORCID, ResearcherID, ScopusID, alexsem-n@yandex.ru

Oksana N. Tomarovshchenko, Cand. Sci. (Eng.), Associate Professor of the Life Safety Department, Belgorod State Technological University named after V.G. Shukhov (46, Kostyukova Str., Belgorod, 308012, Russian Federation), SPIN-code: 2726-5676, ORCID, ResearcherID, ScopusID, ox.guzeeva@yandex.ru

Claimed Contributorship:

The authors contributed equally to the formulation of the research question and the definition of the objectives, conducting experiments and analyzing the results, drawing conclusions, and editing the manuscript.

Conflict of Interest Statement: **the authors do not have any conflict of interest.**

All authors have read and approved the final manuscript.

Об авторах:

Виктория Александровна Петрова, аспирант кафедры безопасность жизнедеятельности Белгородского государственного технологического университета имени В.Г. Шухова (308012, Российская Федерация, г. Белгород, ул. Костюкова, 46), SPIN-код: 2361-2396, ORCID, ResearcherID, ScopusID, lezhand@mail.ru

Елена Владимировна Климова, кандидат технических наук, доцент, заведующая кафедрой безопасность жизнедеятельности Белгородского государственного технологического университета имени В.Г. Шухова (308012, Российская Федерация, г. Белгород, ул. Костюкова, 46), SPIN-код: 7194-0598, ORCID, ScopusID, lena_1109@mail.ru

Александр Юрьевич Семейкин, кандидат технических наук, доцент кафедры безопасность жизнедеятельности Белгородского государственного технологического университета имени В.Г. Шухова (308012, Российская Федерация, г. Белгород, ул. Костюкова, 46), SPIN-код: 4768-3762, ORCID, ResearcherID, ScopusID, alexsem-n@yandex.ru

Оксана Николаевна Томаровщенко, кандидат технических наук, доцент кафедры безопасность жизнедеятельности Белгородского государственного технологического университета имени В.Г. Шухова (308012, Российская Федерация, г. Белгород, ул. Костюкова, 46), SPIN-код: 2726-5676, ORCID, ResearcherID, ScopusID, ox.guzeeva@yandex.ru

***Заявленный вклад авторов*:**

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

Конфликт интересов: **авторы заявляют об отсутствии конфликта интересов.**

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 22.05.2024
Revised / Поступила после рецензирования 11.06.2024
Accepted / Принята к публикации 16.06.2024

TECHNOSPHERE SAFETY
ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ

UDC 517.95
https://doi.org/10.23947/2541-9129-2024-8-3-39-48

Perspective Article

Application of Methods of Observational Data Assimilation to Model the Spread of Pollutants in a Reservoir and Manage Sustainable Development

Yuliya V. Belova ✉, **Alla V. Nikitina**
Don State Technical University, Rostov-on-Don, Russian Federation
✉ yvbelova@yandex.ru

EDN: DHTHBS

Abstract

Introduction. Mathematical models and methods are widely used to study natural phenomena, replacing more expensive field experiments. However, one of the main challenges in modeling processes in complex systems is the lack of available input data and difficulty in selecting model parameters. The use of observational data assimilation methods is one of the ways to provide mathematical models with input data and parameter values. The aim of this study was to predict the development of complex natural systems under conditions of pollution using mathematical modeling techniques. To achieve this, several tasks were completed: a method for assimilating observational data was selected, a mathematical model for biological kinetics was updated, it was integrated with a hydrodynamic model, and a software package was developed. The significance of the work lies in the to the implementation of a model of the dynamics of phytoplankton populations (eutrophication) of the Azov Sea in the presence of pollutants, based on the use of variational methods for assimilating data obtained during expeditionary research.

Materials and Methods. The spread of pollutants was modeled using a three-dimensional mathematical model based on a system of convection — diffusion — reaction equations. The vector of movement of the aquatic environment was the input data for the model. The components of the current velocity vector in the coastal system were calculated using a mathematical model of hydrodynamics, based on three equations of motion and the equation of continuity. The software package developed based on these models received full-scale data collected during expeditionary research as input, and allowed us to refine the model of pollution in the aquatic environment and biota using variational methods for data assimilation.

Results. A short-term forecast for the spread of pollutants at the outlet of the Taganrog Bay was developed. The conducted computational experiment reflected the dynamics of pollutant spread from sources of contamination over a period of 3 to 12 days.

Discussion and Conclusion. The variational methods of assimilating observational data discussed in this study allow for the refinement and supplementation of mathematical models of phytoplankton population dynamics and pollutant spread. The software based on these mathematical models enables the creation of short- and medium-term forecasts for the spread of harmful substances, assessment of their impact on the growth of major phytoplankton species in the Azov Sea, and determination of strategies for sustainable development management.

Keywords: eutrophication model, hydrodynamics model, variational methods, dangerous phenomena, assimilation of observational data

Acknowledgements. The authors would like to thank the Editorial team of the Journal and anonymous reviewers for their competent expertise and valuable recommendations for improving the quality of the article. The authors also express their gratitude to the project leader, Corresponding Member of the Russian Academy of Sciences, Aleksandr I. Sukhinov.

Funding Information. The study was supported by the Russian Science Foundation grant No. 22–11–00295, https://rscf.ru/en/project/22-11-00295/

For citation. Belova YuV, Nikitina AV. Application of Methods of Observational Data Assimilation to Model the Spread of Pollutants in a Reservoir and Manage Sustainable Development. *Safety of Technogenic and Natural Systems.* 2024;8(3):39–48. https://doi.org/10.23947/2541-9129-2024-8-3-39-48

Статья-перспектива

Применение методов усвоения данных наблюдений для моделирования распространения загрязняющих веществ в водоеме и управления устойчивым развитием

Ю.В. Белова ✉, **А.В. Никитина**
Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация
✉ yvbelova@yandex.ru

Аннотация

Введение. Математические модели и методы повсеместно используются для исследования природных объектов, заменяя более дорогие натурные эксперименты. Одними из трудностей, возникающих при моделировании процессов в сложных системах, являются наличие входных данных и подбор параметров модели. Применение методов усвоения данных наблюдений является одним из способов оснащения математических моделей входными данными и значениями параметров. Цель настоящего исследования состоит в прогнозировании на основе методов математического моделирования развития сложных природных систем в условиях загрязнения вредными веществами. Для достижения цели были решены следующие задачи: выбран метод усвоения данных наблюдений, актуализирована математическая модель биологической кинетики, данная модель скомплексирована с моделью гидродинамики, разработан программный комплекс. Актуальность работы заключается в применении нового подхода к реализации модели динамики фитопланктонных популяций (эвтрофикации) Азовского моря при наличии загрязняющих примесей, основанного на применении вариационных методов усвоения данных, полученных в ходе экспедиционных исследований.

Материалы и методы. Распространение загрязняющих веществ моделируется на основе трехмерной математической модели, основанной на системе уравнений конвекции — диффузии — реакции. На входе модели подается вектор движения водной среды. Составляющие вектора скорости течений в прибрежной системе рассчитываются на основе математической модели гидродинамики, базирующейся на трех уравнениях движения и уравнении неразрывности. Разработанный на основе описанных моделей программный комплекс получает на входе натурные данные, собранные в ходе экспедиционных исследований, и позволяет уточнять модель загрязнения водной среды и биоты благодаря применению вариационных методов усвоения данных.

Результаты исследования. Построен краткосрочный прогноз распространения загрязняющих веществ на выходе из Таганрогского залива. Проведенный вычислительный эксперимент отражает динамику распространения загрязняющих веществ от источников заражения на временном интервале от 3 до 12 дней.

Обсуждение и заключение. Рассмотренные в данном исследовании вариационные методы усвоения данных наблюдений позволяют уточнять и дополнять математические модели динамики фитопланктонных популяций и распространения загрязняющих веществ. Программное обеспечение, основанное на описанных в данной работе математических моделях, дает возможность строить кратко- и среднесрочные прогнозы распространения вредных примесей, оценивать их влияние на развитие основных видов фитопланктонных популяций в Азовском море и определять стратегии управления устойчивым развитием.

Ключевые слова: модель эвтрофикации, модель гидродинамики, вариационные методы, опасные явления, усвоение данных наблюдений

Благодарности. Авторы благодарят редакционную команду журнала и анонимных рецензентов за высказанные замечания, которые позволили повысить качество статьи, а также выражают признательность руководителю проекта, члену-корреспонденту РАН Александру Ивановичу Сухинову.

Финансирование. Исследование выполнено за счет гранта Российского научного фонда № 22–11–00295, https://rscf.ru/project/22-11-00295/

Для цитирования. Белова Ю.В., Никитина А.В. Применение методов усвоения данных наблюдений для моделирования распространения загрязняющих веществ в водоеме и управления устойчивым развитием. *Безопасность техногенных и природных систем.* 2024;8(3):39–48. https://doi.org/10.23947/2541-9129-2024-8-3-39-48

Introduction. Mathematical models and methods have been successfully used for decades in conducting research in various fields of science and engineering. These models provide fast, convenient, and relatively inexpensive tools for studying and predicting processes in complex natural systems, compared to expeditions and field experiments. They are used to solve a wide range of scientific and practical problems, such as predictive modeling of siltation of shipping lanes, which is important for safe navigation, as well as predicting the consequences of emergencies and man-made

disasters. An example is the severe storm on November 11, 2007 in the Azov-Black Sea basin, as a result of which more than 20 ships were wrecked, and the Kerch Strait area became the site of an environmental disaster. Several tons of fuel oil and sulfur got into the water, as a result of which the coastline and sediment layer were contaminated with petroleum compounds. Its consequences were observed for several more years. Another example of adverse processes is the transport of bottom materials from the mouth of the Don River to the Taganrog Bay, which affects the habitats of aquatic organisms, promotes intensive eutrophication and leads to the reproduction of *Chironomidae Newman*.

According to Decree of the Government of the Russian Federation No. 2451 dated December 31, 2020[1], researchers, decision makers, and representatives of water protection services have only four hours from the moment of detection or from the moment of receipt of information about a spill in a reservoir to calculate changes in the concentration of oil and petroleum products and their localization. According to the above and other regulatory documents adopted by the Government of the Russian Federation, responsible persons and structures must make a decision and take actions to eliminate a dangerous environmental situation of a natural and man-made nature within a few hours or days. Based on this, the time for making forecasts and scenarios for the development of an emergency situation is limited. This requirement determines the relevance of developing a set of mathematical models of hydrodynamics and hydrobiology that would take into account the features of coastal systems (the effect of winds on the structure of currents, the Coriolis force, the complex geometry of the computational domain, turbulent exchange, evaporation, wind-driven effects, river flows, etc.) and make it possible to obtain forecasts in a minimum time.

When forecasting the development of natural systems and describing a real physical phenomenon through mathematical modeling, it is not enough to simply construct a function of the process state. The use of conjugate problems for mathematical models and algorithms based on variational principles can increase the accuracy of solutions. These principles allow us to establish a connection between the model and field data [1]. This methodology is effective for solving applied problems, including computationally intensive tasks, such as variational and optimization problems in mathematical and nuclear physics [2]. G.I. Marchuk and his colleagues used conjugate equations [3], which made it possible to improve the efficiency of solving problems of aero- and hydrophysics for the atmosphere and deep-water reservoirs. The theory of building conjugate operators for linear and nonlinear models has also been improved [4].

A variational approach to solving combined direct and conjugate problems using assimilation methods has improved the relationship between mathematical models and field data. Methods of data assimilation, which have been developing since the 1960s, are based on the construction of inverse and optimization problems using two approaches: the classical Lagrange variational principle using conjugate problems [4] and optimization methods such as weighted least squares [5].

The assimilation of observational data is a tool that can significantly improve the accuracy of predictive modeling of natural processes. It has long been successfully used by the scientific community [6]. Here, the urgent task is to develop new methods that would significantly reduce the calculation time.

Materials and Methods. When building models for predicting natural phenomena and processes, one of the main problems was the correspondence of the solution obtained using a mathematical model to the real process occurring in the natural system and reducing the percentage of uncertainties.

When constructing mathematical models of hydrodynamic and hydrobiological processes, information about the initial conditions and parameters of the model was required, which could be obtained using observational data. Thus, when constructing predictive scenarios of natural or man-made emergencies, it was very important to assess the adequacy of the mathematical model itself. The next stage of modeling included checking the correctness and stability of the task. The study of a mathematical model at a continuous level involved the study of the influence of input data on the solution of a model problem. The perturbation of the right-hand sides of the equation used or the system of partial differential equations in the Cauchy problem under consideration made it possible, with known operators, to investigate the properties of the constructed mathematical model. The study of stationary and special points of a continuous function or several functions — solutions to the task, for example, the concentration of one or more pollutants in the aquatic environment, allowed us to develop scenarios, from pessimistic to optimistic ones, in order to develop measures for effective management of a complex aquatic ecosystem.

For the first time, the method of polynomial interpolation of data from a constantly replenished database of environmental measurements in the two-dimensional case was used to analyze field data. Areas of influence have been identified for observations. When implementing the algorithm for calculating the current background, the data from the previously received forecast was used as input information.

[1] *On Approval of the Rules for the Organization of Measures to Prevent and Eliminate Oil and Petroleum Product Spills on the Territory of the Russian Federation, with the Exception of the Internal Sea Waters of the Russian Federation and the Territorial Sea of the Russian Federation.* Decree of the Government of the Russian Federation No. 2451 dated 31.12.2020. URL: https://docs.cntd.ru/document/573319208 (accessed: 21.05.2024). (In Russ.)

The OI (Optimal Interpolation) method has brought a new level of sophistication to the methodology for solving problems of data assimilation. This method was based on statistical interpolation techniques.

The next stage in the development of the considered methods was associated with the development and implementation of variational methods, including the theory of optimal control. These methods were based on minimizing the functionality built in a special way, with the help of which a connection was established between solutions and observations (field measurements, expedition data, GIS geographic information system databases).

This theory and methods were widely used in the implementation of the tasks of meteorology [5] and dynamic oceanography [7]. In the process of minimizing the constructed functional, it was necessary to calculate its gradient, for which conjugate equations were successfully applied, which was described in [8, 9].

Model of the Dynamics of Phytoplankton Populations. A mathematical model of the dynamics of phytoplankton populations describes the process of active growth of microalgae in the presence of a sufficient number of biogenic elements. If the development of phytoplankton populations becomes too intense, it is referred to as the process of eutrophication. The causes of eutrophication can be both natural (climatic changes) and anthropogenic in nature (the entry of a significant amount of nutrients into the reservoir from river drains). System C_i contains the concentration values of the i-th substance [10, 11]:

$$\frac{\partial C_k}{\partial t}+\frac{\partial\left(uC_k\right)}{\partial x}+\frac{\partial\left(vC_k\right)}{\partial y}+\frac{\partial\left(\left(w+w_{C,k}\right)C_k\right)}{\partial z}=\frac{\partial}{\partial x}\left(\mu_k\frac{\partial C_k}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_k\frac{\partial C_k}{\partial y}\right)+\frac{\partial}{\partial z}\left(\nu_k\frac{\partial C_k}{\partial z}\right)+\psi_k, \qquad (1)$$

where $\mathbf{u}=\{u, v, w\}$ — velocity vector of the medium (water flow); $w_{C,k}$ — gravitational deposition of the k-th component, if it is in a suspended state; μ_k, ν_k — horizontal and vertical components of the coefficient of turbulent exchange for the k-th componen; ψ_k — chemical-biological source (drain) or term describing aggregation (sticking-splitting), if the corresponding component is a suspension, index k indicates the type of substance, $k=\overline{1,15}$:

1 — hydrogen sulfide (H_2S);
2 — element sulfur S;
3 — thiosulfates (and sulfites);
4 — sulfates (SO_4);
5 — total organic nitrogen (N);
6 — ammonium (NH_4 — ammonium nitrogen);
7 — nitrates (NO_3);
8 — nitrites (NO_2);
9 — phytoplankton;
10 — zooplankton;
11 — silicates (SiO_3 — metasilicate; SiO_4 — orthosilicate);
12 — dissolved oxygen (O_2);
13 — ferrum (Fe^{2+});
14 — phosphates (PO_4);
15 — silicic acid (H_2SiO_4, H_2SiO_3 — orthosilicic and metasilicic acids, respectively);
16 — microplastic.

System (1) contains equations that can be attributed to the convection — diffusion — reaction type. As a computational domain, let us consider enclosed basin G. Undisturbed surface of basin Σ_0 is bounded from above by G, $\Sigma_b=\Sigma_b(x, y)$ — bottom surface from below, σ — cylindrical surface limits G from the side. We will use the following notation: $\Sigma=\Sigma_0\cup\sigma\cup\Sigma_b$ — piecewise smooth boundary of domain G, time interval $0<t\le T_0$. We assume that $\mathbf{n}$ and $\mathbf{u_n}$ — vector of external normal and is the normal component $\mathbf{u}$ to surface Σ.

We consider that initial conditions of system (1) are as follows: $C_k|_{t=0}=C_{k0}(x, y, z)$, $k=\overline{1,15}$.

We combine (1) with the following combined boundary conditions:

for σ: if $\mathbf{u_n}<0$, then $C_k=0$; if $\mathbf{u_n}\ge 0$, then $\frac{\partial C_k}{\partial \mathbf{n}}=0$; for Σ_0: $\frac{\partial C_k}{\partial z}=g\left(C_k\right)$; at the bottom Σ_b: $\frac{\partial C_k}{\partial z}=-\varepsilon_k C_k$, $k=\overline{1,16}$, we define ε_k as the coefficient of absorption of the k-th impurity by bottom sediments.

When there is no wind, especially in summer, almost anaerobic conditions may occur in the bottom layers of shallow reservoirs, such as, for example, the Azov Sea, the Taganrog Bay, and the Gelendzhik Bay. The reduction of water-saturated surface sludge entails the release of iron, phosphates, sulfates, manganese, ammonium and silicates, as well as organic compounds into the solution. Complexed models of type (1) (developed by the team of authors the

model of hydrodynamics [12]) were used to study the mechanisms of manganese oxidation and reduction, NH_4 assimilation, nitrification, nitrate reduction (denitrification), ammonification, H_2S oxidation, sulfate reduction, etc. Experiments with model (1) made it possible to study biogenic and oxygen regimes of the coastal system, to analyze the mechanism of formation due to anthropogenic eutrophication of marine phenomena of fish and other aquatic organisms.

Variational Approach for a Three-Dimensional Spatial Mathematical Model of Water Eutrophication. Let us write down mathematical model (1) for the computational domain (the Azov Sea) in the form of an operator equation:

$$L(C,\mathbf{Y}) \equiv D\frac{\partial C}{\partial t} + J(C,\mathbf{Y}) - \boldsymbol{\psi} - \mathbf{r} = 0, \tag{2}$$

we define **C** as a vector function of the state of the studied aquatic ecosystem $\mathbf{C} = \left\{C_k(\mathbf{x},t), k = \overline{1,16}\right\}$, $\mathbf{C} = \mathbf{C}(\mathbf{x},t) \in Q(Ц_t)$, $Ц_t = G \times (0, T_0)$, $(\mathbf{x},t) \in Ц_t$; $J(\mathbf{S},\mathbf{Y})$ — differential nonlinear spatial operator; D — diagonal matrix; $\boldsymbol{\psi} = \left\{\psi_k(\mathbf{x},t), k = \overline{1,16}\right\}$ — vector the components of which are source functions; $\mathbf{r} = \left\{r_k(\mathbf{x},t), k = \overline{1,16}\right\}$ — vector the components of which contain functions of uncertainties and errors of mathematical model (1) with initial and boundary conditions. Dependencies (observation models), coefficients and parameters $w_{C,k}$, μ_k, u, v, w, ν_k, input data of initial and boundary conditions for model (2), $k = \overline{1,16}$; internal parameters of the operators are included in $\mathbf{Y} \in R(Ц_t)$.

Let $t = 0$, then the initial conditions for (2) take the form:

$$\mathbf{C} = \mathbf{C}_a^0 + \boldsymbol{\xi},\ \mathbf{Y} = \mathbf{Y}_a^0 + \boldsymbol{\zeta}, \tag{3}$$

where $\mathbf{C}_a^0$ and $\mathbf{Y}_a^0$ — a priori estimates of the vector function of the state and the vector of parameters, respectively; the uncertainty functions are denoted using $\boldsymbol{\xi}$ and $\boldsymbol{\zeta}$.

Let us consider the integral identity:

$$I(\mathbf{C},\mathbf{Y},\mathbf{C}^*) \equiv \int_{Ц_t} \left(L(\mathbf{C},\mathbf{Y}),\mathbf{C}^*\right) dGdt = 0, \tag{4}$$

here $\mathbf{C}^*$ — functions conjugate to $\mathbf{C}(\mathbf{C}^* \in Q^*(Ц_t))$. (4) is a variational formulation of model problem (2), (3), or an energy-type functional. Let us rewrite (4) in the following form:

$$I(\mathbf{C},\mathbf{Y},\mathbf{C}^*) \equiv \sum_{k=1}^{16} \left\{ \left(\Lambda\mathbf{C},\mathbf{C}^*\right)_k - \int_{Ц_t} (\psi_k + r_k)\mathbf{C}_k^* dGdt \right\} = 0. \tag{5}$$

The operators of turbulent exchange and transfer are included in terms ($\Lambda\mathbf{C}$, $\mathbf{C}^*$).

Hydrodynamics model [12] will be considered as a model of the process. In hydrobiology models, parameterization of parameters and the resulting functional dependencies, for example, for describing production and destruction processes or the growth of phyto- or zooplankton, will be considered submodels, or observation models. Let us define the relationship between measurements and state functions:

$$\boldsymbol{\varphi}_m = \left[\mathbf{W}(\mathbf{C})\right]_m + \boldsymbol{\eta}(\mathbf{x},t), \tag{6}$$

where $[\mathbf{W}(\mathbf{C})]_m$ — vector of submodels (observation models); $\boldsymbol{\eta}(\mathbf{x}, t)$ — vector of errors and uncertainties; $\boldsymbol{\varphi}_m$ — values that we are monitoring.

Let us define $\boldsymbol{\varphi}_m$ on $Ц_t^m \in Ц_t$. In (6), the operation of transferring information from $Ц_t$ to $Ц_t^m$ is indicated by square brackets.

Let us expand the modeling system with data from field measurements (we consider them close to accurate), while the "quality" functionality will have a look:

$$\Phi_0(\mathbf{C}) = \left\{ \left(\boldsymbol{\varphi}_m - \left[\mathbf{W}(\mathbf{C})\right]_m\right)^{\tau} M\chi_0 \left(\boldsymbol{\varphi}_m - \left[\mathbf{W}(\mathbf{C})\right]_m\right) \right\}_{Ц_t^m} \equiv \left(\boldsymbol{\eta}^{\tau} C_1 \boldsymbol{\eta}\right), \tag{7}$$

we define χ_0 as a weight function for determining the configuration of the observation carrier $Ц_t^m$ in $Ц_t$ and the integrals over domain $Ц_t$, representing a measure for (7) in the form $C_1 = M\chi_0(\mathbf{x}, t)$, where M — weight matrix.

Let us consider functionals representing generalized characteristics of hydrobiogeocenosis behavior:

$$\Phi_k(\mathbf{C}) = \int_{Ц_t} F_k(\mathbf{C})\chi_k(\mathbf{x},t) dGdt \equiv (F_k, \chi_k),\ \chi_k \subset Q^*(Ц_t),\ k = \overline{1,K}.$$

$F_k(\mathbf{C})$ — limited and differentiable relative to $\mathbf{C} \in Q(Ц_t)$ functions that we will evaluate.

Let us define a functional to minimize uncertainties:

$$\tilde{\Phi}_k^h(\mathbf{C}) = \Phi_k^h(\mathbf{C}) + \left\{ \left(\boldsymbol{\eta}^\tau C_1 \boldsymbol{\eta}\right)_{Ц_t^m}^h + \left(\mathbf{r}^\tau C_2 \mathbf{r}\right)_{Ц_t^m}^h + \left(\left(\mathbf{C}^0 - \mathbf{C}_a^0\right)^\tau C_3 \left(\mathbf{C}^0 - \mathbf{C}_a^0\right) \right)_{Ц_t^m}^h + \right.$$
$$\left. + \left(\left(\mathbf{Y}^0 - \mathbf{Y}_a^0\right)^\tau C_4 \left(\mathbf{Y}^0 - \mathbf{Y}_a^0\right) \right)_{R^h\left(Ц_t^m\right)}^h \right\} / 2 + I^h\left(\mathbf{C}, \mathbf{Y}, \mathbf{C}^*\right), k \geq 1. \tag{8}$$

We assume that C_i — weight matrices, $i = \overline{1,4}$. Let us consider the system:

$$\frac{\partial \tilde{\Phi}_k^h}{\partial \mathbf{C}^*} \equiv D\Lambda_t \mathbf{C} + J^h(\mathbf{C}, \mathbf{Y}) - \boldsymbol{\psi} - \mathbf{r} = 0; \tag{9}$$

$$\frac{\partial \tilde{\Phi}_k^h}{\partial \mathbf{C}} \equiv \left(D\Lambda_t\right)^\tau \mathbf{C}_k^* + A^\tau(\mathbf{C}, \mathbf{Y}) \mathbf{C}_k^* + \mathbf{d}_k = 0;$$

$$\mathbf{C}_k^*(\mathbf{x})\big|_{t=T_0} = 0; \mathbf{d}_k = \frac{\partial}{\partial \mathbf{C}} \left(\tilde{\Phi}_k^h(\mathbf{C}) + 0{,}5\left(\boldsymbol{\eta}^\tau C_1 \boldsymbol{\eta}\right) \right);$$

$$\mathbf{C}^0 = \mathbf{C}_a^0 + C_3^{-1} \mathbf{C}_k^*(0),\ t = 0; \mathbf{r}(\mathbf{x}, t) = C_2^{-1} \mathbf{C}_k^*(\mathbf{x}, t);$$

$$\mathbf{Y} = \mathbf{Y}_a + C_4^{-1} \Gamma_k; \Gamma_k = \frac{\partial}{\partial \mathbf{Y}} I^h\left(\mathbf{C}, \mathbf{Y}, \mathbf{C}_k^*\right);$$

$$A(\mathbf{C}, \mathbf{Y}) \mathbf{C}' = \frac{\partial}{\partial \alpha} \left\{ J^h\left(\mathbf{C} + \alpha \mathbf{C}', \mathbf{Y}\right) \right\}\Big|_{\alpha=0},\ k \geq 1.$$

$A^\tau(\mathbf{C}', \mathbf{Y})$, Λ_t we define as operators of the conjugate problem and derivatives or their discrete approximations in time; $\boldsymbol{\Gamma}_k$ — functions of the sensitivity of models to changes in parameters; $\mathbf{C}' \equiv \delta\mathbf{C}$; α — set number.

Let us consider algorithms for assimilation of data from successive observations coming from various observational tools into a real-time modeling system. To do this, we will use the methods of splitting and decomposition:

$$Ц_t^h = \sum_{n=1}^{N_t - 1} Ц_{tn}^h; Ц_{tn}^h = G^h \times [t_{n-1}, t_n]; \tilde{\Phi}^h\left(\mathbf{C}, \mathbf{C}^*, \mathbf{Y}, \boldsymbol{\varphi}\right) = \sum_{n=1}^{N_t - 1} \sum_{l=1}^{p} \tilde{\Phi}_{nl}^h, \tag{10}$$

here $\tilde{\Phi}_{nl}^h$ — part of functional (9) for $[t_{n-1}, t_n]$ on the l-th stage of splitting, $n = \overline{1, N_t}$, p we define as the total number of splitting steps. We will carry out the discretization on the basis of additive-averaged splitting schemes. We will use an algorithm to find a solution in domain $Ц_t^h$ with regular uniform time grid $\overline{\omega}_t^h \equiv \left\{ t_n, n = \overline{0, N_t} \right\}$. For research, we will use a structure with phase spaces:

$$\left\{ \mathbf{C}_l^n,\ \mathbf{C}_l^{*n},\ \mathbf{r}_l^n, l = \overline{1, p} \right\} = \bigcup_{l=1}^{p} Q_l^h\left(Ц_t^h\right) \subset Q^h\left(Ц_t^h\right).$$

Method of Solving the Problem. For solution (9), we consider that $n = \overline{1, N_t}$. Let us describe the algorithm of the method used step by step.

1. Switch to the subgrid decomposition structure, while $t = t_{n-1}$:

$$\left\{ \mathbf{C}^{n-1} \in Q^h\left(Ц_t^h\right) \right\},\ \bigcup_{l=1}^{p} \left\{ \mathbf{C}_l^{n-1} \in Q_l^h\left(Ц_t^h\right) \right\},\ \mathbf{C}_l^{n-1} = \mathbf{C}^{n-1}.$$

2. In the subgrid structure, obtain solutions to direct and conjugate problems:

$$\Lambda_l^n \mathbf{C}_l^n - \boldsymbol{\psi}_l^n - \mathbf{r}_l^n = 0,\ l = \overline{1, p},\ p \geq 1.$$

$$\Lambda_l^{*n} \mathbf{C}_l^{*n} = \left[\frac{\partial \Phi_{kl}(\mathbf{C})}{\partial \mathbf{C}} + U^\tau C_1 \left(\boldsymbol{\varphi}_m - \left[\mathbf{W}(\mathbf{C}) \right]_m \right) \right]_l^{n-1},$$

$$\mathbf{C}_l^{*n+1} = 0,\ \mathbf{r}_l^n = \left(C_2^n\right)^{-1} \mathbf{C}_l^{*n},\ t_n \leq t \leq t_n.$$

Functions $\boldsymbol{\psi}_l^n$ include $\mathbf{C}_l^{n-1}$. $\mathbf{r}_l^n$ takes into account all the uncertainties in the step $[t_{n-1}, t_n]$.

3. Return to main structure $Q^h\left(Ц_t^h\right)$ at $t = t_n$:

$$\bigcup_{l=1}^{p}\left\{\mathbf{C}_l^n \in Q_l^h\left(\text{Ц}_t^h\right)\right\} \Rightarrow \left\{\mathbf{C}^n \in Q^h\left(\text{Ц}_t^h\right)\right\},\ \ \mathbf{C}^n = \frac{1}{p}\sum_{l=1}^{p}\mathbf{C}_l^n .$$

We believe that the last stage of splitting can be implemented using formula:

$$\Lambda_{pn}\mathbf{C}^n - \boldsymbol{\psi}_p^n - \mathbf{r}_p^n = 0, \tag{11}$$

here $\Lambda_{pn}\mathbf{C}^n$ — approximation operator part of the model at the p-th stage; $\boldsymbol{\psi}_p^n$ — source functions; $\mathbf{r}_p^n$ — function of uncertainties of model (2) and the splits introduced into the discrete model at a step. We believe that matrices of weights C_{1n} and C_{2n} are known.

Let us consider the following task:

$$\Lambda_{pn}^*\mathbf{C}^{*n} = \alpha_{1n}C_{1n}\left(\boldsymbol{\varphi}^{n-1} - \mathbf{C}^{n-1}\right); \tag{12}$$

$$\mathbf{r}_p^n = \left(C_{2n}^{-1} / \alpha_{2n}\right)\mathbf{C}^{*n}. \tag{13}$$

For the solution, we will use the following method, the algorithm of which we will describe step by step:

1. Calculate $\mathbf{C}^{*n}$ using (12).

2. Find $\mathbf{r}_p^n$, using (13).

3. Find $\mathbf{C}^n$, using formula (11).

The problem that arises during the implementation of the algorithm of the system of linear equations method will be solved by the sweep method.

Let us consider the transformed algorithm:

$$\Lambda_{pn}^*\mathbf{C}^{*n} = \alpha_{1n}C_{1n}\left(\boldsymbol{\varphi}^n - \mathbf{C}^n\right), \tag{14}$$

$$\Lambda_{pn}\mathbf{C}^n - \boldsymbol{\psi}^n - \left(C_{2n}^{-1} / \alpha_{2n}\right)\mathbf{C}^{*n} = 0. \tag{15}$$

We will solve the system by the sweep method. For the modifications considered, the stability of the splitting schemes ensures the stability of the data assimilation schemes used. If in (8) $\mathbf{C}^* = const$, then it gives a balance ratio of the first order. If $\mathbf{C}^* = \mathbf{C}$, then we obtain the equation of the energy balance of the analyzed system.

Let us write out the quality functionality for the new subsequent modification:

$$\Phi_{0n}(\mathbf{C}) = 0{,}5\left[\alpha_1\left(\boldsymbol{\eta}_n^{\tau}W_{1n}\boldsymbol{\eta}_n\right) + \alpha_2\left(\mathbf{r}_n^{\tau}W_{2n}\mathbf{r}_n\right)\right], \tag{16}$$

$$\mathbf{r}_n = \Lambda_{pn}\mathbf{C}_n - \boldsymbol{\psi}_n;\ \boldsymbol{\eta}_n = \boldsymbol{\varphi}_n - \mathbf{C}_n;\ \alpha_1 + \alpha_2 = 1,\ \alpha_1, \alpha_2 > 0. \tag{17}$$

We find the minimum of the functional relative to function $\mathbf{C}^n$:

$$\Lambda_{pn}^*C_{1n}\left(\Lambda_{pn}\mathbf{C}^n - \boldsymbol{\Psi}^n\right) + \frac{\alpha_{1n}}{\alpha_{2n}}C_{2n}\left(\mathbf{C}^n - \boldsymbol{\varphi}^n\right) = 0. \tag{18}$$

We obtain a uniquely solvable system with a five-diagonal matrix. Let us solve the resulting system of linear equations using the sweep method.

A new class of real-time assimilation methods includes a scheme of additive sequential assimilation. Due to the large amount of computational work, the built modifications are focused on supercomputing systems, including cluster systems and graphics accelerators.

Measurements $\boldsymbol{\varphi}_m$ are used in the form of maps and digital images. This representation gives a significant density of data in domain Ц_t, measurements are information fields. The planning of observations is based on the values of the uncertainty function. If these values are high, additional field measurements or observations are scheduled.

Results. To solve the problem of modeling the eutrophication of the Azov Sea waters (1), a set of parallel programs has been developed, including:

– a module of hydrodynamic processes that calculates the flow field of a water stream based on a mathematical model for a shallow reservoir [12];

– a module for the spread of pollutants in the aquatic environment and changes in the concentration of basic aquatic organisms (1), which allows us to assess the effect of pollutants on the biological productivity of the water area;

– a map of depths of the Azov Sea for the construction of computational grids for the numerical implementation of the developed algorithms;

– a database of expedition data, which allows refining the model of pollution of the aquatic environment and the spread of biota through the use of methods of data assimilation described above.

The numerical experiment was conducted using the developed software. The velocity vector of the water flow was calculated using a hydrodynamic model with an easterly wind at a speed of 5 m/s and fed into the input for calculating the movement of pollutants containing microplastic particles based on convection-diffusion equations. Figure 1 *a* shows the results of the numerical experiment to calculate water flow current fields under specified meteorological conditions. Vortex structures of currents were observed in the region of spits, in the northeastern part of the sea in Taganrog Bay. The color gradient in Figure 1 *a* represents the distribution of water flow velocity, with the maximum value at 4.822 m/s. Figures 1 *b, c,* and *d* show the results of calculations for a hypothetical scenario of the spread of microplastic contamination in the aquatic environment, considering the input of microplastics into the Azov Sea through the drains of the Don and Kuban rivers and the presence of a source of hazardous substances including microplastics at the outlet of Taganrog Bay. The figures also include a short-term forecast for the spread of contaminants 3, 6, and 12 days after the initial input. The initial concentration of pollutants was 5 mg/L, and after 3 days, the maximum concentration at the Taganrog Bay outlet was 1.363 mg/L. After 6 days, it decreased to 0.83 mg/L and after 12 days, it dropped to 0.336 mg/L.

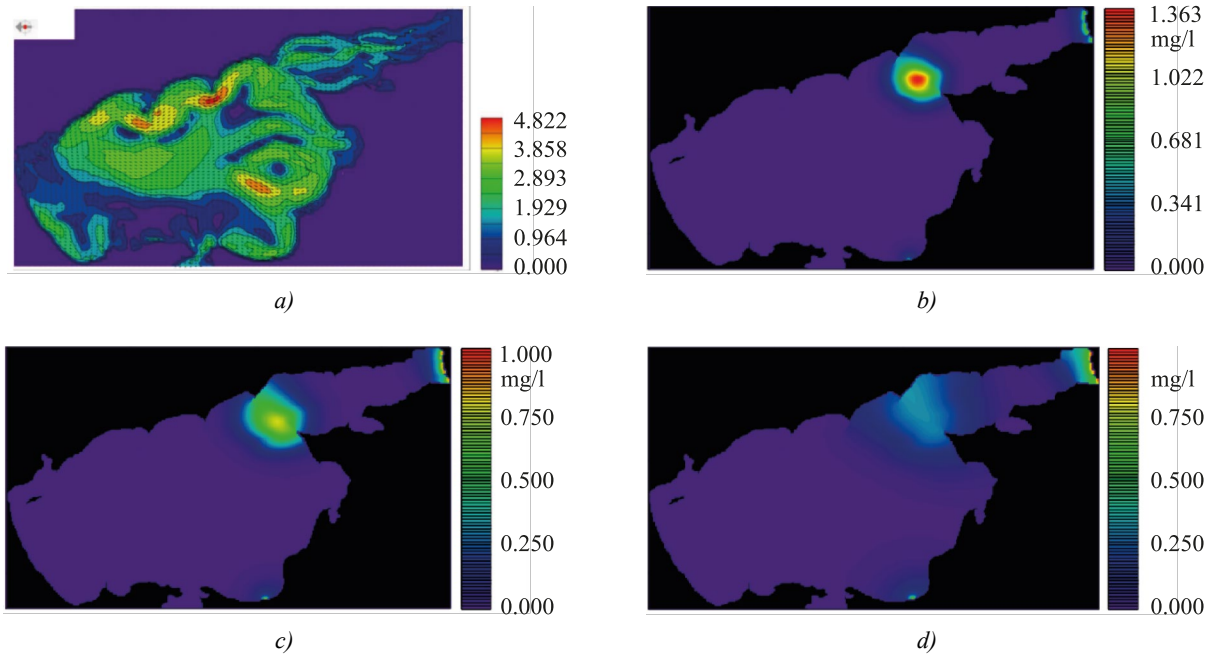


Fig. 1. Currents in the Azov Sea and the spread of pollutants, time interval:
a — initial concentration; *b* — 3 days; *c* — 6 days; *d* — 12 days

Discussion and Conclusion. The computational experiment shows that, despite the easterly wind, vortex structures in the currents captured pollutants and transported them to the Taganrog Bay. Stable vortices have the potential to capture and retain microplastic particles that enter the sea from river drains. They also contribute to the accumulation of pollutants in the lower layers due to biofouling by microplastic particles and their sinking.

As mentioned above, when creating mathematical models to predict natural phenomena and processes, one of the main challenges is to validate their accuracy by analyzing the outcomes obtained from them to ensure they match the behavior of the natural system under study. When creating mathematical models of hydrodynamic and hydrobiological processes, information on initial conditions and parameters (input data) is needed, which can be acquired through observations. Therefore, when creating predictive scenarios, it is essential not only to assess the quality of the developed mathematical model but also to incorporate observational data and investigate the sensitivity of these models to variations in input data.

The paper presents an approach to implementing a model of phytoplankton population dynamics (eutrophication) in the Azov Sea using variational methods for assimilating data obtained during field studies. The software package developed uses materials from the field studies, constantly updated environmental databases, and GIS, and allows refining the model of aquatic pollution and the spread of aquatic organisms using variational data assimilation techniques. The developed software makes it possible to forecast the spread of pollutants in the coastal system, including biogenic substances that act as a nutrient medium for the growth of dangerous microalgae, leading to eutrophication. This forecast enables the development of strategies for sustainable management of the natural system and its protection.

References

1. Penenko AV, Khassenova ZT, Penenko VV, Pyanova EA. Numerical Study of a Direct Variational Data Assimilation Algorithm in Almaty City Conditions. *Eurasian Journal of Mathematical and Computer Applications*. 2019;7(1):53–64 https://doi.org/10.32523/2306-6172-2019-7-1-53-64

2. Kuleshov A, Smirnov I, Tanajura K, Belyaev K. Comparison of Data Assimilation Methods into Hydrodynamic Models of Ocean Circulation. *Matematicheskoe modelirovanie.* 2018;30(12):39–54. https://doi.org/10.31857/S023408790001935-2 (In Russ.)

3. Marchuk GI. Adjoint Equations and Analysis of Complex Systems. Report by Academician G.I. Marchuk, Laureate of the 2004 Lomonosov Grand Gold Medal of the Russian Academy of Sciences. *Herald of the Russian Academy of Sciences.* 2005;75(10):911–916. (In Russ.)

4. Marchuk GI. *Selected Works.* Vol. 2. Moscow: Russian Academy of Sciences; 2018. 500 p. (In Russ.)

5. Kagermazov AKh. *Digital Atmosphere. Modern Methods and Methodology for the Study of Hazardous Meteorological Processes and Phenomena.* Nalchik: Pechatnyi dvor. 2015. 214 p. (In Russ.)

6. Shutyaev V, Zalesny V, Agoshkov V, Parmuzin E, Zakharova N. Four-Dimensional Variational Data Assimilation and Sensitivity of Ocean Model State Variables to Observation Errors. *Journal of Marine Science and Engineering*. 2023;11(6):1253. https://doi.org/10.3390/jmse11061253

7. Kaurkin MN, Ibrayev RA, Belyaev KP. Assimilation of Observational Data in the High-Resolution Ocean Dynamics Model Using the Parallel Programming Methods. *Meteorologiya i Gidrologiya.* 2016;7:49–59. URL: https://rucont.ru/efd/607637 (accessed: 22.05.2024). (In Russ.)

8. Parmuzin EI, Shutyaev VP. Sensitivity of Functionals of the Solution to the Variational Assimilation Problem to the Input Data on the Heat Flux for a Model of Sea Thermodynamics. *Žurnal vyčislitel'noj matematiki i matematičeskoj fiziki*. 2023;63(4):657–666. https://doi.org/10.31857/S0044466923040130 (In Russ.)

9. Marchuk GI, Shutyaev VP. Adjoint Equations and Iterative Algorithms in Problems of Variational Data Assimilation. *Proceedings of the Steklov Institute of Mathematics*. 2011;17(2):136–150. https://doi.org/10.1134/S0081543812020113 (In Russ.)

10. Belova YuV, Rahimbaeva EO, Litvinov VN, Chistyakov AE, Nikitina AV, Atayan AM. The Qualitative Regularities of the Eutrophication Process of a Shallow Water Research Based on a Biological Kinetics Mathematical Model. *Bulletin of the South Ural State University. Ser. Mathematical Modelling, Programming & Computer Software.* 2023;16(2):14–27. https://doi.org/10.14529/mmp230202 (In Russ.)

11. Nikitina AV, Sukhinov AI, Ugolnitsky GA, Usov AB, Chistyakov AE, Puchkin MV, et al. Optimal Control of Sustainable Development in Biological Rehabilitation of the Azov Sea. *Matematicheskoe modelirovanie*. 2016;28(7):96–106. (In Russ.)

12. Sukhinov A, Chistyakov A, Kuznetsova I, Belova Y, Rahimbaeva E. Solving Hydrodynamic Problems Based on a Modified Upwind Leapfrog Scheme in Areas with Complex Geometry. *Mathematics*. 2022;10(18):3248. https://doi.org/10.3390/math10183248

About the Authors:

Yuliya V. Belova, Cand. Sci. (Phys.-Math.), Associate Professor of the Department of Mathematics and Computer Science, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), SPIN-code: 6008-2235, ORCID, ResearcherID, ScopusID, yvbelova@yandex.ru

Alla V. Nikitina, Dr. Sci. (Eng.), Professor of the Department of Computer Engineering and Automated Systems Software, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), SPIN-code: 4320-8190, ORCID, ResearcherID, nikitina.vm@gmail.com

Claimed Contributorship:

YuV Belova: development of a software module, predictive calculation of the movement of pollutants, design of a scientific article.

AV Nikitina: description of the theoretical part of studying the spread of pollutants using variational methods for assimilating observational data.

Conflict of Interest Statement: **the authors do not have any conflict of interest.**

All authors have read and approved the final manuscript

Об авторах:

Юлия Валериевна Белова, кандидат физико-математических наук, доцент кафедры математики и информатики Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), SPIN-код: 6008-2235, ORCID, ResearcherID, ScopusID, yvbelova@yandex.ru

Алла Валерьевна Никитина, доктор технических наук, профессор кафедры программного обеспечения вычислительной техники и автоматизированных систем Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), SPIN-код: 4320-8190, ORCID, ResearcherID, nikitina.vm@gmail.com

Заявленный вклад авторов:

Ю.В. Белова: разработка программного модуля, проведение прогностического расчета движения загрязняющих веществ, оформление научной статьи.

А.В. Никитина: описание теоретической части исследования распространения загрязняющих веществ с применением вариационных методов усвоения данных наблюдений.

Конфликт интересов: **авторы заявляют об отсутствии конфликта интересов.**

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 27.05.2024
Revised / Поступила после рецензирования 19.06.2024
Accepted / Принята к публикации 26.06.2024

ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ
TECHNOSPHERE SAFETY

UDC 504.06:613.1/.9
https://doi.org/10.23947/2541-9129-2024-8-3-49-56

Original Empirical Research

Assessment of the Level of Air Pollution and Aerogenic Risk to the Health of the People of Novocherkassk

Petr V. Klimov, Elena S. Andreeva ✉
Don State Technical University, Rostov-on-Don, Russian Federation
✉ meteo0717@yandex.ru

EDN: SKECCW

Abstract

Introduction. Assessment of the level of urban air pollution and its impact on public health is a crucial scientific task. Ensuring the environmental safety of urban areas is impossible if the air quality does not meet the established standards. Despite well-developed methodologies for assessing the health risks of urban environments, the results of such research in the regional context are insufficient. Currently, almost half of the population of the Russian Federation lives in cities with high or very high levels of air pollution. Among these cities, Novocherkassk in the south of Russia was identified as one of the most polluted in the period from 2014 to 2021. This necessitates conducting scientific research to assess the health risks associated with atmospheric air pollution in Novocherkassk. The aim of this study was to evaluate the health risks posed to the population of Novocherkassk due to air pollution.

Materials and Methods. The study used data from annual reports on the state of air pollution in cities in Russia from 2014 to 2021, which were prepared by the Federal State Budgetary Institution "Voeikov Main Geophysical Observatory" [1]. The authors used literary methods and methods of mathematical and statistical analysis in their work.

Results. The level of atmospheric air pollution for the period from 2017 to 2021 reached dangerous values for public health. Suspended solids and carbon oxide contributed most to the risk of health problems. The values of the complex indicator *P*, estimated by average annual concentrations, showed that the level of atmospheric air pollution in Novocherkassk was 1.68 times higher than in the largest city in the region, Rostov-on-Don. The highest level of atmospheric air pollution in Novocherkassk was noted within Post II, located at the intersection of highways and close to the impact zone of industrial enterprises.

Discussion and Conclusion. The calculations showed that exposure to polluted atmospheric air could cause symptoms of chronic intoxication in 240–280 out of every thousand people. When the maximum concentrations of pollutants in the atmospheric air of Novocherkassk were reached, from 579 to 692 people out of a thousand residents might experience adverse reflex reactions. In light of the identified health risks from air pollution, it is recommended to increase the number of green spaces and establish two additional monitoring stations for atmospheric pollution: one in the city's residential area and one near the Novocherkassk GRES power plant in the Donskoy district.

Keywords: level of atmospheric air pollution, aerogenic risks to public health, non-carcinogenic effects, carcinogenic health risks, intoxication, acute and chronic effects

Acknowledgements. The authors would like to express their gratitude to the colleagues and specialists of the Federal State Budgetary Institution "Voeikov Main Geophysical Observatory" for providing materials for the research.

For citation. Klimov PV, Andreeva ES. Assessment of the Level of Air Pollution and Aerogenic Risk to the Health of the People of Novocherkassk. *Safety of Technogenic and Natural Systems.* 2024;8(3):49–56. https://doi.org/10.23947/2541-9129-2024-8-3-49-56

[1] Yearbooks. 2014-2021. URL: http://voeikovmgo.ru/index.php (accessed: 23.05.2024). (In Russ.)

Оригинальное эмпирическое исследование

Оценка уровня загрязнения атмосферного воздуха и аэрогенного риска здоровью населения города Новочеркасска

П.В. Климов, Е.С. Андреева ✉
Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация
✉ meteo0717@yandex.ru

Аннотация

Введение. Оценка уровня загрязнения воздуха городской среды и обусловленного им риска здоровью населения является актуальной научной задачей. Как представляется, невозможно обеспечить экологическую безопасность урбанизированных зон, если качество воздуха в их пределах не соответствует установленным стандартам. Несмотря на хорошо разработанный методический аппарат, позволяющий оценить риск здоровью населения городской среды, результатов подобных исследований в региональном аспекте недостаточно. В то же время почти половина всех жителей Российской Федерации в настоящее время проживает в городах с высоким и очень высоким уровнем загрязнения воздуха. На юге России в число городов с наиболее загрязненной воздушной средой в исследуемый период 2014–2021 гг. был включен г. Новочеркасск, что и обусловило необходимость проведения соответствующих научных изысканий. Цель данного исследования — оценить показатели риска здоровью населения г. Новочеркасска, вызванного загрязнением атмосферного воздуха.

Материалы и методы. В работе использованы данные ежегодников о состоянии загрязнения атмосферы в городах на территории России за 2014–2021 гг., подготовленных в Федеральном государственном бюджетном учреждении «Главная геофизическая обсерватория им. А.И. Воейкова». В числе примененных авторами методов литературные, методы математико-статистического анализа.

Результаты исследования. Уровень загрязнения атмосферного воздуха за период 2017–2021 годов достигал опасных для здоровья населения значений. Наибольший вклад в риск нарушения здоровья вносят взвешенные вещества и оксид углерода. Значения комплексного показателя *P*, оцененного по среднегодовым концентрациям, показали, что уровень загрязнения атмосферного воздуха в г. Новочеркасске в 1,68 раза выше, чем в крупнейшем городе региона Ростове-на-Дону. Наибольший уровень загрязнения атмосферного воздуха г. Новочеркасска отмечен в пределах поста II, находящегося на пересечении автомагистралей и приближенного к зоне воздействия промышленных предприятий.

Обсуждение и заключение. Проведенные расчеты показали, что воздействие загрязненного атмосферного воздуха может вызвать симптомы хронической интоксикации у 240–280 человек из тысячи, при достижении максимальных концентраций загрязняющих веществ в атмосферном воздухе г. Новочеркасска от 579 до 692 человек из тысячи жителей могут испытать неблагоприятные рефлекторные реакции. В связи с выявленным опасным для здоровья населения загрязнением атмосферного воздуха рекомендуется расширение площади зеленых насаждений и создание двух дополнительных постов наблюдения за загрязнением атмосферного воздуха: в селитебной зоне города и вблизи Новочеркасской ГРЭС, в микрорайоне «Донской».

Ключевые слова: уровень загрязнения атмосферного воздуха, аэрогенные риски здоровью населения, неканцерогенные эффекты, канцерогенные риски здоровью, интоксикация, острое и хроническое действие

Благодарности. Авторы выражают благодарность коллегам, специалистам Федерального государственного бюджетного учреждения «Главная геофизическая обсерватория им. А.И. Воейкова» за предоставленные материалы для исследований.

Для цитирования. Климов П.В., Андреева Е.С. Оценка уровня загрязнения атмосферного воздуха и аэрогенного риска здоровью населения города Новочеркасска. *Безопасность техногенных и природных систем.* 2024;8(3):49–56. https://doi.org/10.23947/2541-9129-2024-8-3-49-56

Introduction. The quality of life and health of the population is related to environmental factors, particularly those caused by human activity. In the Russian Federation, 63.6% of the population experiences a significant impact on their health from various natural, environmental, and socio-hygienic factors[2].

For urbanized areas, the main factor causing such an impact is physical and chemical transformation of the lower atmosphere due to pollution. According to the World Health Organization (WHO), 99% of the global population lived in areas with high concentrations of air pollutants in 2022. Air pollution also caused premature deaths of about 7 million people worldwide in the same year. It is important to note that the analysis of the effects of environmental factors in Russia shows that about 70% of non-communicable diseases can be attributed to atmospheric air pollution [1].

[2] *On the State of Sanitary and Epidemiological Welfare of the Population in the Russian Federation in 2021.* State Report. URL: https://www.rospotrebnadzor.ru/documents/details.php?ELEMENT_ID=21796 (accessed: 20.04.2024). (In Russ.)

As practice shows, concentrations of pollutants that are dangerous to public health are often found in central parts of large cities and territories located near industrial facilities or transport routes. Therefore, the assessment of air pollution in these areas is still a pressing issue in the field of environmental research. A reliable way to measure air pollution is through the use of risk indicators that can help to determine the impact of pollution on public health. This approach allows for a comprehensive understanding of the scale of air pollution's impact on the population, which can complement the current Russian system for assessing effects of pollution on health.

Currently, slightly less than half of the total population of the Russian Federation lives in urbanized areas with high and very high air pollution[3]. The convenient transport location and the labor potential of Novocherkassk contributed to the formation of a diversified industrial complex that has a significant impact on the environment and public health. In 2021, Novocherkassk was added to the list of cities of the Russian Federation with the highest level of atmospheric air pollution [2]. Due to its status as a major production and logistics hub in the Rostov region, Novocherkassk is the focus of this study, as it has the highest level of air pollution among all cities in the region.

Most of large industrial enterprises in Novocherkassk are located in an industrial area, away from the historical city center along the floodplain of the Tuzlov River. The only exception is the Novocherkassk GRES, which is located near the Donskoy district, which was incorporated into Novocherkassk in 2004. In the eastern wind direction, the air from the Novocherkassk GRES flows into the city and pollutes the air. In the western and southwestern directions, it affects the air in the Donskoy district. It is important to note that the self-purification coefficient of the atmosphere in this area is 4.39 per year. This does not contribute to the dispersal of anthropogenic pollutants [3, 4]. This is due to the high frequency of meteorological events that lead to the accumulation of harmful substances to dangerous levels in the surface air. In addition, the amount of green space in the urban area of Novocherkassk only accounts for 44% of the recommended amount, which is not enough to effectively purify the air.

It seems to the authors that there has not been a comprehensive assessment of surface air pollution in urban areas recently. Only in 2017, three stationary monitoring stations for surface air quality began operating here, and before that, route observations were the only method used to monitor the air quality within the city. This study aims to assess the health risks posed to the population of Novocherkassk due to pollution of the upper layers of the atmosphere.

To achieve this goal, we have carried out the following tasks:

1. We have assessed the level of air pollution in the city.

2. We have calculated numerical values of coefficients and indices related to non-carcinogenic effects on public health in acute and chronic situations.

3. We have conducted calculations of public health risks caused by chronic intoxication and the immediate effects of various pollutants.

4. We have identified the contribution of pollutants to the formation of public health indicators.

Materials and Methods. The study was based on data from stationary air pollution monitoring posts operated by the Federal State Budgetary Institution “North Caucasus Department of Hydrometeorological Service”. These posts collected data on the concentrations of various airborne pollutants in Novocherkassk between 2017 and 2021 [5]. Three of these posts were operational in Novocherkassk since 2017. They were designated as Posts I, II, and III in the study. Post I was located in the city center, at the intersection of major highways. Post III was in the area influenced by industrial enterprises. Post II was also in the impact zone of industrial activity, but was located at an intersection of highways as well.

Due to the insufficient number of monitoring posts for atmospheric air pollution, it was recommended to create two additional posts, one of which, conventionally designated as Post 1, should to be placed in a residential area on Petrovskaya Street, 1. To monitor atmospheric air pollution near Novocherkasskaya GRES, it was proposed to create a post in the Donskoy district, conventionally designated as Post 2. The existing stationary monitoring posts for atmospheric air pollution (designated as numbers I, II, and III) and recommended for monitoring the city's air quality (designated as numbers 1 and 2) are shown in Figure 1.

In order to achieve the goal of the study, we calculated the multiplicity of the average annual and maximum single concentrations of airborne pollutants analyzed, which corresponded to the maximum allowable hygienic standards. We also calculated the level of outdoor air pollution using indicator P[4].

Calculation of indicator P was carried out according to formula:

$$P = \sqrt{\sum K_I^2}, \quad (1)$$

where, K — multiplicity of exceeding the MPC of substances of various hazard classes reduced to the third class.

[3] *On the State and Environmental Protection of the Russian Federation in 2021.* State Report. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/gosudarstvennyy_doklad_o_sostoyanii_i_ob_okhrane_okruzhayushchey_sredy_rossiyskoy_federatsii_v_2021_/?ysclid=lwoteqy14b321565566 (accessed: 19.04.2024). (In Russ.)

[4] *Guidelines for Assessing the Risk to Public Health from Exposure to Chemicals that Pollute the Environment.* R 2.1.10.192–04. URL: https://docs.cntd.ru/document/1200037399 (accessed: 28.03.2024). (In Russ.)

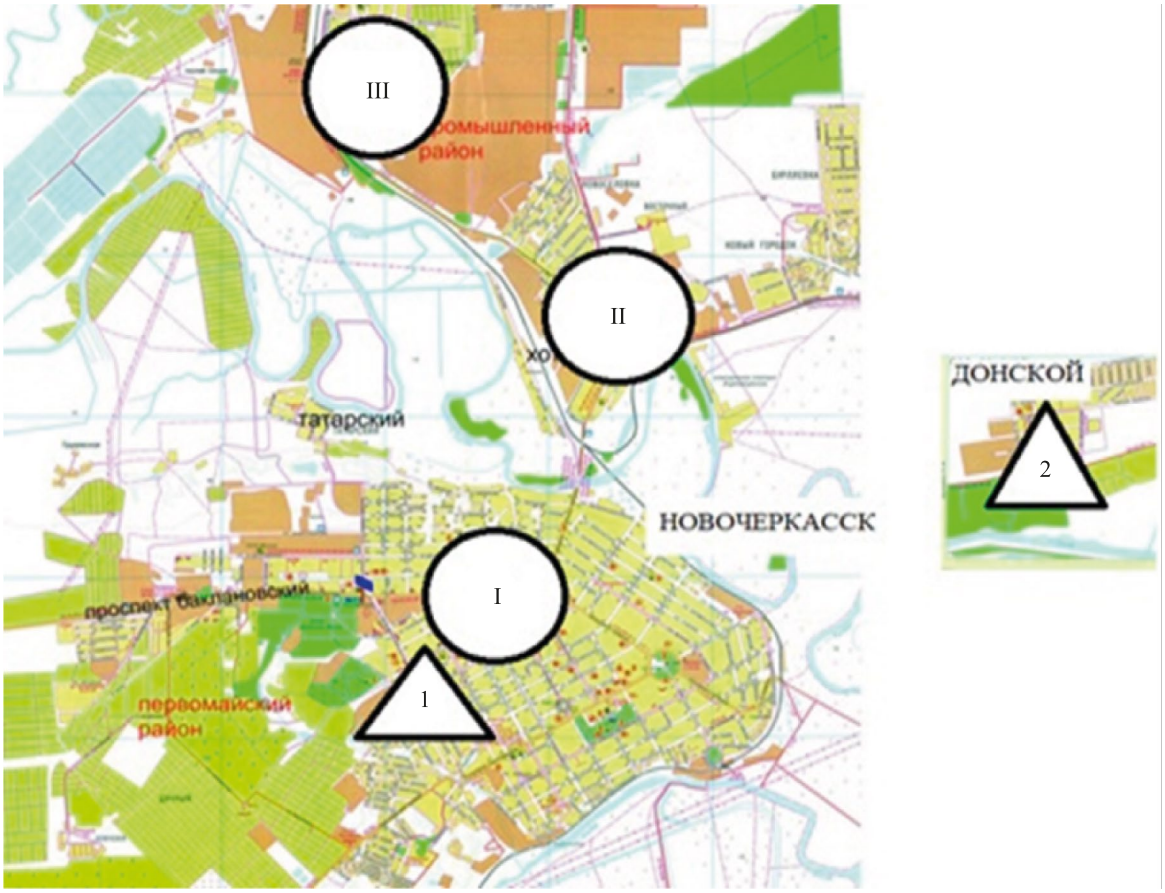


Fig. 1. Monitoring posts for atmospheric air pollution in the city of Novocherkassk[5]

The choice of non-carcinogenic effects as risk indicators was determined by the list of harmful substances of non-carcinogenic action[6], the concentrations of which were monitored at stationary monitoring posts for atmospheric air pollution in Novocherkassk.

The method of calculating coefficients and indices of non-carcinogenic effects in chronic and acute exposure was used as the main method of risk assessment [6, 7]. As an additional procedure, the risks of chronic intoxication and immediate action were determined[7].

Results. Increased emissions from motor vehicles and industrial enterprises led to dangerous air pollution in Novocherkassk. Thus, from 2017 to 2021, the average annual concentrations of suspended solids, nitrogen dioxides, carbon oxides, formaldehyde were exceeded, which have both carcinogenic and non-carcinogenic effects on public health. At the same time, the greatest multiplicities of exceeding the average daily MPC over the studied period of time were revealed for average annual concentrations of suspended solids (from 1.8 to 6 MPC), formaldehyde (from 0.7 to 2.7 MPC), nitrogen dioxides (from 0.4 to 2.2 MPC), carbon oxides (from 0.63 to 2.17 MPC).

It is important to note that the greatest multiplicities of exceeding of the maximum single MPC were also detected in the case of suspended solids and carbon monoxide, amounting to 2.0–13.2 MPC and 1.25–10.0 MPC, respectively. The excess of MPC of formaldehyde in the surface air of the city reached 1.44–3.74, nitrogen dioxide — 0.45–1.85. The average annual and maximum single concentrations of sulfur dioxide and nitrogen oxides during the studied time interval, as shown by the conducted studies, did not exceed the values of the corresponding MPC.

Based on the average annual concentrations of the substances assessed, we calculated the values of complex parameter *P*, which ranged from 4.0 to 5.0 over the specified period. This allowed us to conclude that there was a dangerous level of surface air pollution.

Calculations of parameter *P*, based on the maximum single concentration of the substances studied in this work, revealed a worrying level of contamination of the surface layer, since the values of parameter *P* were 22.0–28.5.

[5] *Ecological Bulletin of the Don.*URL: https://xn--d1ahaoghbejbc5k.xn--p1ai/about/projects/all/19/?ysclid=lwotyc7mh7723274679 (accessed: 28.03.2024). (In Russ.)
[6] R 2.1.10.192-04. *Guidelines for Assessing the Risk to Public Health from Exposure to Chemicals that Pollute the Environment.* Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/1200037399 (accessed: 28.03.2024). (In Russ.)
[7] *Cancer.* World Health Organization (April 21, 2024). URL: https://www.who.int/health-topics/cancer#tab=tab_1 (accessed: 28.03.2024).

Within the limits of Post II, the highest values of parameter *P* were identified, estimated by the average annual and maximum single concentrations of pollutants considered in this study. As shown by the analysis of values of risk indices of chronic exposure calculated in the work, depending on the location of the observation post, their values varied from 33.5 to 37.1. The range of values of the acute exposure index was 15.9–22.6.

According to medical statistics, the respiratory system was the most vulnerable to acute and chronic health effects. The proportion of respiratory disorders ranged from 38.22% to 42.37%. The contribution of the above-mentioned threats and failures in the human respiratory system to the overall level of the acute exposure index reached maximum values — from 45.47 to 49.81%. Therefore, it was obvious that the increased level of pollution of the surface air layer posed a greater risk of acute exposure, which was consistent with both theoretical models and practical observations.

The value of the total risk of chronic intoxication varied depending on the location of the observation post — from 0.24 to 0.28. The risk level of chronic intoxication, as calculations showed, was mainly formed due to concentrations of suspended solids, the contribution of which caused a wide range of values (from 35.27 to 47.81%) depending on the location of the observation post of the atmospheric environmental monitoring network. Significant values of maximum risk for individual impurities led to high levels of the total risk from pollutants identified in the studied composition

It is interesting to note that within observation Posts I and II located near highways, the value of the total risk of immediate action was significantly influenced by the maximum risk level in terms of suspended matter concentrations, reaching values of 0.58 and 0.69, respectively.

Near Post III, high concentrations of carbon monoxide, causing a significant level of maximum risk, led to an increase in the total risk values to 0.58.

The air pollution analysis results in Novocherkassk were compared to data from the monitoring of surface air pollution in Rostov-on-Don of the same range of pollutants for the period from 2017 to 2021.

The assessment of air pollution levels in Rostov-on-Don was based on the analysis of data collected from three air pollution monitoring stations located in different parts of the city by the Federal State Budgetary Institution “North Caucasian Department of Hydrometeorological Service” (Posts 51, 52, 55), which had the most representative spectrum of substances taken into account [8].

Thus, Post 51 was located in the central part of Rostov-on-Don, at the intersection of highways with heavy traffic; Post 52 was close to the location of industrial enterprises; Post 55 was located in the residential area of the city.

Table 1 presents the results of the comparative assessment of the levels of air pollution in urbanized and industrial territories of Novocherkassk and Rostov-on-Don for 2017–2021. Indicators illustrating the level of air pollution turned out to be more than 1.5 times higher in Novocherkassk than in Rostov-on-Don.

In Rostov-on-Don, the contribution of suspended solids to the immediate health risk was 24% higher than in Novocherkassk. However, in Novocherkassk, the contribution of carbon oxide concentration to this type of risk was 2.5 times more significant than in Rostov-on-Don [9].

Table 1

Assessment of atmospheric air pollution levels in Novocherkassk and Rostov-on-Don

Indicator	Novocherkassk	Rostov-on-Don
P parameter for average annual concentrations	4.42	2.63
P parameter for maximum concentrations	24.59	23.52
Hazard index for chronic exposure	35.70	24.34
Hazard index for acute exposure	19.47	20.94
Risk of chronic intoxication	0.25	0.18
Risk of immediate action	0.61	0.53

The results of the assessment of contributions of various airborne pollutants to the risk of immediate action are presented in Figures 2 and 3.

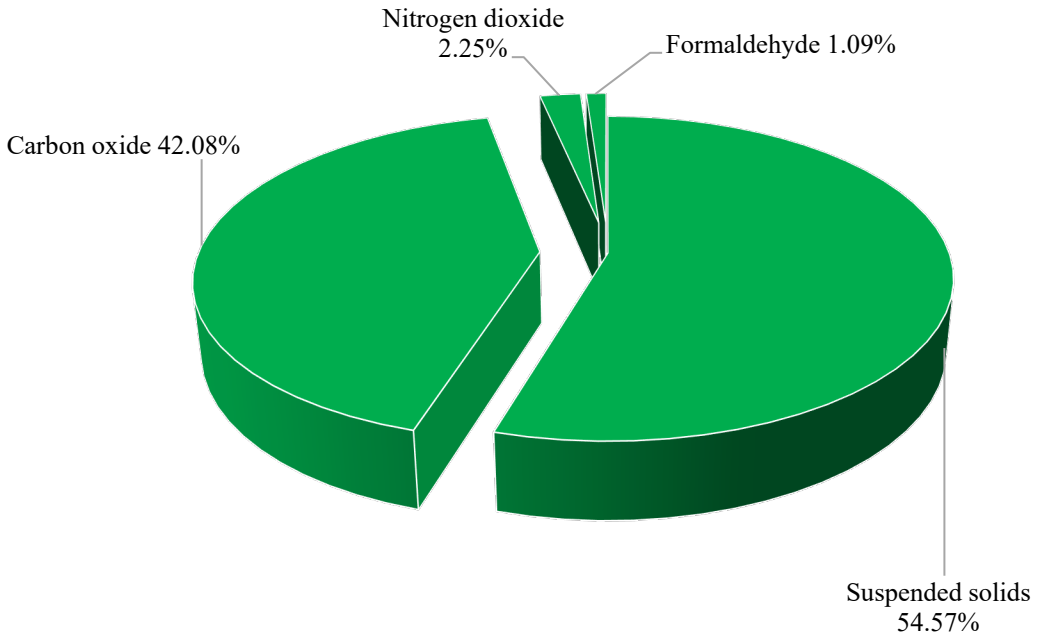


Fig. 2. Contribution of pollutants to the risk of immediate health effects for the population of Novocherkassk

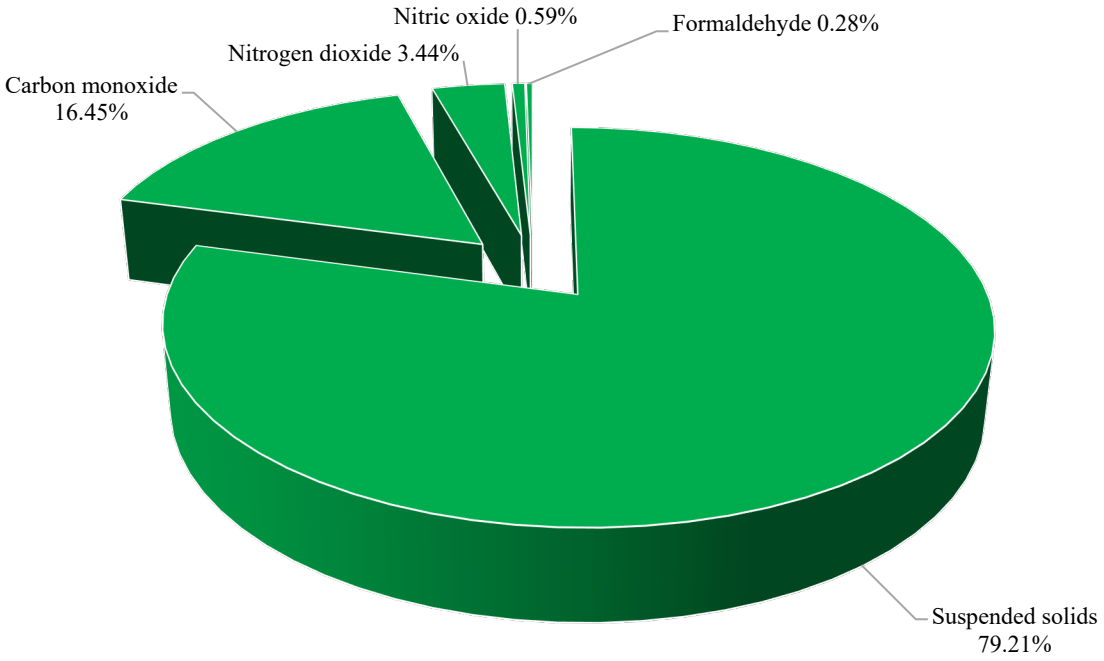


Fig. 3. Contribution of pollutants to the risk of immediate health effects for the population of Rostov-on-Don

Meanwhile, there were no significant differences between these two cities in terms of the contribution of pollutants to the risk of chronic intoxication.

Discussion and Conclusion. The calculations and analysis of the findings in this study reveal that the level of surface air pollution in Novocherkassk, which is harmful to public health, is caused not only by the significant emissions from industrial plants and vehicles but also by a combination of such natural and human-made factors as insufficient rainfall against the backdrop of frequent meteorological conditions that facilitate the accumulation of human-made pollutants in the surface layer, with a decrease in the proportion of green spaces, including urban forests and park areas [10].

Among the most significant results of the study are the following:

1. The state of the surface air layer within Novocherkassk is unfavorable, since the established pollution levels exceed permissible sanitary and hygienic standards. The highest danger to the health of the city's population is posed by suspended solids and carbon oxides in the surface layer.

2. The analysis of the results of calculations of indicator *P* within Novocherkassk allowed us to establish a dangerous level of air pollution. At the same time, the accumulation of pollutants in the atmosphere of Rostov-on-Don was assessed as causing concern.

3. Exposure to polluted air can lead to symptoms of chronic poisoning in 240 to 280 out of every thousand people. When maximum concentrations of pollutants are reached, 579 to 692 residents may experience adverse reactions.

4. The most significant concern is the pollution of air space in Novocherkassk, particularly within the boundaries of Post II, which is located at the junction of highways and near the impact zone of industrial enterprises.

5. Due to the dangerous level of atmospheric air pollution, it is recommended to expand the area of green spaces and create two additional monitoring posts for atmospheric pollution: in the residential area of the city and near Novocherkassk GRES, in the Donskoy district.

References

1. Rakhmanin YuA, Mikhaylova RI. Environment and Health: Priorities for Preventive Medicine. *Hygiene and Sanitation.* 2014;93(5);5–10. (In Russ.)

2. Andreev SS. *Integral Assessment of Climatic Comfort on the Example of the Territory of the Southern Federal District of Russia.* Saint Petersburg: Russian State Hydrometeorological University; 2011. 302 p. URL: http://elib.rshu.ru/files_books/pdf/rid_23963a035bf3491da5cc5a42d941e7d6.pdf (accessed: 23.05.2024). (In Russ.)

3. Kiselev AV, Shcherbo AP, Kislitsin VA, Novikov SM. Comparative Analysis of Methods for Calculating the Average Inhalational Exposure Loads in the Assessment of Health Risk. *Hygiene and Sanitation.* 2006;1;42–44. (In Russ.)

4. Shcherbo AP, Meltser AV, Kiselev AV. *Assessment of the Risk of the Impact of Production Factors on the Health of Workers.* St. Petersburg: Tertsiya; 2005. 115 p. URL: https://search.rsl.ru/ru/record/01002854973 (accessed: 23.05.2024). (In Russ.)

5. Andreeva ES, Klimov PV, Shtenske KS. Atmospheric Air Pollution as One of the Factors of the Non-Carcinogenic Risk to Human Health in Rostov-on-Don. *Geography and Natural Resources.* 2021;42(1):42–48. https://doi.org/10.15372/GIPR20210105 (In Russ.)

6. Klimova DN, Andreeva ES. Optimization of the Monitoring System of Atmospheric Air Pollution in Ensuring the Environmental Safety of Large Cities. *Advances in current natural sciences*. 2023;6:40–46. https://doi.org/10.17513/use.38051 (In Russ.)

7. Seleguei TS. *Development of an Improved Integrated Meteorological Measure the Scattering Power of the Atmosphere*. Otchet o nauchno-issledovatel'skoj rabote po teme 1.43.15. Novosibirsk: FGBU SibNIGMI, 2014. 131 p. (In Russ.)

8. Wild CP, Weiderpass E, Stewart BW (Eds.). World Cancer Report: Cancer Research for Cancer Prevention. 2021. URL: https://shop.iarc.fr/products/world-cancer-report-cancer-research-for-cancer-prevention-pdf

9. Denisov OV, Bulygin YuI, Ponomarev AE, Ponomareva LA, Lebedeva VV. Innovative Solutions Shockproof Protection in Occupations Associated with an Increased Risk of Injury. *IOP Conference Series: Earth and Environmental Science*. 2017;50(1):012044. https://doi.org/10.1088/1755-1315/50/1/012044

10. Bulygin YuI, Zharkova MG, Alekseenko LN. Aerodynamical Probation of Semi-Industrial Production Plant for Centrifugal Dust Collectors' Efficiency Research. *IOP Conference Series: Earth and Environmental Science*. 2017;50(1);012002. https://doi.org/10.1088/1755-1315/50/1/012002

About the Authors:

Petr V. Klimov, Cand. Sci. (Biol.), Associate Professor of the Life Safety and Environmental Protection Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), SPIN-code: 8088-6868, ORCID, ResearcherID, ScopusID

Elena S. Andreeva, Dr. Sci. (Geog.), Associate Professor, Professor of the Life Safety and Environmental Protection Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), SPIN-code: 2056-7152, ORCID, ResearcherID, ScopusID, meteo0717@yandex.ru

Claimed Contributorship:

PV Klimov: discussion of the basic concept and the results, revision of the text and conclusions.

ES Andreeva: formulation of the basic concept, goals and objectives of the study, calculations, preparation of the text, formulation of conclusions, design.

Conflict of Interest Statement: **the authors do not have any conflict of interest.**

All authors have read and approved the final manuscript.

Об авторах:

Петр Валерьевич Климов, кандидат биологических наук, доцент кафедры безопасности жизнедеятельности и защиты окружающей среды Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), SPIN-код: 8088-6868, ORCID, ResearcherID, ScopusID

Елена Сергеевна Андреева, доктор географических наук, доцент, профессор кафедры безопасности жизнедеятельности и защиты окружающей среды Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), SPIN-код: 2056-7152, ORCID, ResearcherID, ScopusID, meteo0717@yandex.ru

Заявленный вклад авторов:

П.В. Климов: обсуждение основной концепции и полученных результатов, доработка текста, выводов.

Е.С. Андреева: формирование основной концепции, цели и задачи исследования, проведение расчетов, подготовка текста, формирование выводов, оформление.

Конфликт интересов: **авторы заявляют об отсутствии конфликта интересов.**

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 06.06.2024
Revised / Поступила после рецензирования 28.06.2024
Accepted / Принята к публикации 14.07.2024

TECHNOSPHERE SAFETY
ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ

UDC 519.6:616-036.2
https://doi.org/10.23947/2541-9129-2024-8-3-57-66

Original Empirical Research

Update of the COVID-19 Incidence Forecast with the Overlap of Seasonal Flu Outbreaks

Natalya N. Azimova, Dzhakhangul Kh. Zairova ✉, Aleksandr S. Ermakov, Evgenii N. Ladosha
Don State Technical University, Rostov-on-Don, Russian Federation
✉ gulyazair@gmail.com

EDN: PTULTJ

Abstract

Introduction. The emergence of new vector-borne diseases necessitates the development of adequate medical regulations, prevention measures, rehabilitation programs, etc. Among all these measures, timeliness is the most crucial element, which cannot be achieved without reliable forecasting of the epidemic situation. In fact, the situation can deteriorate when two epidemics occur simultaneously, emphasizing the need for predicting the corresponding time intervals accurately. The aim of this study is to scientifically predict the periods when traditional influenza and COVID-19 epidemics may overlap.

Materials and Methods. The scientific research was based on the analysis of statistical data, which was processed using Fourier decomposition and autoregression techniques to study and predict various processes. The original mathematical model of COVID-19 dynamics was adjusted with new statistical data. The resulting scale-time and random characteristics of COVID-19 within the model were compared with known parameters of traditional influenza.

Results. It was established that the dynamics of the COVID-19 epidemic had a pronounced seasonal character with a frequency of three times a year. It was found that the method of forecasting COVID-19 incidence using Fourier decomposition was not reliable, but it allowed for a good description of the observed dynamics of the epidemic. Autoregressive analysis, on the other hand, was only suitable for short-term forecasting of coronavirus epidemics. The features of the two seasonal diseases, COVID-19 and influenza, have been compared, and the moments when their combined effects on a person would be particularly harmful have been predicted.

Discussion and Conclusion. All methods of mathematical analysis have convincingly demonstrated that the frequency of COVID-19 outbreaks occurs three times per year, while influenza occurs annually. During times when the activities of both viruses (coronavirus and influenza) coincide, special attention should be paid and measures taken to reduce the risk of contracting a seasonal viral infection, including through regular vaccination.

Keywords: epidemic, pandemic, COVID-19, epidemiological characteristics of the virus, counteracting the spread of COVID-19, mathematical model of epidemic process, omicron

Acknowledgements. The authors would like to express their special gratitude to Associate Professor, Cand. Sci. (Phys.-Math.) O.V. Yatsenko, who made an important contribution to the comparison of the characteristics of influenza and COVID-19 viruses. His comments were essential in the design and development of this research.

For citation. Azimova NN, Zairova DKh, Ermakov AS, Ladosha EN. Update of the COVID-19 Incidence Forecast with the Overlap of Seasonal Flu Outbreaks. *Safety of Technogenic and Natural Systems.* 2024;8(3):57–66. https://doi.org/10.23947/2541-9129-2024-8-3-57-66

Оригинальное эмпирическое исследование

Уточнение прогноза заболеваемости COVID-19 с наложением на сезонные вспышки гриппа

Н.Н. Азимова, Д.Х. Заирова ✉, А.С. Ермаков, Е.Н. Ладоша
Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация
✉ gulyazair@gmail.com

Аннотация

Введение. Появление новых трансмиссивных заболеваний требует разработки соответствующих лечебных регламентов, мер предупреждения болезни, схем реабилитации и т. д. Важнейшим элементом всех обозначенных выше мероприятий является своевременность, которая невозможна без надёжного прогнозирования эпидемической обстановки. Фактически эпидемическая ситуация может обостриться при наложении двух эпидемий, что актуализует прогнозирование соответствующих временных интервалов. Цель данной работы — научно обоснованное предсказание периодов, отвечающих наложению эпидемий традиционного гриппа и вновь появившегося COVID-19.

Материалы и методы. Научные изыскания основываются на анализе статистических данных. Для изучения и прогнозирования процессов использованы техники Фурье-разложения и авторегрессии. Скорректирована оригинальная математическая модель динамики COVID-19 с учетом новых статистических данных. Сопоставлены результирующие масштабно-временные и случайные характеристики COVID-19 в рамках модели с известными параметрами традиционного гриппа.

Результаты исследования. Установлено, что динамика эпидемии COVID-19 имеет ярко выраженный сезонный характер с периодичностью три раза в год. Выявлено, что алгоритм прогноза заболеваемости COVID-19 методом Фурье-разложения не является надежным, однако позволяет хорошо описать наблюдаемую динамику развития эпидемии. Авторегрессионный анализ подходит лишь для краткосрочного прогнозирования коронавирусной эпидемии. Сопоставлены особенности течения двух заболеваний сезонного характера — COVID-19 и гриппа. Спрогнозированы моменты, когда их совместное действие на человека окажется особенно пагубным.

Обсуждение и заключения. Все методы математического анализа убедительно доказали, что периодичность вспышек COVID-19 — трижды в год, а гриппа — ежегодно. В периоды, когда действия двух вирусов (коронавируса и гриппа) накладываются, следует быть особо осторожными и соблюдать меры, направленные на снижение риска заболеть сезонной вирусной инфекцией, в том числе проводить регулярную вакцинацию.

Ключевые слова: эпидемия, пандемия, COVID-19, эпидемиологические характеристики вируса, противодействие распространению COVID-19, математическая модель эпидемического процесса, омикрон

Благодарности. Авторы выражают особую благодарность консультанту научного проекта О.В. Яценко, доценту, кандидату физико-математических наук, который внес немаловажный вклад в сопоставление характеристик вирусов гриппа и COVID-19 и дал ценные замечания при оформлении данной работы.

Для цитирования. Азимова Н.Н., Заирова Д.Х., Ермаков А.С., Ладоша Е.Н. Уточнение прогноза заболеваемости COVID-19 с наложением на сезонные вспышки гриппа. *Безопасность техногенных и природных систем.* 2024;8(3):57–66. https://doi.org/10.23947/2541-9129-2024-8-3-57-66

Introduction. Harmful effects of epidemics on humans and their livelihoods as a whole are prevented through the constant improvement of preventive measures. These measures aim to break the chain of disease transmission, reduce its severity, and reduce the risk of infection. These elements have been carefully developed for seasonal viral diseases, such as SARS and influenza, in particular. The emergence of new vector-borne diseases requires the development of new measures, such as medical regulations, prevention strategies, rehabilitation plans, medications, and specialized medical facilities. An example of this is the recent COVID-19 pandemic and the response from global governments and healthcare systems [1]. The most important aspect of these measures is their timeliness, which requires reliable forecasting of epidemic situations.

The aim of this study is to identify the periods of overlap between traditional influenza epidemics and the recently emerged COVID-19 pandemic. This information will help us prepare for future outbreaks, minimizing the severity and impact of the diseases.

Materials and Methods. The emergence of new epidemiological data for the period from September 23, 2021, to March 3, 2023, requires a radical revision of the previous scenario for the development of the disease. Specifically, the previous scenario assumed that the pandemic would continue indefinitely, with an average daily incidence of 600,000 people, fluctuating three times per year with an amplitude of ±300,000. This corresponded to what was referred to as the “pessimistic” scenario. However, the emergence of new viral strains has led to an increased fitness between the

virus and human hosts, redirecting the dynamics of COVID-19 towards an “optimistic” trajectory. This development necessitates adjusting the mathematical model in order to accurately predict the timing and magnitude of disease outbreaks [2, 3]. To accomplish this, the following objectives should be addressed:

1. to clarify the results of parametric identification of the external model based on new data [4];
2. to assess the impact of the regular component and random factors on the dynamics of the pandemic;
3. to make a forecast of the epidemic situation using both a stochastic model (adjusted based on new data) and new algorithms — Fourier analysis and autoregression;
4. to compare the resulting time-scale and random characteristics of COVID-19 within the framework of the model with the known parameters of traditional influenza.

As a template function describing the dynamics of COVID-19, we take

$$\Phi(t,A,B,C,D,E,F,\alpha,\beta,\gamma,\delta,\varepsilon)=\frac{A\left[\alpha+cos\left(\beta t+\gamma\right)\right]}{ch^2\left(Bt+C\right)}+D\left[1+th\left(Et+F\right)\right]\left(\delta+cos\left(\delta t+\varepsilon\right)\right). \quad (1)$$

The first term of this function corresponds to a high peak caused by the Omicron strain. The second term represents the scenario where morbidity exits to an average level of 500,000 people, oscillating around this value with a frequency of $\beta/(2\pi)$. The parameters included in equation (1) have an obvious meaning of duration, frequency, amplitude and initial phase of individual disease modes.

To find all the parameters of model (1), according to the updated WHO data for the period from 01.04.2022 to 03.03.2023, we solved a significantly nonlinear mathematical programming problem:

$$ЦФ=\Sigma_i\left(lg\,\Phi\left(t_i,A,B,C,D,E,F,\alpha,\beta,\gamma,\delta,\varepsilon\right)-lg\,\Phi_i\right)^2\rightarrow min. \quad (2)$$

The results of parametric identification (1) are shown in Table 1 and in Figure 1.

Table 1

Numerical characteristics of the COVID-19 template morbidity model

A	B	C	D	E	F	α	β	γ	δ	ε	ЦФ
4381.458	0.036	–25.085	58.159	0.009	–1.280	1.233	0.043	–1.827	4.346	1.767	23.64

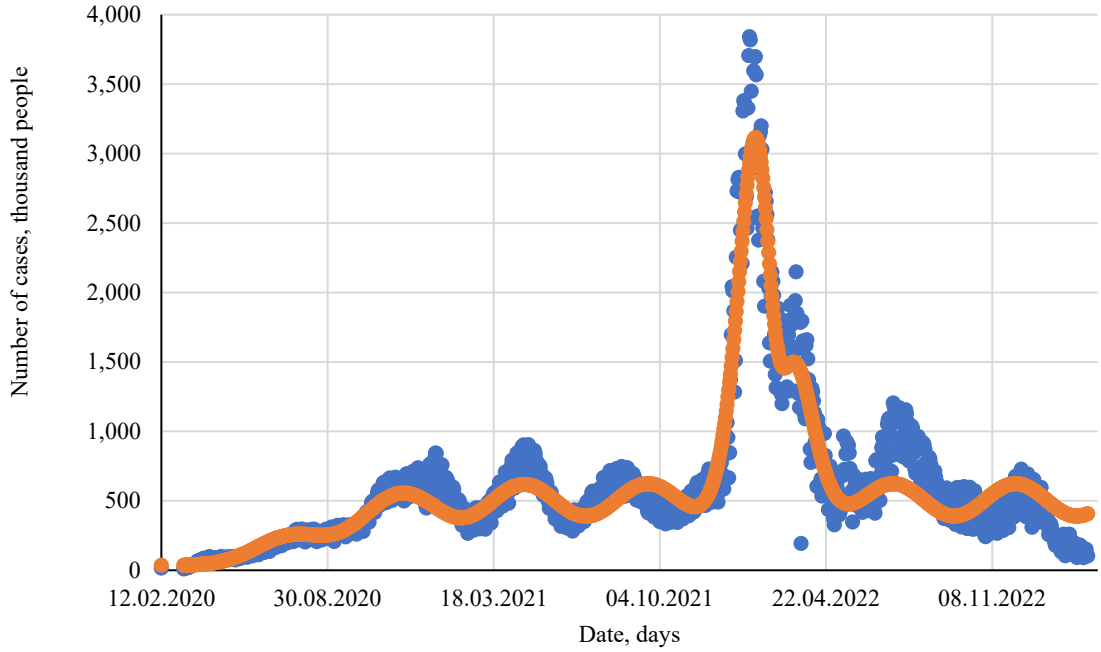


Fig. 1. Results of calculating the number of cases by date

According to the calculations performed, formula (1) takes the form:

$$\Phi(t)=\left(\frac{4{,}381.458\left[1{,}233+cos\left(0.043t-1.827\right)\right]}{ch^2\,0.036t-25.085}\right)58.159\left[1+th\left(0.009t-1.280\right)\right]\left(4.346+cos\left(0.043t+1.767\right)\right). \quad (3)$$

Oscillation period is 147 days versus 120–125 in the previous version of model [2]. However, this increase appears to be an artifact (Fig. 1) and is the result of a failure of the morbidity phase in an outbreak of omicron. Value $(\gamma-\varepsilon)$ characterizes the phase shift between the incidence of traditional COVID-19 and omicron modification.

The removal of the trend and oscillatory components from the data prevented us from obtaining a purely noise background (Fig. 2) [5]. This is due to the presence of some non-linear interaction in reality that does not fit within the framework of our model (3).

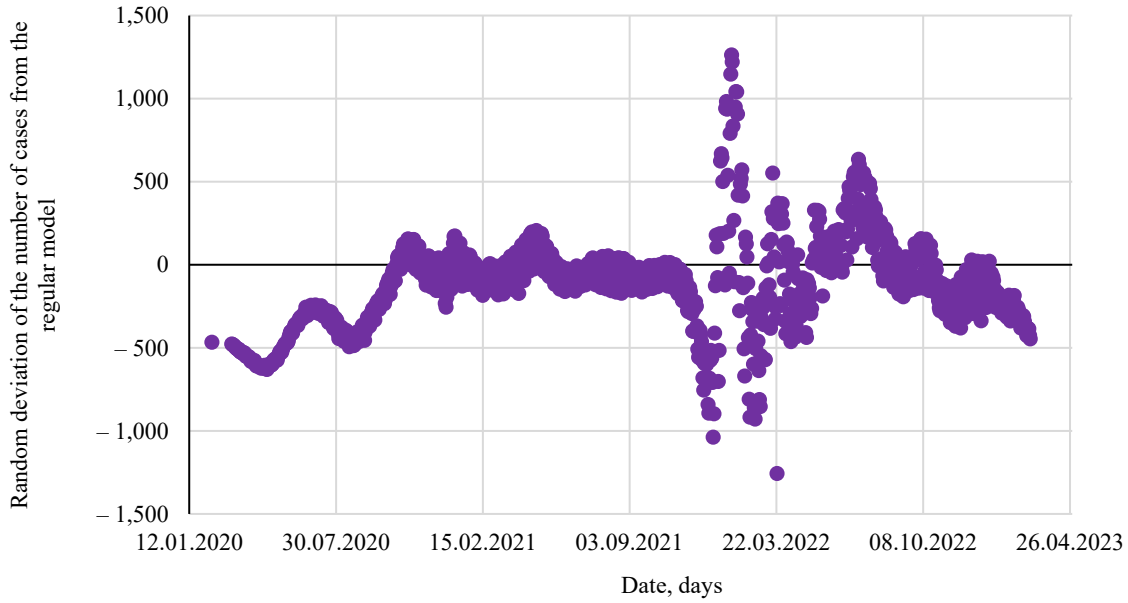


Fig. 2. Error in the approximation of WHO data by model (3)

The inability to accurately describe the dynamics of COVID-19 with 11-parametric function (1) encourages the use of alternative approaches for this purpose.

The results of representing the observed dynamics of the epidemic using Fourier decomposition with 40 and 100 harmonics are shown in Fig. 3.

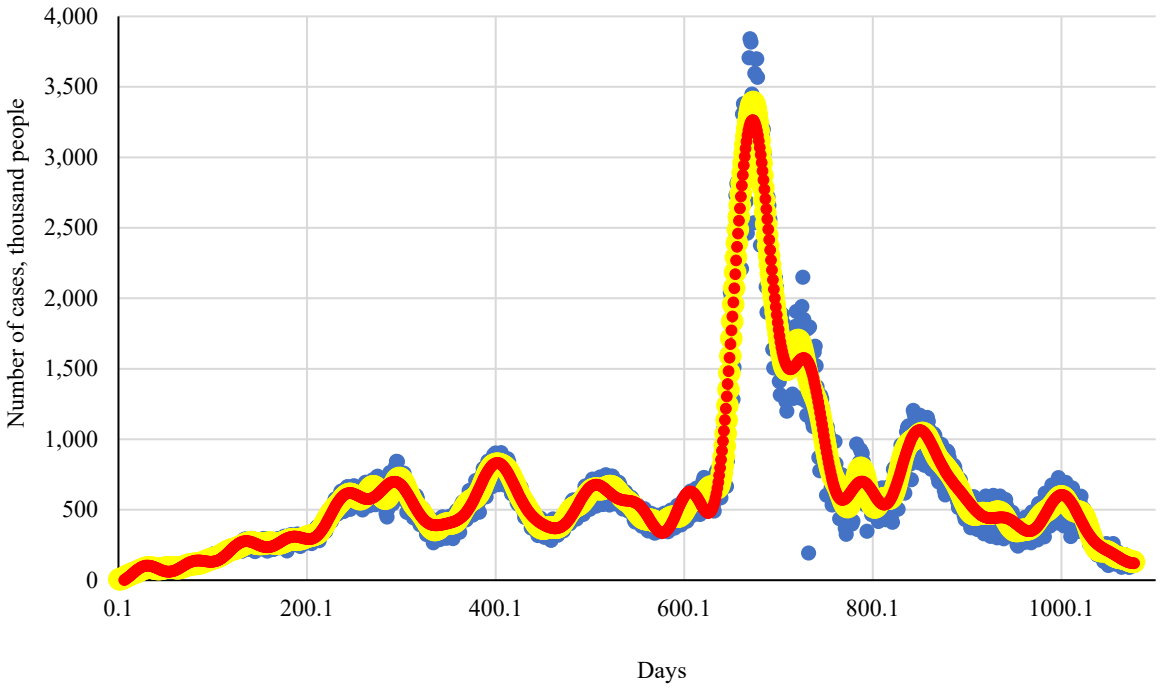


Fig. 3. The initial dynamics of the epidemic and its Fourier approximation. The initial data is shown in blue. The Fourier decomposition with 100 harmonics is shown in yellow, and the decomposition with 40 harmonics is in red

Comparison of the data in Figures 1 and 3 shows that considering a larger number of modes allows for a better description of the real dynamics of the epidemic. This is supported by both the slower decrease of a_i coefficients in the decomposition (Fig. 4) and the more dispersed nature of the residual random component (Fig. 5).

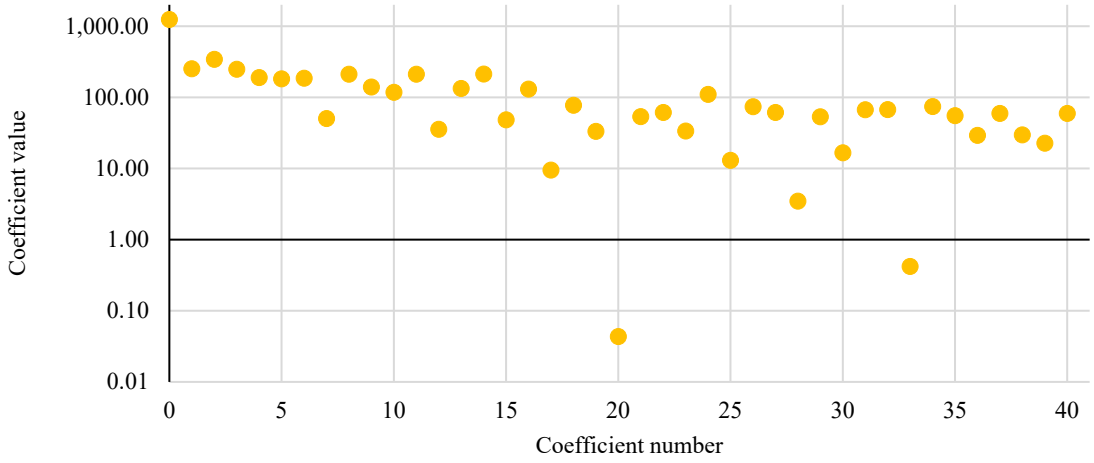
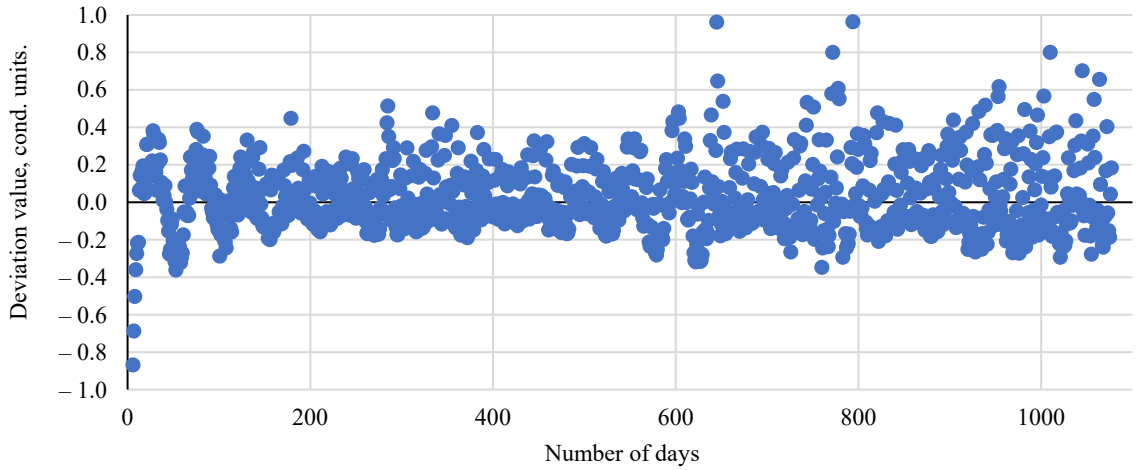
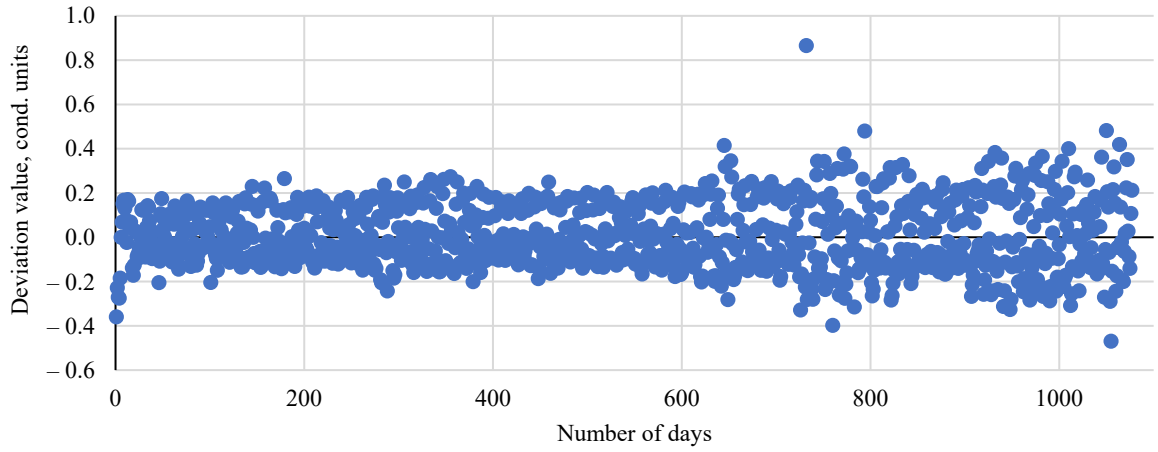


Fig. 4. The change in coefficients of decomposition a_i as the number increases



a)



b)

Fig. 5. The result of the elimination of the Fourier image from the source data:
a — Fourier decomposition into 40 harmonics; *b* — Fourier decomposition into 100 harmonics

According to the data in Figure 5, the residual relative noise is random. In practice, knowledge of the Fourier expansion coefficients a_i [6] makes it possible to synthesize a regularly random function for forecasting [7]. To make the result more transparent, only the trend is included in the forecast line (brown in Fig. 6) and compared with new statistical data [8]. The comparison suggests that the proposed algorithm does not provide long-term forecasts [9].

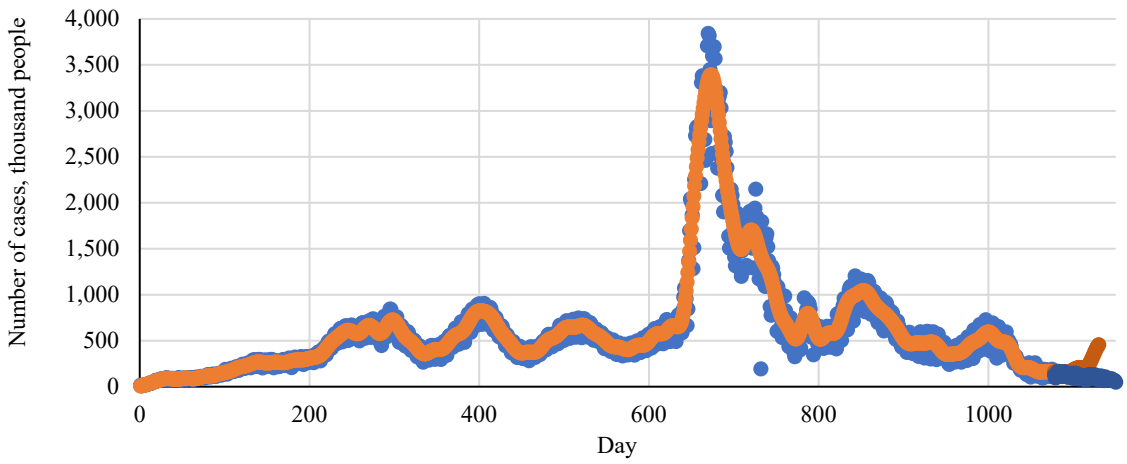


Fig. 6. Forecast of epidemic situation based on Fourier decomposition in comparison with new WHO data. Orange indicates a model based on the Fourier decomposition of a time series; brown indicates the predicted development of the coronavirus; blue indicates the initial data; dark blue indicates the real data compared to the predicted values

In this regard, the possibility of improving the quality of forecasting based on the autoregressive approach is investigated. The autoregression procedure is regulated by the following algorithm: 1) initialization of the initial data; 2) a suitable model is selected, depending on the characteristics of the time series and the requirements of the forecast; 3) training the model on a training sample; 4) validation of the model (checking the quality of the forecast on a test sample); 5) forecasting.

The dynamics of the epidemic have been predicted from March 4, 2023 until the present, comparing the results with current WHO data [6–8]. The results of this comparison are shown in Figure 7. As it can be seen, the autoregression technique is only suitable as a tool for short-term forecasting.

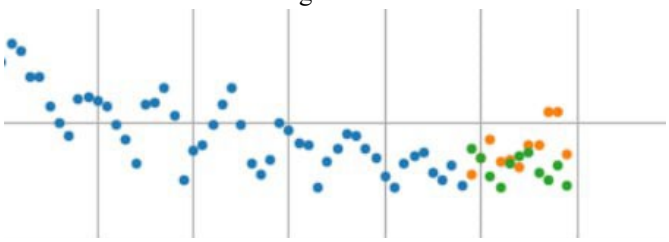


Fig. 7. Forecast of epidemic situation based on the autoregression method in comparison with new WHO data. The blue dots indicate the source data; orange — predicted values; green — real data compared to predicted values

Due to the fact that COVID-19 has rapidly evolved into a seasonal viral disease, it is interesting to compare its epidemic characteristics with those of influenza, as well as to analyze the combined effects of two virulent diseases on the human population.

To successfully compare the characteristics of the COVID-19 and influenza epidemics, statistical data on the incidence of influenza on a global scale from 03.01.2000 to 03.20.2023 were used, which can be found on the resource and shown in Figure 8.

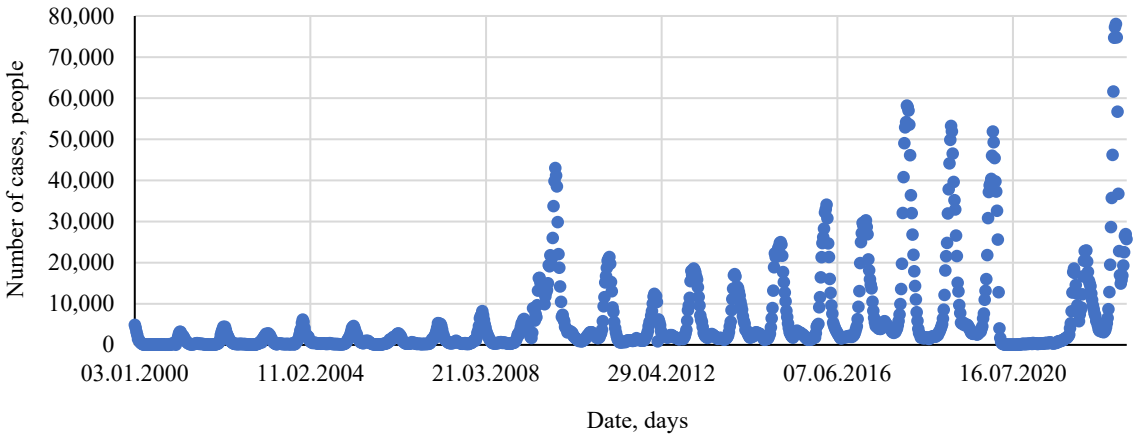


Fig. 8. Actual data on the influenza incidence according to WHO data

The logistic dependence was used as a trend model for the influenza epidemic [10] (Fig. 9):

$$N(t) = \frac{\mu \cdot e^{\eta(t-\chi)}}{1+e^{\eta(t-\chi)}}. \quad (4)$$

Initialization of the model using mathematical programming methods gives the following parameter values: μ = 6,847 thousand people/day (the maximum average incidence of influenza); η = 0.29 years^{-1} (the rate of increase in the coverage of patients with the global morbidity control system); χ = 2,013.9 year (the moment of half coverage of patients with the accounting system). Within the framework of this trend model, the incidence of influenza is reaching a historical plateau, and its recorded growth is associated exclusively with informatization in healthcare.

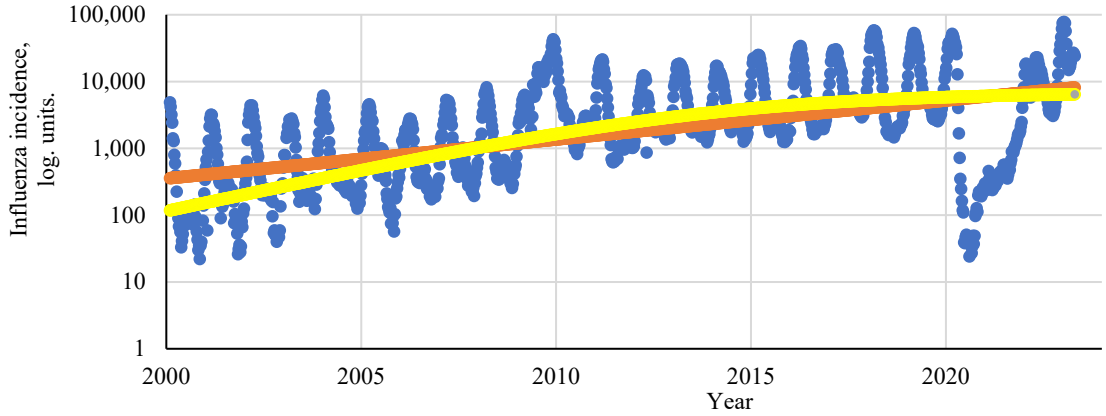


Fig. 9. Initialization of the influenza incidence trend. The blue color represents the incidence of influenza on a logarithmic scale; the orange line shows the assumed exponential trend; the yellow one shows trend model (4)

If you know the trend you can exclude it from the observed statistics and thereby highlight the oscillatory component:

$$P(t) = A \cdot sin^6(Bt+\varphi). \quad (5)$$

The degree of sine chosen here equal to 6 is responsible for the "blurring" of the outbreak of the disease over time. To find the coefficients of the model, optimization problem should be solved

$$\Sigma_i (F_i - P_i)^2 \to min, \quad (6)$$

where F_i — incidence; P_i — model value; $i \in [1,1212]$.

The results of the calculations are shown in Figure 10 and can be calculated using the following formula:

$$P(t) = 5.03 \cdot sin^6(3.2 \cdot t - 0.29). \quad (7)$$

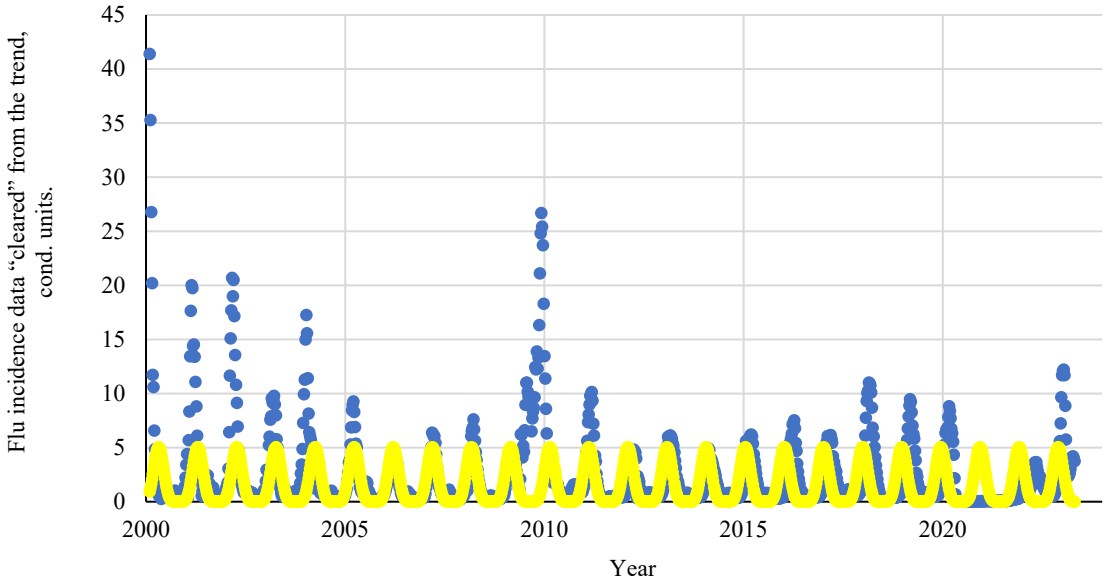


Fig. 10. The result of solving the optimization problem for the improved trend. The blue color shows the initial data cleared from the trend; the yellow color shows the curve corresponding to the random component

The presented data indicate that the influenza epidemic is a seasonal process that occurs annually [11, 12]. This means that, depending on the timing of the initial stages of epidemics, overlapping periods of high morbidity can occur. To determine these moments, the dynamics of influenza and COVID-19 incidence is presented in parametric form based on the results of [2]:

$$G(t) = 5.03 \cdot sin^6\left(3.15 \cdot \left(2{,}022.48 + \frac{t}{365}\right) - 0.18\right) \text{ — для гриппа;} \quad (8)$$

$$K(t) = 1 + 0.2 \cdot sin\left(0.043 \cdot t - \frac{\pi}{2}\right) \text{ — для COVID-19.} \quad (9)$$

In formulas (8, 9), time t is counted from moment t_0 = {03.01.2000} in units of one day. The standard representation of these data in Figure 11 is not informative, which prompts them to be converted into a parametric form (Fig. 12).

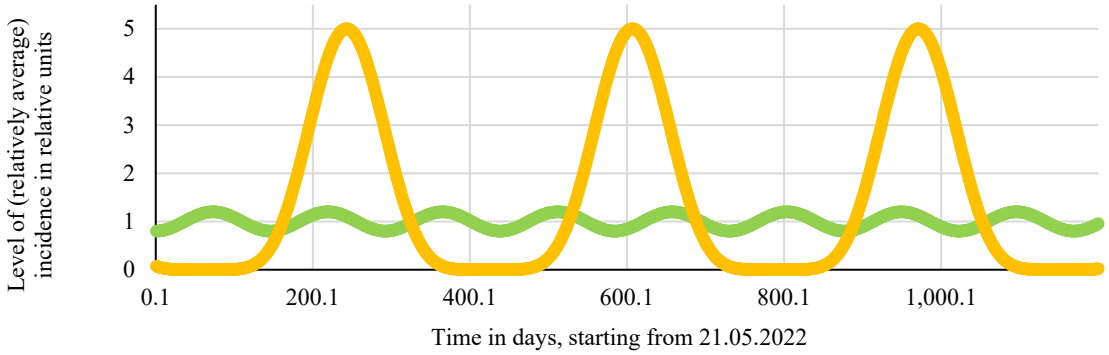


Fig. 11. Comparison of the dynamics of incidence of COVID-19 and influenza in relative units. The curve corresponding to the incidence of COVID-19 is shown in green, and the incidence of influenza is shown in orange

Since all methods of mathematical analysis have convincingly proved that COVID-19 outbreaks occur three times a year and influenza occurs annually, we will plot the data in Figure 11 in a parametric form (Fig. 12)

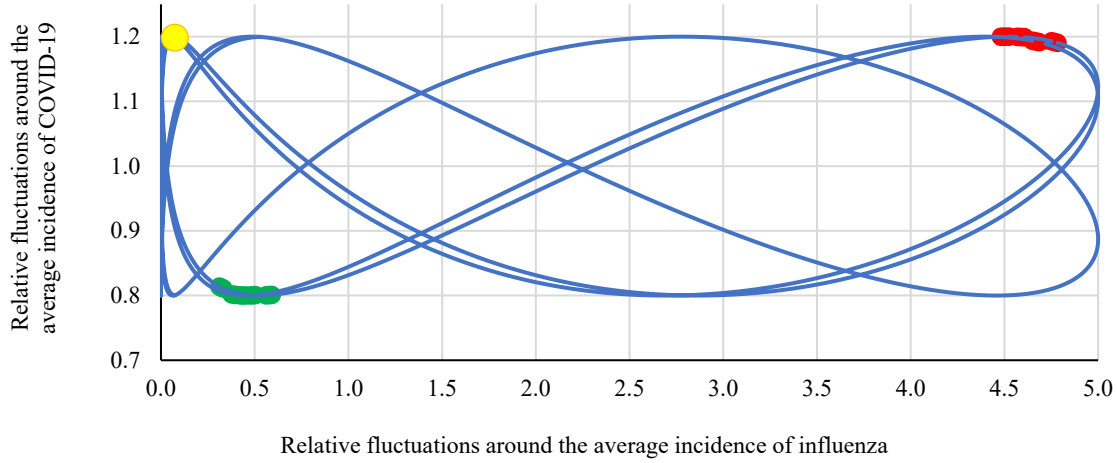


Fig. 12. Comparison of the dynamics of incidence of COVID-19 and influenza in parametric form

The joint display of the incidence of influenza and COVID-19, as shown in Figure 12, allows us to identify the most challenging moments when the effects of these two viruses overlap. During these periods, it is especially important to be cautious and follow all regulations for sanitary and epidemic control [13–15]. Currently, we are in a situation indicated by a yellow dot on the graph. From the most severe moment in terms of the epidemic (the red area), we are separated by approximately 580 days.

Results. As a result of our research, we have reached the following conclusions:

1. We have made significant adjustments to align the existing model with new data.
2. Previous estimates of the severity of COVID-19 were overly pessimistic.
3. We used new methods, such as Fourier analysis and autoregressive techniques, to increase the information content and reliability of our analysis and epidemic forecasting.
4. Even with the combined use of these methods, we can only make a short-term forecast.
5. We compared the features of two seasonal diseases, COVID-19 and influenza.
6. We predicted the moments when the combined effect of these diseases will be most harmful to humans.

Discussion and Conclusion. The authors substantiate the need to reliably predict the coincidence of peaks in the incidence of influenza and COVID-19. It is shown that the visibility of the coincidence is achieved by presenting the dynamics of both diseases in a parametric form. It has been established that due to the multiplicity of the period of both epidemics, the maximum and minimum danger of their imposition is also periodic. Numerical indicators of the cyclical nature of epidemics were revealed according to experimental data by direct approximation, Fourier decomposition and autoregressive algorithm. A computer experiment has shown that even the combined use of these methods allows only a short-term forecast of the epidemic situation. The authors predicted the moments when the peaks of the incidence of influenza and COVID-19 will coincide.

References

1. Mollarasouli F, Zare-Shehneh N, Ghaedi M. A Review on Corona Virus Disease 2019 (COVID-19): Current Progress, Clinical Features and Bioanalytical Diagnostic Methods. *Microchimica Acta.* 2022;189:103. https://doi.org/10.1007/s00604-022-05167-y

2. Azimova NN, Bedoidze MV, Kholodova SN, Mokina TA, Zairova DKh, Ermakov AS. Statistical Assessment of Biogenic Risk for the Human Population from New Viral Infections Based on COVID-19. *Safety of Technogenic and Natural Systems.* 2023;(1):4-15. https://doi.org/10.23947/2541-9129-2023-1-4-15

3. Siettos CI, Russo L. Mathematical Modeling of Infectious Disease Dynamics. *Virulence.* 2013;4(4):295–306. https://doi.org/10.4161%2Fviru.24041

4. Steinberg DM, Balicer RD, Benjamini Y, De-Leon H, Gazit D, Rossman H, et al. The Role of Models in the Covid-19 Pandemic. *Israel Journal of Health Policy Research.* 2022;11:36. https://doi.org/10.1186/s13584-022-00546-5

5. Vinogradov AYu. *Numerical Methods for Solving Rigid and Non-Rigid Boundary Value Problems.* Moscow: National Research; 2017. 112 p. URL: https://eqworld.ipmnet.ru/ru/library/books/Vinogradov2017ru.pdf (accessed: 10.03.2024). (In Russ.)

6. Šušteršic T, Blagojevic A, Cvetkovic D, Cvetkovic A, Lorencin I, Šegota B, et al. Epidemiological Predictive Modeling of COVID-19 Infection: Development, Testing, and Implementation on the Population of the Benelux Union. Frontiers in Public Health. 2021;9:727274. https://doi.org/10.3389/fpubh.2021.727274

7. Roosa K, Yiseul Lee, Riuyan Luo, Kirpich A, Rothenberg R, Hyman JM, et al. Short-term Forecasts of the COVID-19 Epidemic in Guangdong and Zhejiang, China: February 13–23, 2020. *Journal of Clinical Medicine.* 2020;9(2):596. https://doi.org/10.3390/jcm9020596

8. Makarovskikh TA, Abotaleb MSA. Automatic Selection of ARIMA Model Parameters to Forecast COVID-19 Infection and Death Cases. *Bulletin of the South Ural State University. Series: Computational Mathematics and Software Engineering.* 2021;10(2):20–37. https://doi.org/10.14529/cmse210202 (In Russ.)

9. Ioannidis JPA, Cripps S, Tanner MA. Forecasting for COVID-19 Has Failed, *International Journal of Forecasting.* 2022;38(2):423–438. https://doi.org/10.1016/j.ijforecast.2020.08.004

10. Sonal Jain, Ho-Hon Leung, Firuz Kamalov. A Computational Numerical Performance for Solving the Mathematical Epidemiological Model Based on Influenza Disease, *Scientific African*. 2022;17:e01383. https://doi.org/10.1016/j.sciaf.2022.e01383

11. Bucyibaruta G, Dean CB, Mahmoud Torabi. A Discrete-Time Susceptible-Infectious-Recovered-Susceptible Model for the Analysis of Influenza Data. *Infectious Disease Modelling.* 2023;8(2):471–483. https://doi.org/10.1016/j.idm.2023.04.008

12. Xinzhu Guan, Fan Yang, Yongli Cai, Weiming Wang. Global Stability of an Influenza A Model with Vaccination. *Applied Mathematics Letters.* 2022;134:108322. https://doi.org/10.1016/j.aml.2022.108322

13. Fong Min W, Gao Huizhi, Wong Jessica Y, Xiao Jingyi, Shiu Eunice YC, Ryu Sukhyun, et al. Nonpharmaceutical Measures for Pandemic Influenza in Non healthcare Settings-Social Distancing Measures. *Emerging Infectious Diseases.* 2020;26(5):976–984. https://doi.org/10.3201/eid2605.190995

14. Lazarus JV, Wyka K, White TM, Picchio CA, Gostin LO, Larson HJ, et al. A Survey of COVID-19 Vaccine Acceptance across 23 Countries in 2022. *Nature Medicine* 2023;29:366–375 https://doi.org/10.1038/s41591-022-02185-4

15. Lin J, Li C, He W, Trends in Influenza Vaccine Uptake before and during the COVID-19 Pandemic in the USA. *Public Health.* 2023;225:291–298, https://doi.org/10.1016/j.puhe.2023.10.028

About the Authors:

Natalya N. Azimova, Cand. Sci. (Eng.), Associate Professor of the Applied Mathematics Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), ORCID, arkomaazimov@mail.ru

Dzhakhangul Kh. Zairova, Master's Degree Student of the Media Technologies Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), SPIN-code: 8187-5637, ORCID, gulyazair@gmail.com

Aleksandr S. Ermakov, Master's Degree Student of the Automation of Production Processes Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), SPIN-code: 4966-2084, ORCID, ermakov_sahsa11@mail.ru

Evgenii N. Ladosha, Cand. Sci. (Eng.), Associate Professor of the Media Technologies Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation).

Claimed Contributorship:

NN Azimova: development and implementation of a dynamic epidemic model, development of statistical analysis methods.

DKh Zairova: selection and verification of new statistical data, comparison of the results of experiments on forecasting the epidemic dynamics with the real data.

AS Ermakov: comparative characteristics of the COVID-19 and influenza epidemics, performing experiments to predict the dynamics of the epidemic, preparing the text of the article.

EN Ladosha: formulation of meaningful conclusions and recommendations, revision of the text.

Conflict of Interest Statement: **the authors do not have any conflict of interest.**

All authors have read and approved the final manuscript.

Об авторах:

Наталья Николаевна Азимова, кандидат технических наук, доцент кафедры прикладной математики Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), ORCID, arkomaazimov@mail.ru

Джахангул Хайруллаевна Заирова, магистрант кафедры медиатехнологий Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), SPIN-код: 8187-5637, ORCID, gulyazair@gmail.com

Александр Сергеевич Ермаков, магистрант кафедры автоматизации производственных процессов Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), SPIN-код: 4966-2084, ORCID, ermakov_sahsa11@mail.ru

Евгений Николаевич Ладоша, кандидат технических наук, доцент кафедры медиатехнологий Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1).

Заявленный вклад авторов:

Н.Н. Азимова: разработка и реализация динамической модели эпидемии, разработка методов статистического анализа.

Д.Х. Заирова: подбор и верификация новых статистических данных, сопоставление результатов экспериментов по прогнозированию динамики эпидемии с реальными данными.

А.С. Ермаков: сравнительная характеристика эпидемий COVID-19 и гриппа, выполнение экспериментов по прогнозированию динамики эпидемии, подготовка текста статьи.

Е.Н. Ладоша: формулировка содержательных выводов и рекомендаций, доработка текста.

Конфликт интересов: **авторы заявляют об отсутствии конфликта интересов.**

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 31.05.2024
Revised / Поступила после рецензирования 21.06.2024
Accepted / Принята к публикации 27.06.2024

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

UDC 621.762. 1
https://doi.org/10.23947/2541-9129-2024-8-3-67-77

Original Empirical Research

Phase Transformations in Powder Sintered Steels during Cooling

Maxim S. Egorov [1], Rimma V. Egorova[1], Vladimir Yu. Lopatin[2]
[1]Don State Technical University, Rostov-on-Don, Russian Federation
[2]National Research Technical University MISIS, Russian Federation, Moscow, Russian Federation
✉ aquavdonsk@mail.ru

EDN: QZFWTB

Abstract

Introduction. Heat treatment is a common post-processing operation applied to powder steel (PS) after deformation. The fundamental principles of heat treatment theory, developed for solid materials, also apply to PS. However, the specific structure of PS introduces quantitative and qualitative differences in the kinetics of heat treatment processes. Therefore, it is important to understand the effect of heat treatment on the structure and properties of PS when developing new materials. The aim of this study is to investigate phase transformations in sintered powder steels during cooling and to determine their mechanical properties after heat treatment.

Materials and Methods. The study used domestic powders of brands PZHRV 2.200.28 (TU 14-1-5365-98) and PL-N4D2M (TU 14-5402-2002) produced by PJSC Severstal (Cherepovets). During the mixing process, ultrafine additives of silicon nitride (Si3N4) and nickel oxide (NiO) manufactured by Plasnotherm (Moscow) were added to the charge. Before use, the powders were tested on a universal laser particle size measuring device (FRITSCH ANALYSETTE 22 MicroTec plus) and a submicron particle analyzer (Beckman COULTER No. 5). To prepare the charge, we used a two-cone mixer RT-NM05S (Taiwan) and an ultrasonic station for sieving and mixing powders with ultrafine particles Assonic SPC (China). Static cold pressing was carried out in laboratory molds on a hydraulic press model TS0500-6 (China) with a maximum force of 50 tons. Homogenizing sintering was performed in the laboratory of heat treatment at the Department of Materials Science and Technology of Metals at Don State Technical University in a muffle electric furnace model 6.7/1300 in the temperature range of 900–1150°C, in a protective gas environment — dissociated ammonia. Sintering time was 15–180 minutes. Heat treatment of sintered powder steels was also performed in these furnaces. Quenching of sintered samples was carried out at a temperature of 800°C. The initial porosity of sintered samples was 10.15.25%. Sintered samples were cooled at a temperature between 100 and 300°C. Tensile testing was conducted in accordance with GOST 18227–851, using a floor-mounted servohydraulic tensile testing machine MGS-V15 in an automatic mode, with the help of a personal computer. Hardness was measured using a Rockwell hardness tester TK-2M with a diamond cone indenter under a total load of 1471 N.

Results. The study conducted allowed us to identify the patterns of phase transformation in powder-sintered steels with ultra-fine particles during cooling after quenching. We experimentally determined the values of critical cooling points for powder-sintered eutectic steels at cooling rates of 60–400°C per minute. Additionally, we determined the mechanical properties of sintered powder steels with ultrafine particles depending on the temperature range of transformations

Discussion and Conclusion. The research has allowed us to establish the effect of ultrafine particles on the temperature of the critical points of sintered eutectoid PS, to construct diagrams of isothermal transformation of austenite, as well as to determine the mechanical properties of powder-sintered steels containing ultrafine particles. The analysis of the results obtained from the research has shown a multifaceted impact of nickel oxide and silicon nitride particles on phase transformations in powder-sintered steel.

[1] GOST 18227-85 (ISO 2740-86). *Powder materials. Tensile test method.* URL: https://docs.cntd.ru/document/1200010599 (accessed: 12.04.2024). (In Russ.)

Keywords: sintered powder steels, ultrafine particles, critical cooling points, isothermal transformation, mechanical properties

Acknowledgements. The authors would like to express their sincere gratitude to the staff of the Department of Powder Metallurgy and Functional Coatings at National Research Technological University MISIS, and particularly to Associate Professor, Cand. Sci. (Engineering) V.Yu. Lopatin. They also extend their thanks to the staff of the Materials Science and Technology of Metals Department at Don State Technical University, including Dr. Sci. (Engineering), Professor V.N. Pustovoit and Dr. Sci. (Engineering), Professor Yu.M. Dombrovskii. Their assistance in obtaining and discussing the study's results is greatly appreciated.

For citation. Egorov MS, Egorova RV, Lopatin VYu. Phase Transformations in Powder Sintered Steels during Cooling. *Safety of Technogenic and Natural Systems.* 2024;8(3):67–77. https://doi.org/10.23947/2541-9129-2024-8-3-67-77

Оригинальное эмпирическое исследование

Фазовые превращения в порошковых спеченных сталях при охлаждении

М.С. Егоров[1], Р.В. Егорова[1], В.Ю. Лопатин[2]

[1]Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация

[2]Национальный исследовательский технологический университет МИСиС, г. Москва, Российская Федерация

✉ aquavdonsk@mail.ru

Аннотация

Введение. Термическая обработка является наиболее распространенной последеформационной операцией, применяемой к порошковым сталям (ПС). Принципиальные положения теории этого процесса, разработанные для компактных материалов, справедливы и для рассматриваемых ПС. Однако специфика структуры последних вносит количественные и качественные изменения в кинетику процессов, происходящих при различных видах термической обработки. Поэтому при разработке новых материалов необходимо уделять большое внимание влиянию термической обработки на их структуру и свойства. В связи с этим целью данного исследования является анализ фазовых превращений в порошковых спеченных сталях при охлаждении и определение их механических свойств.

Материалы и методы. В работе использованы отечественные порошки марок ПЖРВ 2.200.28 (ТУ 14-1-5365-98) и ПЛ-Н4Д2М (ТУ 14-5402-2002) производства ПАО «Северсталь» (г. Череповец). При смешивании в шихту добавлялись ультрадисперсные добавки нитрида кремния (Si_3N_4) и оксида никеля (NiO) производства компании «Плазнотерм» (г. Москва). Перед использованием порошки проходили контроль на универсальном лазерном приборе измерения размера частиц (модель FRITSCH ANALYSETTE 22 MicroTec plus) и анализаторе субмикронных частиц (Beckman COULTER № 5). Для приготовления шихты использовались двухконусный смеситель марки RT-NM05S (Тайвань) и ультразвуковая станция для просеивания и смешивания порошка с ультрадисперсными частицами Assonic SPC (Китай). Статическое холодное прессование проводилось в лабораторных пресс-формах на гидравлическом прессе модели TS0500-6 (Китай) с максимальным усилием в 50 тонн. Гомогенизирующее спекание проведено в лаборатории термической обработки кафедры «Материаловедение и технологии металлов» ДГТУ в муфельной электропечи модели SNOL 6,7/1300 в диапазоне температур 900–1150 °С в среде защитного газа — диссоциированного аммиака. Время спекания — 15–180 минут. В таких же печах производилась и термическая обработка спеченных порошковых сталей. Закалка осуществлялась на спеченных образцах при температуре 800 °С. Исходная пористость спеченных образцов составляла 10,15,25 %. Отпуск спеченных образцов проходил при температуре 100–300 °С. Испытания на растяжение проводились в соответствии с ГОСТ 18227–85 с использованием сервогидравлической напольной разрывной машины МГС-В 15 в автоматическом режиме с помощью персонального компьютера. Для измерения твердости использовался твердомер Роквелла ТК-2М с индентированным алмазным конусом при общей нагрузке 1471 Н.

Результаты исследования. В работе выполнены исследования, которые позволили определить закономерности фазовых превращений в порошковых спеченных сталях с ультрадисперсными частицами при охлаждении после операции закалки. Экспериментально определены значения критических точек охлаждения для спеченных порошковых сталей эвтектоидного состава для скоростей охлаждения 60–400 °С/мин. Определены также механические свойства спеченных порошковых сталей с ультрадисперсными частицами в зависимости от температурного интервала превращений.

Обсуждение и заключение. Исследования позволили установить влияние ультрадисперсных частиц на температуру критических точек спеченных ПС эвтектоидного состава, построить диаграммы изотермического превращения аустенита, а также определить механические свойства спеченных порошковых сталей с ультрадисперсными частицами. Анализ полученных результатов исследований показал разнонаправленное влияние частиц оксида никеля и нитрида кремния на фазовые превращения в порошковых спеченных сталях.

Ключевые слова: спеченные порошковые стали, ультрадисперсные частицы, критические точки охлаждения, изотермическое превращение, механические свойства

Благодарности. За помощь в получении и обсуждении результатов исследования авторы выражают искреннюю признательность сотрудникам кафедры ПМиФП НИТУ МИСиС и лично доценту, кандидату технических наук В.Ю. Лопатину, сотрудникам кафедры «Материаловедение и технологии металлов» ДГТУ доктору технических наук, профессору В.Н. Пустовойту, доктору технических наук, профессору Ю.М. Домбровскому.

Для цитирования. Егоров М.С., Егорова Р.В., Лопатин В.Ю. Фазовые превращения в порошковых спеченных сталях при охлаждении. *Безопасность техногенных и природных систем.* 2024;8(3):67–77. https://doi.org/10.23947/2541-9129-2024-8-3-67-77

Introduction. Heat treatment is understood as a set of heating, holding at high temperatures and cooling operations in order to change the structure and workability of the material, improve the combination of its mechanical and physical properties without changing the shape and size of the product. Heat treatment is an effective method of increasing physical and mechanical properties and wear resistance of steel [1].

Specific features of sintered steels (porosity, heterogeneity of structure, high oxidation capacity, etc.) make it difficult to use the technological modes of heat treatment developed for cast steels, although the main patterns of processes occurring during heating and cooling of compact steel can be transferred to sintered materials [2].

Studies of powder materials, including heat treatment, show a significant effect of porosity, as one of the features of their structure, on the development of phase transformations both during heating and cooling [3]. The presence of pores in powder materials and powder steels, as well as a high content of non-metallic inclusions, including those that modify the structure and density of dislocations, facilitate the formation of nuclei of new phases. This statement is supported by the results of thermodynamic analysis of phase transformations conducted on the basis of relevant data [4].

The aim of this work is to identify the features of the kinetics of phase transformations in powder sintered steels with ultrafine particles during cooling, to determine their mechanical properties depending on the temperature range. The main task of the study in this regard is to analyze the effect of porosity and cooling rate on the change in the position of critical points Ar_1 and Ar_3, as well as the effect of ultrafine additives on the initial phase of austenite decomposition and the mechanical properties of sintered powder steels

Materials and Methods. Powders of PZhRV 2.200.28[2] and N4D2M[3] brands by PJSC Severstal (Cherepovets) and ultrafine particles of nickel oxide and silicon nitride from Plasmotherm were used in the work[4]. Table 1 presents data on the total chemical composition.

Table 1

Chemical composition of powders

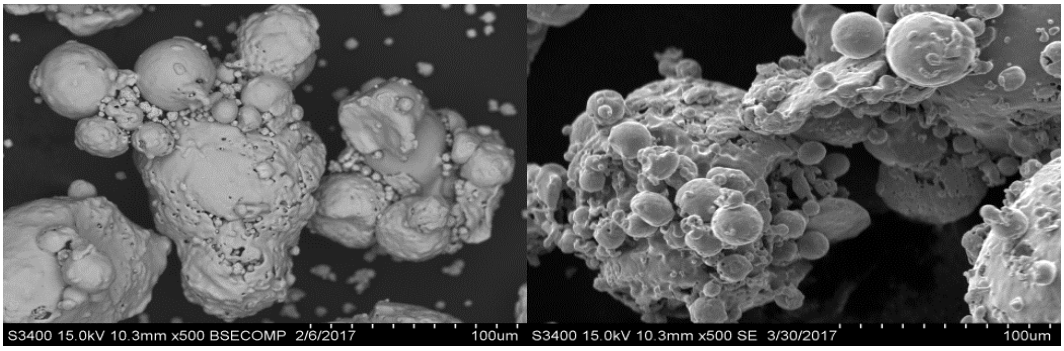
Powder grade	Mass content of components, %									
	Mo	Ni	C	O	H	Cu	Si	Mn	0P	S
PZhRV 2.200.26	–	–	0.090	0.140	–	–	0.014	0.087	0.012	0.005
N4D2M	0.400–0.500	3.600–4.400	0.020	0.025	–	1.300–1.700	0.050	0.150	0.020	0.020

Technological properties of PZhRV 2.200.26 powder: bulk density was from 2.4 to 3.0 g/cm^3, fluidity was no more than 37 sec/50 g, density at P = 700 MPa was 7.0–7.05 g/cm^3, strength at density of 6.5 g/cm^3 was more than 14 N/mm^2. The analog was the powders of the Swedish company Höganäs: AHC 100.29, NC 100.24, SC100.26, ASC100.29. Scope of application: shock absorption group parts, transmission parts, body parts, gears, connecting rods, couplings, bushings, etc.

According to TU 14-5402-2002, the powder of PL-N4D2M brand produced by Severstal contained 4% of nickel, 1.5% of copper and 0.5% of molybdenum. It was developed by specialists of Central Research Institute chermet named after Baikov. It was based on the iron powder of the PZHRV line. The final product was a partially alloyed mixture with excellent compaction (at a compacting pressure of 600 MPa, the density values were at least 7.1 g/cm^3).

[2] TU 14-5365-98. *Iron powder, sprayed with air.* (In Russ.)
[3] TU 14-5402-2002. *Diffusion-doped iron powder.* (In Russ.)
[4] *Plasmotherm LLC company. Metal Nanopowders.* URL: https://plasmotherm.ru/catalog/metal/item_4.html (accessed: 12.04.2024). (In Russ.)

Figure 1 provides the morphology of the studied powders.



a) *b)*

Fig. 1. Powder particles: *a* — PL-N4D2M; *b* — PZhRV 2.200.26

Figure 2 shows a SEM image of ultrafine nickel oxide particles. Table 2 shows the properties of nickel oxide particles. The powder had a wide particle size distribution and represented individual spherical particles[5].

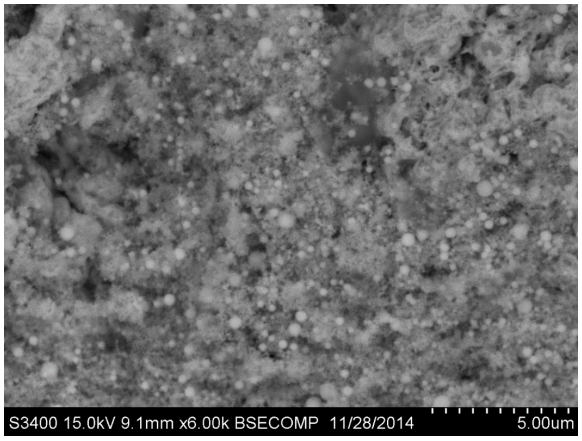


Fig. 2. SEM images of ultrafine NiO particles

Table 2

Main properties and characteristics of ultrafine nickel oxide powder

Production technology	Plasma chemical synthesis
Powder color	black
Particle size, nm	50–85
Average size of agglomerates, μm	30–80
Specific surface area, m^2/g	5–20
Content of the main component, %	99.8

Table 3 shows the characteristics of ultrafine nitride powder[6].

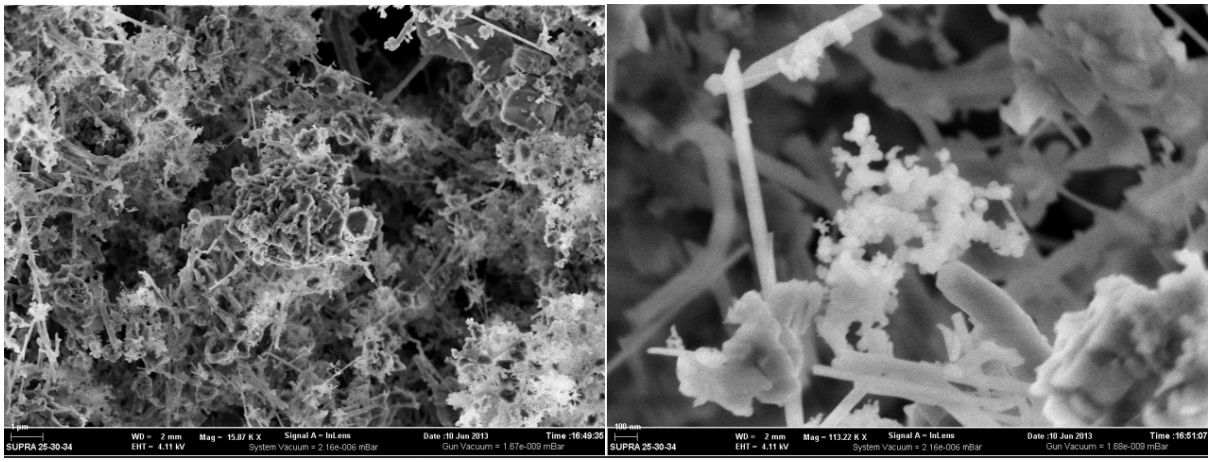
Table 3

Characteristics of ultrafine silicon nitride powder

Parameter	Value
Particle size, nm	10–30
Specific geometric surface, m^2/g	50–140
Content of the main component, %	99.75

[5] TU 14-5402-2002 *Diffusion-doped iron powder.* (In Russ.)
[6] Id.

Ultrafine particles had a shape of needles (Fig. 3), formed fleecy flakes after contact with water and did not change size after ultrasonic treatment[7].



a) *b)*

Fig. 3. Image through a scanning electron microscope of ultrafine Si_3N_4 particles:
a — general view of the particle; *b* — particles at magnification 10^9

Experiments. Pressing was carried out using laboratory molds and a hydraulic press model TS0500-6 (China) with a maximum force of 30 tons. The prismatic blanks were molded in a mold shown in Figure 4. This mold consisted of container (1), two semi-matrixes (2), punch (3), inserts (4), which were made of tool steels U8, U10A. Their hardness after heat treatment reached 55–62 HRC. The residual porosity of the samples after pressing, depending on the applied pressure, was 10–40%. The prismatic blanks after molding had dimensions of 9.5x54.3 mm.

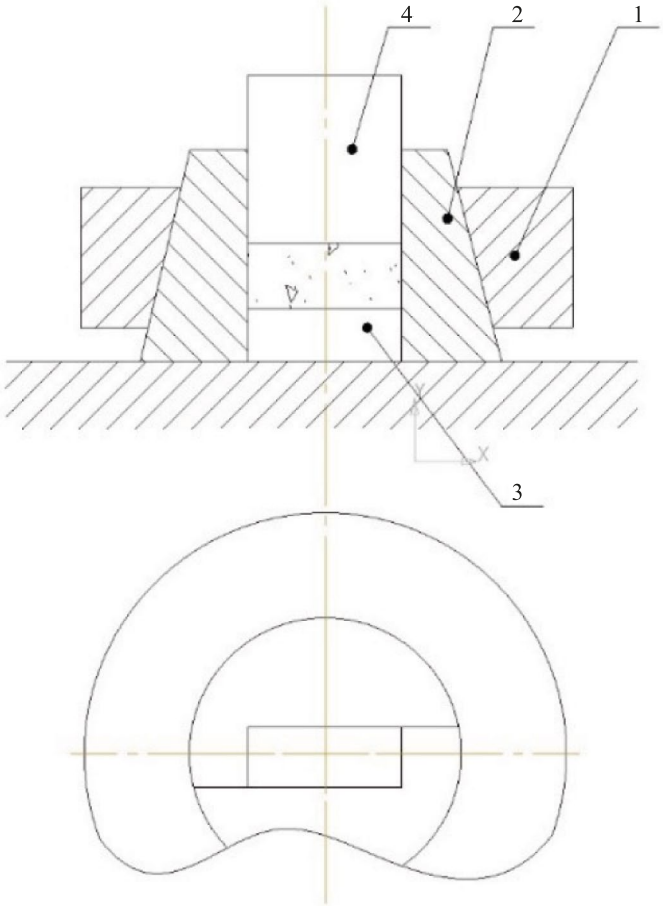


Fig. 4. Diagram of the mold for cold pressing of prismatic samples

[7] TU 14-5402-2002 *Diffusion-doped iron powder.* (In Russ.)

Figure 5 shows a mold used for the production of tensile strength test samples.

Fig 5. Laboratory mold for the manufacture of tensile test samples according to GOST 8227-98 for cold-pressed and sintered samples

Sintering and heat treatment were carried out in the laboratory of heat treatment at the Department of Materials Science and Technology of Metals at Don State Technical University in a chamber electric furnace with protective atmosphere PKZ-1.0-7 (Russia) in a temperature range 900–1150 °C in a protective gas environment — dissociated ammonia (Fig. 6). Sintering time was 15–180 minutes.

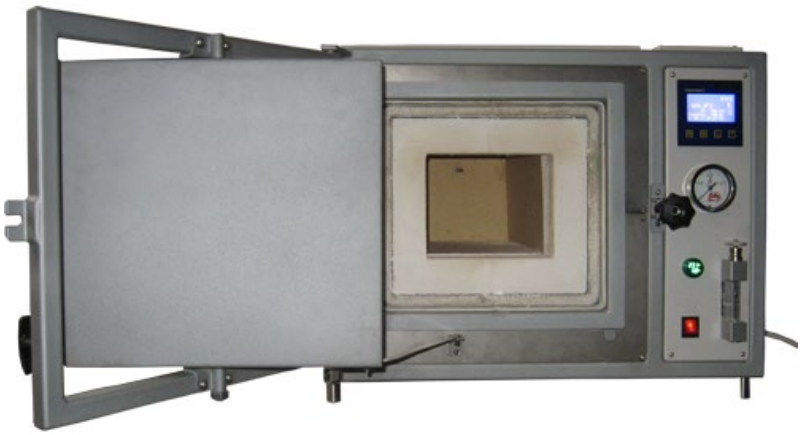


Fig. 6. Laboratory chamber electric furnace with protective atmosphere PKZ-1.0-7

Results. Let us imagine the process of phase transformations of powder sintered steels depending on their structural state. The dependence of the location of points A_{r1} and A_{r3} was established depending on such parameters as cooling rate ($V_{охл}$), porosity of samples and the introduction of ultrafine particles into the steel (Fig. 7). These parameters have different effects on the temperature ranges of phase transformations and the kinetics of austenite transformation [5]. A higher cooling rate slowed down, and greater porosity accelerated the transformation of austenite, shifting temperature ranges in opposite directions.

The effect of nickel oxide and silicon nitride additives was multidirectional [6]. If the first additive lowered the temperature of critical points, then the second one increased it. Table 4 provides the values of critical points for sintered PS of eutectoid composition for cooling rates of 60–400 °C/min. For PS based on N4D2M powder, the temperature of critical points was lower than that of iron powder, due to a slowdown in diffusion processes in the alloyed matrix [7].

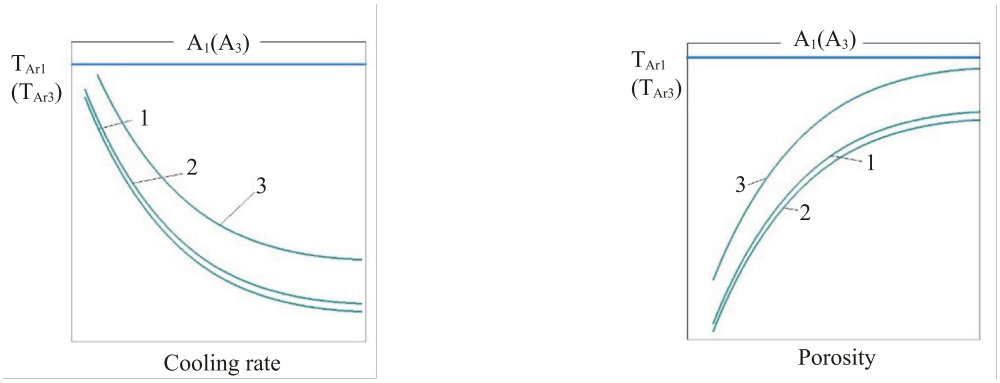


Fig. 7. Dependence of the position of points Ar_1 and Ar_3 for powder steels: 1 — clear; 2 — PS + 1 % NiO, 3 — PS + 0.2 % Si_3N_4; *a* — on cooling rate; *b* — on porosity

Table 4

Temperature points Ar_1 and Ar_3 of powder steels

Base of the alloy	Carbon content	Porosity, %	Point A_{r1}temperature, C	Point A_{r3}temperature
PZhRV 2.200.26	0.5	10	695*; 693**; 690***	725; 722; 719
		20	705; 702; 698	730; 727; 720
		30	712; 710; 708	737; 735; 732
	0.8	10	715; 713; 710	–
		20	718; 713; 708	–
		30	720; 716; 712	–
PZhRV 2.200.26 + 1% NiO	0.5	10	693; 690; 688	723; 720; 717
		20	703; 700; 696	728; 725; 718
		30	710; 708; 705	735; 732; 728
	0.8	10	712; 710; 708	–
		20	716; 711; 705	–
		30	723; 720; 716	–
PZhRV 2.200.26 + 0.2% Si_3N_4	0.5	10	700; 695; 693	730; 726; 722
		20	710; 707; 702	736; 732; 726
		30	718; 715; 712	740; 737; 735
	0.8	10	720; 722; 724	–
		20	723; 720; 717	–
		30	725; 722; 718	–
N4D2M	0.5	10	692; 690; 687	723; 719; 715
		20	700; 698; 695	726; 723; 716
		30	708; 705; 702	734; 730; 728
	0.8	10	710; 708; 702	–
		20	714; 711; 706	–
		30	717; 712; 708	–
N4D2M + 1% NiO	0.5	10	690; 686; 682	720; 717; 713
		20	700; 696; 692	725; 722; 716
		30	705; 703; 697	730; 728; 722
	0.8	10	707; 704; 698	–
		20	711; 708; 706	–
		30	715; 710; 706	–
N4D2M + 0.2% Si_3N_4	0.5	10	696; 692; 688	724; 720; 718
		20	706; 702; 698	732; 728; 722
		30	714; 710; 706	736; 730; 725
	0.8	10	716; 714; 710	–
		20	718; 720; 722	–
		30	720; 722; 726	–
*Note: cooling rates, °/min: *–60; **–200; ***–400*				

Upon slow cooling, austenite decomposed into a eutectoid ferrite-cementite mixture, the dispersion of which depended on the degree of supercooling [8]. During the incubation period, supercooled austenite remained stable, but after that, its decay began. C-shaped curves were used to describe the decay of austenite (Fig. 8) [9].

The analysis of the diagrams of isothermal transformation of austenite of powdered steels PZhRV 2.200.26 + 0.8%C and N4D2M + 0.8%C showed that with increasing porosity, the stability of supercooled austenite decreased, as evidenced by the displacement of C-shaped curves to the left. The area of minimum stability of austenite moved towards elevated temperatures. The total time of isothermal decomposition of austenite increased.

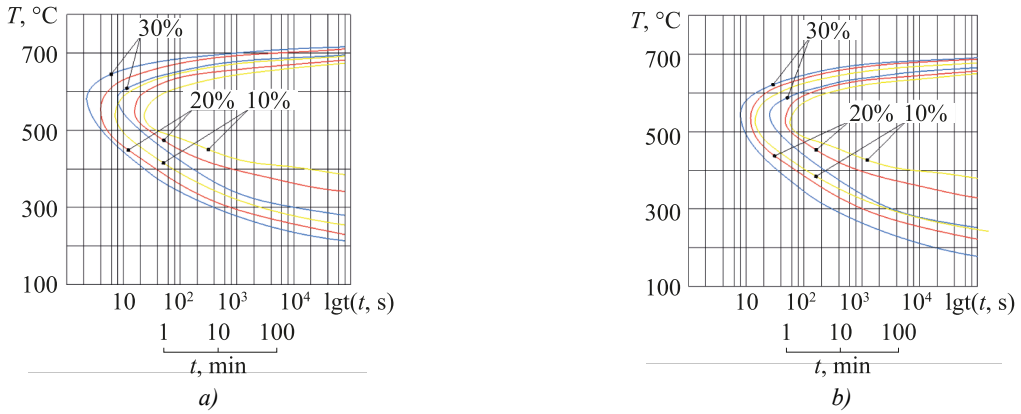


Fig. 8. Diagram of isothermal transformation of austenite samples with porosity of 10, 20, 30%: *a* — from steel PZhRV 2.200.26 + 0.8% C; *b* — from steel N4D2M + 0.8 %

When using an alloyed powder, the C-shaped curves shifted to the left and to the region of lower temperatures, which confirmed the theoretical position about the diffusive nature of the formation of a ferrite-cementite mixture during the decomposition of austenite. How did ultrafine additives (0.2 % Si_3N_4 and 1 % NiO) affect the decomposition of austenite? To determine this, experiments were conducted in the field of minimal austenite stability. The results are shown in Figure 9. The solid line is steel based on PZhRV 2.200.26 powder, the dashed line is steel based on N4D2M powder.

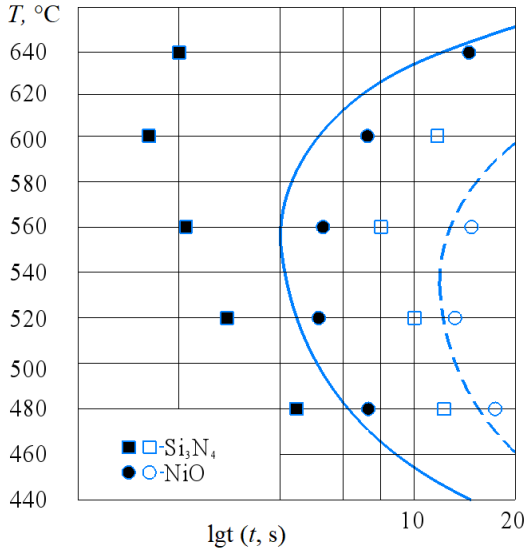


Fig. 9. The effect of ultrafine additives in steel based on PZhRV 2.200.26 powder (dashed markers) and in steel based on N4D2M powder (unshaded markers) on the initial phase of austenite decomposition

The addition of silicon nitride promoted the decomposition of austenite, increasing the temperature of the minimum stability of austenite, and shortening the incubation period [9]. This was due to the creation of areas of facilitated appearance of ferrite and iron carbide nuclei by the inclusions of the additive. The addition of nickel oxide led to an increase in the nickel content in the solid solution, which slowed down the diffusion processes and the decomposition of austenite.

It was shown in [10] that in the temperature range 700-600 °C austenite decomposed into lamellar perlite. At a temperature of minimal stability, the product of austenite decomposition was troostite, and in the temperature range from 500 to 250 °C, austenite transformation occurred with the formation of bainite.

In proeutectoid steels, the decomposition of austenite was preceded by the release of ferrite. At the same time, the pore surface was an area of predominant release and growth of ferritic inclusions, compared with high-angle boundaries [11]. Such a mechanism of nucleation of ferrite grains caused the absence of a Widmanstatten structure that

reduced mechanical properties. The release of the excess ferritic component occurred in stages. First, a micro-volume with a crystalline structure close to the equilibrium structure of ferrite was formed. Then this micro-volume was transformed into a stable center of a new phase by diffusive changes in the chemical composition [12].

The peculiarity of the powder structure of steel, namely the presence of free pore surfaces with increased diffusion mobility of atoms, led to the predominant nucleation of the ferritic phase on these surfaces, which was reflected in the displacement of C-curves of austenite transformation in the diagrams. Table 5 shows the mechanical properties of sintered PS (porosity 10%) depending on the temperature range of transformation [13].

Table 5

Mechanical properties of sintered powder steels

Steel composition	Temperature range, °C	Mechanical properties		
		$\sigma_в$, MPa	HRB	δ, %
PZhRV 2.200.26 + 0.8% °C	700–680	220	70	11
	650–630	260	82	13
	600–550	280	88	13
PZhRV 2.200.26 + 0.8% °C + 1% NiO	700–680	222	71	11
	650–630	262	83	12
	600–550	281	89	12
PZhRV 2.200.26 + 0.8% °C + 0.2% Si_3N_4	700–680	270	85	10
	650–630	290	90	10
	600–550	310	95	9
N4D2M + 0.8% °C	680–660	780	80	8
	630–600	795	83	9
	570–540	800	87	10
N4D2M + 0.8% °C + 1% NiO	680–660	850	92	11
	630–600	860	103	11
	570–540	880	106	12
N4D3M + 0.8% °C + 0.2% Si_3N_4	680–660	810	102	7
	630–600	860	105	8
	570–540	880	108	8

Discussion and Conclusion. As a result of the studies, it was found that increasing the cooling rate reduced the temperature range of austenite decomposition. This, in turn, led to an increase in the discreteness of the ferrite-cementite mixture, which resulted in an increase in tensile strength and hardness [14]. The addition of nickel oxide to the charge based on PZhRV 2.200.26 powder had a negligible effect on the mechanical properties of steel. The beneficial effect of this additive was manifested at the sintering stage, during which the oxide was reduced and nickel dissolved in the iron matrix. Cooling after sintering led to the formation of a pearlitic structure without metallographically detectable dispersed hardening inclusions. Therefore, during subsequent heat treatment based on austenite-pearlite transformation, there was no hardening effect from additional inclusions. When using N4D2M powder, the effect of the nickel oxide additive introduced into the charge was more noticeable. This circumstance was explained by the concentration of nickel in the ferritic component up to 5% and an increase in the efficiency of ferrite hardening with an increase in the nickel content in solid solution [15]. Unlike nickel oxide, silicon nitride particles that were added to the charge remained as inclusions in the steel's structure, contributing to the formation of new phase nucleation during austenite decomposition. This contributed to increased tensile strength and hardness through the effect of dispersion hardening [16]. The analysis of diagrams of isothermal transformations of austenite of powdered steels PZhRV 2.200.26 + 0.8%C and N4D2M + 0.8% with a porosity of 10, 20, 30% was carried out. When using an alloyed powder, the C-shaped curves shifted to the left and to the region of lower temperatures, which confirmed the theoretical position about the diffusive nature of the formation of a ferrite-cementite mixture during the decomposition of austenite. The dependencies of the mechanical properties of sintered powder steels with ultrafine particles on the temperature range of transformations were determined.

References

1. Petrosyan HS, Galstyan LZ. Peculiarities of Heat Treatment of the П40ХН - Gradepowder Steels with Improved Properties. *Proceedings of NPUA. Metallurgy, Material Science, Mining Engineering.* 2017;(2):40–48. (In Russ.)

2. Dorofeev YuG. Establishment, Formation, and Prospects for the Development of Novocherkassk Scientific School in the Field of Studying Functional Powdered Materials. *Powder Metallurgy and Functional Coatings.* 2008;(1):50–55. (In Russ.)

3. Shorshorov MKh, Gvozdev AE, Zolotukhin VI, Sergeev AN, Kalinin AA, Breki AD, et al. *Development of Advanced Technologies for the Production and Processing of Metals, Alloys, Powder and Composite Nanomaterials.* Monograph. Tula: TulSU Publishing House; 2016. 235 p. (In Russ.)

4. Dombrovskyi YuM, Stepanov MS. New Facilities of Surface Alloyage of Steels in Powder Environments. *Vestnik mashinostroeniya.* 2015;(8):79–81. (In Russ.)

5. Krokhalev AV, Kharlamov VO, Tupitsin MA, Kuzmin SV, Lysak VI. On the Possibility of Obtaining Hard Alloys from Mixtures of Carbide Powders and Metals by Explosive Compacting without Sintering. *Powder Metallurgy and Functional Coatings.* 2017;(2):22–30. https://doi.org/10.17073/1997-308X-2017-2-22-30 (In Russ.)

6. Shishka VG, Skorikov AV, Ivanova IV, Shishka NV. Selection of Alloying Elements to Improve the Machinability of Powder Structural Steels. *Engineering journal of Don.* 2018;4(51):11. URL: http://www.ivdon.ru/ru/magazine/archive/n4y2018/5307 (accessed: 20.06.2024). (In Russ.)

7. D'yachkova LN, Dechko MM. Influence of Dispersed Microadditives on the Structure and Properties of Powder Carbon and High-Chromium Steel. *Powder Metallurgy and Functional Coatings.* 2015;(2):8–14. https://doi.org/10.17073/1997-308X-2015-2-8-14 (In Russ.)

8. Pavlenko DV. Features of Sealing Sintered Titanium Alloys by Pressure Treatment Methods. *Obrabotka materialov davleniem.* 2017;(1):173–180. (In Russ.)

9. Bernshtein ML, Dobatkin SV, Kaputkina LM, Prokoshkin SD. *Diagrams of Hot Deformation, Structure and Properties of Steels*. Moscow: Metallurgiya; 1989. 544 p. (In Russ.)

10. Dyachkova LN. Features of the Formation of the Structure and Properties of Powder Steels with Additives that Activate Diffusion Processes during Sintering. *Proceedings of the National Academy of Sciences of Belarus. Physical-technical series.* 2020;65(1):45–53. https://doi.org/10.29235/1561-8358-2020-65-1-43-53 (In Russ.)

11. Egorov MS, Egorova RV, Meskhi BCh, Egorov SN. Development of Contact Surface during Sintering of Powder Steels. *Metallurg.* 2022;(10):74–79. https://doi.org/10.52351/00260827_2022_10_74 (In Russ.)

12. Dorofeyev VYu, Sviridova AN, Samoilov VA. Formation of Structure and Properties of Hot-Deformed Powder Steels Microalloyed with Sodium and Calcium in the Process of Thermal and Thermomechanical Treatment. *Russian Journal of Non-Ferrous Metals.* 2021;62(6):723–731 https://doi.org/10.3103/S1067821221060080

13. Egorov MS, Egorova RV, Egorov SN, Lyudmirskiy YuG, Baranov IV. Determination of Driving Migration Force of Interparticle Splice Surface of Powder Steels. *Zagotovitel'nye proizvodstva v mashinostroenii (kuznechno-pressovoe, liteinoe i drugie proizvodstva).* 2024;22(4):183–187. https://doi.org/10.36652/1684-1107-2024-22-4-183-187 (In Russ.)

14. Akhmetov AS, Eremeeva ZhV. Investigation of Structure of Sintered Blanks from Powder Mixture of R6M5K5 High-Speed Steel Containing Diffusion-Alloyed Powder. *Metallurg.* 2022;(3):57–60. (In Russ.)

15. Gostev AS, Gosteva EG, Gulevskii VA. The Role of Nanopowders in Alloy Modification. *Molodoi uchenyi.* 2010;1(11):53–55. (In Russ.)

16. Egorov MS, Egorova RV, Egorov SN. Sintered Steels Modified with Nanoscale Silicon Nitride. *Metallurg.* 2023;(3):36–41. https://doi.org/10.52351/00260827_2023_03_36 (In Russ.)

About the Authors:

Maxim S. Egorov, Cand. Sci. (Eng.), Associate Professor, Head of the Department of Materials Science and Metal Technology, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), SPIN-code: 2126-1642, ORCID, Scopus ID, aquavdonsk@mail.ru

Rimma V. Egorova, Cand. Sci. (Eng.), Associate Professor of the Department of Cybersecurity of Information Systems, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), SPIN-code: 8182-6940, ORCID, rimmaruminskaya@gmail.com

Vladimir Yu. Lopatin, Cand. Sci. (Eng.), Associate Professor of the Department of Powder Metallurgy and Functional Coatings, National Research Technological University MISIS (4, Leninsky Aave., building 1, Moscow, 119049, Russian Federation).

Claimed Contributorship:

MS Egorov: formulation of the basic concept, goals and objectives of the study, calculations, text preparation, conclusions formulation.

RV Egorova: academic advising, research results analysis, text revision, conclusions correction.

VYu Loptin: preparation of samples for studies of mechanical properties, analysis of the results of cooling rates and construction of mathematical dependencies.

Conflict of Interest Statement: **the authors do not have any conflict of interest.**

All authors have read and approved the final manuscript.

Об авторах:

Максим Сергеевич Егоров, кандидат технических наук, доцент, заведующий кафедрой материаловедения и технологии металлов Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), SPIN-код: 2126-1642, ORCID, Scopus ID, aquavdonsk@mail.ru

Римма Викторовна Егорова, кандидат технических наук, доцент кафедры кибербезопасности информационных систем Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), SPIN-код: 8182-6940, ORCID, rimmaruminskaya@gmail.com

Владимир Юрьевич Лопатин, кандидат технических наук, доцент кафедры порошковой металлургии и функциональных покрытий Национального исследовательского технологического университета «МИСиС» (119049, РФ, г. Москва, Ленинский пр., 4, стр. 1).

Заявленный вклад авторов:

М.С. Егоров: формирование основной концепции, цели и задачи исследования, проведение расчетов, подготовка текста, формирование выводов.

Р.В. Егорова: научное руководство, анализ результатов исследований, доработка текста, корректировка выводов.

В.Ю. Лоптин: подготовка образцов для исследований механических свойств, анализ результатов скоростей охлаждения и построение математических зависимостей.

Конфликт интересов: **авторы заявляют об отсутствии конфликта интересов.**

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 12.07.2024
Revised / Поступила после рецензирования 23.07.2024
Accepted / Принята к публикации 31.07.2024

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

UDC 669.716
https://doi.org/10.23947/2541-9129-2024-8-3-78-87

Original Empirical Research

Influence of Heat Treatment Modes on the Structure and Properties of Large-Sized Products of Advanced Aviation Equipment Made of Alloys of the Al-Zn-Mg-Cu System

Vladimir S. Muratov[1], **Nikolai S. Yakimov**[2] ✉
[1]Samata State Technical University, Samara, Russian Federation
[2]Aviaagregat JSC, Samara, Russian Federation
✉ andrej.bakin2013@yandex.ru

EDN: NTBOKI

Abstract

Introduction. High-strength aluminum-based alloys of the Al-Zn-Mg-Cu alloying system are commonly used in aircraft manufacturing. However, there is a need to address the issue of achieving the desired level of mechanical properties in large-scale parts made from these alloys during heat treatment. Additionally, studies on the evaluation of corrosion resistance during heat treatment are also essential. The aim of this work was to determine the modes of heat treatment to achieve the necessary values of mechanical properties and resistance to corrosion cracking of parts made of large-sized deformed blanks of alloys of the Al-Zn-Mg-Cu alloying system.

Materials and Methods. The research was conducted on parts made from forged 1933 alloy forgings and B93pch stamped blanks. The influence of heat treatment on the mechanical properties (strength, ductility, hardness) and microstructure, as well as electrical conductivity, was determined. Tensile tests were carried out both on samples subjected to heat treatment after cutting from forgings and stamped blanks, and on samples cut from massive templets that were heat treated together with the products. Electrical conductivity allowed us to assess the level of solid solution supersaturation and predict resistance to corrosion cracking.

Results. The results of the study showed the necessity of a differentiated approach to assigning the duration of aging stages, depending on the alloy grade, configuration, and dimensions of the products, as well as the requirements for the level of properties. Variants and modes of heat treatment were proposed for products made from alloys 1933 and B93pch, providing the necessary level of mechanical properties and resistance to corrosion cracking.

Discussion and Conclusion. Cases of inconsistency in strength properties in the longitudinal and transverse (in width) directions of the fiber of parts made from large-sized blanks of alloys 1933 and B93pch have been established. Modes and options for heat treatment of parts were proposed, allowing the achievement of the required values of mechanical properties and corrosion resistance. This provides for a halving of the aging time for alloy 1933 or an increase of 25% for alloy B95pch.

Keywords: aluminum alloys, large-sized products, heat treatment, structure, properties

Acknowledgements. The authors would like to thank the Editorial team of the Journal and anonymous reviewers for their competent expertise and valuable recommendations for improving the quality of the article.

For citation. Muratov VS, Yakimov NS. Influence of Heat Treatment Modes on the Structure and Properties of Large-Sized Products of Advanced Aviation Equipment Made of Alloys of the Al-Zn-Mg-Cu System. *Safety of Technogenic and Natural Systems.* 2024;8(3):78–87. https://doi.org/10.23947/2541-9129-2024-8-3-78-87

Оригинальное эмпирическое исследование

Влияние режимов термической обработки на структуру и свойства крупногабаритных изделий перспективной авиационной техники из сплавов системы Al-Zn-Mg-Cu

В.С. Муратов[1], **Н.С. Якимов**[2] ✉

[1]Самарский государственный технический университет, г. Самара, Российская Федерация

[2]АО «Авиаагрегат», г. Самара, Российская Федерация

✉ andrej.bakin2013@yandex.ru

Аннотация

Введение. Высокопрочные сплавы на алюминиевой основе системы легирования Al-Zn-Mg-Cu широко используются для изготовления деталей авиационной техники. Требует решения проблема достижения необходимого уровня механических свойств крупногабаритных деталей из сплавов этой системы легирования при термической обработке. Актуальны также исследования по оценке особенностей формирования коррозионных свойств в процессе реализации операций термической обработки. Цель данной работы — определить режимы термической обработки для достижения необходимых значений механических свойств и стойкости к коррозионному растрескиванию деталей из крупногабаритных деформированных заготовок сплавов системы легирования Al-Zn-Mg-Cu.

Материалы и методы. Исследования выполнены на деталях, изготавливаемых из поковок сплава 1933 и штампованных заготовок сплава В93пч. Определялось влияние режимов термической обработки на комплекс механических свойств (характеристики прочности, пластичности, твердости), микроструктуру и электропроводность сплавов. Испытания на растяжение реализовывались как на образцах, подвергнутых термической обработке после вырезки из поковок и штампованных заготовок, так и на образцах, вырезанных из массивных темплетов, которые подвергались термической обработке вместе с изделиями. Электропроводность позволяла оценивать степень пересыщенности твердого раствора и прогнозировать сопротивляемость сплава коррозионному растрескиванию.

Результаты исследования. Показана необходимость дифференцированного подхода к назначению длительности ступеней старения в зависимости от марки сплава, конфигурации и габаритов изделий, требований к уровню свойств. Предложены варианты и режимы термической обработки для изделий из сплавов 1933 и В93пч, обеспечивающие необходимый уровень механических свойств и сопротивляемости коррозионному растрескиванию.

Обсуждение и заключение. Установлены случаи несоответствия прочностных свойств в продольном и поперечном (по ширине) направлениях волокна деталей, изготавливаемых из крупногабаритных заготовок сплавов 1933 и В93пч. Предложены режимы и варианты термической обработки деталей, позволяющие достигать требуемых значений механических свойств и коррозионной стойкости, которые предусматривают сокращение в два раза (для сплава 1933) или увеличение на 25 % (для сплава В95пч) времени выдержки при ступенях старения.

Ключевые слова: алюминиевые сплавы, крупногабаритные изделия, термическая обработка, структура, свойства

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

Для цитирования. Муратов В.С., Якимов Н.С. Влияние режимов термической обработки на структуру и свойства крупногабаритных изделий перспективной авиационной техники из сплавов системы Al-Zn-Mg-Cu. *Безопасность техногенных и природных систем.* 2024;8(3):78–87. https://doi.org/10.23947/2541-9129-2024-8-3-78-87

Introduction. In the production of modern and promising aircrafts and helicopters of new generation, first and foremost, attention should be paid to the reliability and safety of flights and transportation [1], as well as the reduction in product weight [2]. This requires the use of high-strength alloys [3] with good fatigue resistance [4], fracture toughness [5], and corrosion resistance [6]. In recent years, high-strength aluminum alloys, in particular alloys 1933 and B93pch, have been widely used for the production of new promising civil aircrafts such as SSJ-NEW, MS-21, Tu-214, Il-96, etc. They are designed for the manufacture of critical power components of the aircraft — frames, traverse, fittings, rods, frames, housings, spars [7]. Aluminum high-strength alloys [8] of Al-Zn-Mg-Cu alloying system [9] are one of the main structural materials [10] for the manufacture of aviation equipment [11]. This group includes alloys of grades B93 [12], B93pch [13], B95 [14], B95och [15], B95pch [16], 1933. Alloy 1933 is a modification of alloy B93, not differing from B93 in terms of content of the main components. Alloy 1933 contains 0.12% Zr instead of Fe as an additive. Such a change in composition provides higher strength, fracture toughness and fatigue resistance, but alloy 1933 has a lower hardenability than alloy B93 [17].

One of the challenges in ensuring the successful operation of products made from alloys based on the Al-Zn-Mg-Cu system is ensuring sufficient corrosion resistance. Analysis of the corrosion damage processes in aluminum alloys has shown that the development of structural deterioration under the main corrosion mechanisms — corrosion cracking (CC) and intergranular damage — occurs in a similar manner. It should be noted that CC is mainly inherent in dispersion-hardened aluminum-based alloys. CC is not typical for alloys characterized by a reduced supersaturation of solid solution. The sensitivity to CC of alloys [15] of a certain alloying system depends on the number of alloying elements [17].

Susceptibility of aluminum alloys to CC reliably correlates with the degree of supersaturation of solid solutions and is significantly less dependent on the electron concentration and inhomogeneity of electrochemical potential that occurs during the decomposition of supersaturated solid solutions. The process of delayed destruction, occurring in mildly aggressive environments (for example, in air having a relative humidity of about 50%), develops at sufficiently high values of atomic concentration of elements used for alloying. Aluminum alloys of the Al-Zn-Mg-Cu alloying system have a 10 CC score, which means corrosion damage in mildly aggressive environments on uncut samples. At the same time, the main way to increase resistance to dangerous types of corrosion is the development and implementation of stepwise modes of softening aging (T2, T3)[1].

According to [18], reliable correlations of mechanical properties (yield strength $\sigma_{0,2}$ strength $\sigma_{в}$, elongation δ) and values of specific electrical conductivity γ were obtained for aluminum alloys hardened during heat treatment. It has been revealed that with a decrease in the specific electrical conductivity of such alloys, strength increases and ductility decreases. It should be borne in mind that the values of electrical properties are determined not only by the chemical composition of alloys, but also by the peculiarities of the state of the crystal lattice structure, which are formed by the modes of deformation and thermal treatments. All of the above makes it possible to evaluate corrosion resistance based on electrical conductivity values.

There is a problem with the formation of specified properties in large-sized parts made from alloys 1933 and B93pch, which are used for SSJ-NEW and Tu-214 aircraft, after heat treatment. It is also necessary to conduct research to assess the characteristics of how the level of mechanical and corrosion properties is formed in critical power components during heat treatment operations.

The aim of the authors of this article is to determine heat treatment modes to achieve the necessary values of mechanical properties and resistance to corrosion cracking of parts made of large-sized deformed blanks of alloys of the Al-Zn-Mg-Cu alloying system.

Materials and Methods. The research was conducted on parts made from large-sized forgings of the 1933 alloy produced at the Kamensk-Ural Metallurgical Plant, and stamped blanks made of the B93pch alloy produced at the Arkonik SMP (Samara). Figure 1 provides the dimensions of the forgings. The overall dimensions of the stamped blanks were 1790x980 mm. Chemical composition of the studied alloys is shown in Table 1.

Heat treatment of the products was carried out in electric furnaces PA-56 and PA-54. Microstructural studies were performed using an Olympus GX71 light microscope. Electrical conductivity measurements were conducted with a Constant K6 device. Mechanical properties were tested in accordance with GOST 1497-84. The test samples were made from templets (cut from blanks) of sizes 70×70×140 mm, which were heat-treated together with the products. Proportional cylindrical W type samples with initial diameters of 5 mm or 15 mm were used. Tensile tests of the samples were performed on a GURM-20 installation. The Brinell method was used to determine their hardness (GOST 9012–9, ISO 410–82)[2].

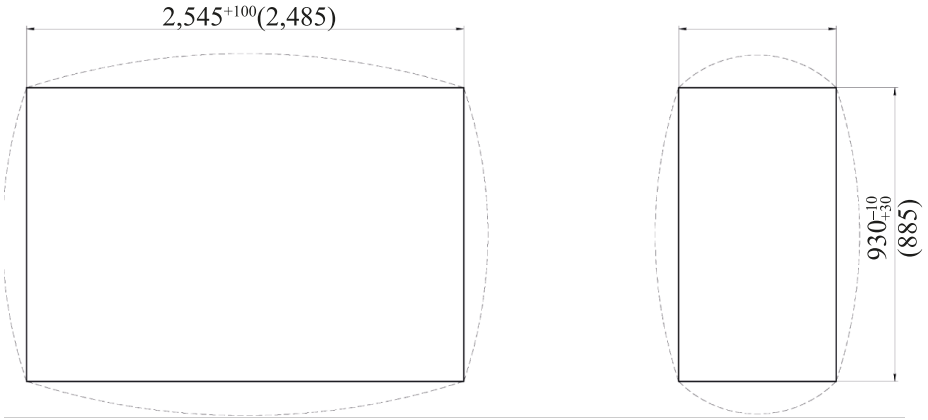


Fig. 1. Sketch of a large-sized forging made of alloy 1933

[1] GOST 1497–84. *Metals. Methods o f tension test.* Moscow: Standartinform; 2008. 26 p. URL: https://files.stroyinf.ru/Data2/1/4294852/4294852801.pdf (accessed: 29.04.2024). (In Russ.)

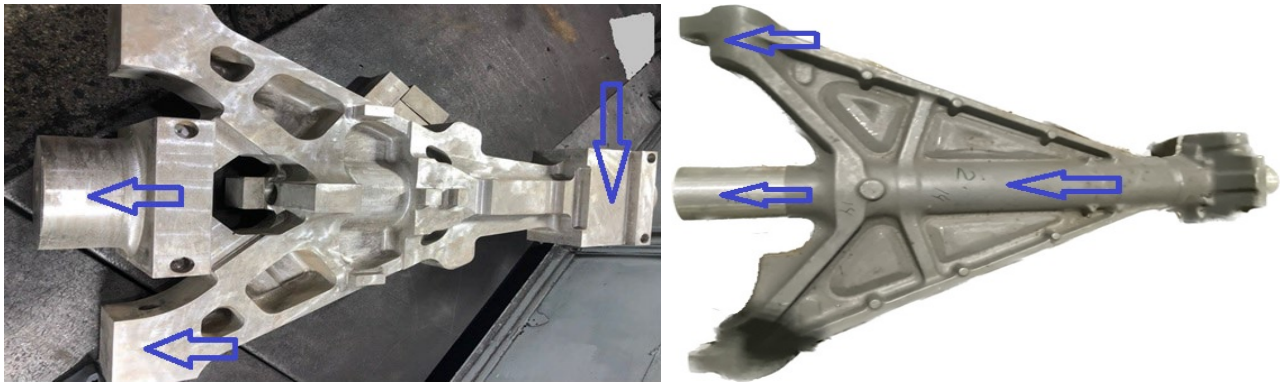
[2] GOST 9012–59. ISO 410–82 *Metals. Method of Brinell hardness measurement.* Moscow: Standartinform; 2008. 40 p URL: https://files.stroyinf.ru/Data2/1/4294850/4294850482.pdf (accessed: 29.04.2024). (In Russ.)

Table 1

Chemical composition of the studied alloys (wt., %)

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr	Be	Al
1933	0.020	0.090	0.900	0.010	1.800	0.010	6.500	0.400	0.040	0.001	Base
B93pch	–	0.310	1.000	–	1.900	–	6.700	0.010	–	–	Base

Figure 2 shows the parts subjected to hardening heat treatment (arrows indicate the places where the electrical conductivity of the alloy was measured).



a) *b)*

Fig. 2. Heat-treated parts: *a* — traverse made of 1933 alloy; *b* — frame of the shock-absorbing strut made of B93pch alloy

Results. Studies in the state as received (after annealing) of the macrostructure of forgings and stamped workpieces, fractures, and performed ultrasonic inspection did not reveal unacceptable deviations. The electrical conductivity of alloy 1933 was 24.7 mSm/m, and for alloy B93h — 23.5 mSm/m. Figure 3 shows the microstructure of the 1933 alloy in the delivery state. The grain structure of the alloy did not have a pronounced oriented character.

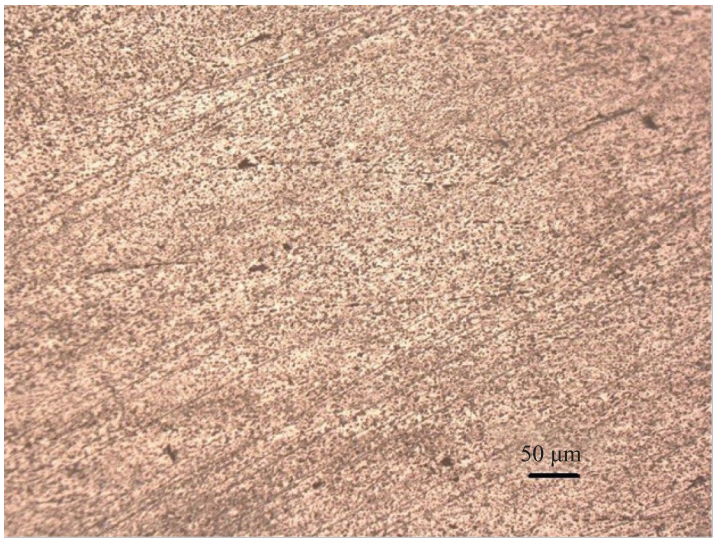


Fig. 3. Microstructure of alloy 1933 in the state as received

The characteristics of mechanical properties on longitudinal and transverse in width and transverse in thickness samples, which were made from forged and stamped blanks, were determined. Heat treatment of samples (standard version) was performed according to the following modes: alloy 1933 — the temperature of heating for quenching was 470 °C, cooling in water with a temperature of 75–85 °C, artificial aging: 1 stage — 110 °C (holding time 24 hours, air cooling), 2 stage — 180 °C (holding time 10–12 hours, cooling outdoors); alloy B93pch — quenching heating temperature 460 °C, holding time 180 minutes, cooling in water at a temperature of 75–85 °C, artificial aging: 1 stage — 120 °C (holding time — 8 hours, air cooling), 2 stage — 170 °C (holding time — 8 hours, air cooling). The results of the studies are shown in Table 2. It follows from the presented data that the values obtained after heat treatment of samples cut from forgings and stamped blanks comply with the requirements of regulatory documents (RD).

Table 2

Values of mechanical properties of heat-treated samples cut from forgings (alloy 1933) and stamped blanks (alloy B93pch)

Results of mechanical properties					RD Standard			
Fiber direction	$\sigma_в$, MPa	$\sigma_{0,2}$, MPa	δ, %	HB	$\sigma_в$, MPa	$\sigma_{0,2}$, MPa	δ,%, not less than	HB, not less than
Longitudinal	480 480	____ 433	17.0 11.2	149 163	440–530 430–500	390–470	7.0 7.0	110
Transverse in width	480 500	___ 457	12.2 8.0		430–530 430–500	390–470	5.0 5.0	
Transverse in thickness	490 470	–	8.1 3.5		420–500 430–500	–	3.0 3.0	

Note. The numerator contains the property values for alloy 1933, and the denominator — for alloy B93pch.

The technological process of manufacturing the products in question was multi-stage. After mechanical processing, hardening heat treatment was carried out on large-sized parts with complex geometries. After heat treatment of the parts according to traditional modes, a discrepancy in the indicators of RD mechanical properties was revealed. In this regard, a number of modes and options of heat treatment have been investigated (Table 3):

Mode No. 1 (1933) — a typical version of heat treatment of a “traverse” part made of alloy 1933 according to the production instructions;

Mode No. 2 (1933) — either a variant of repeated heat treatment carried out to correct the discrepancy in the level of properties after Mode No. 1 (1933), or a variant of heat treatment instead of Mode No. 1 (1933);

Mode No. 1 (B93) — a typical variant of heat treatment of a “frame” part made of B93pch alloy according to the production instructions;

Mode No. 2 (B93) — either a variant of repeated heat treatment carried out to correct the discrepancy in the level of properties after Mode No. 1 (B93), or a variant of heat treatment instead of Mode No. 1 (B93).

Table 3

Hardening heat treatment modes of “traverse” parts made of alloy 1933 and “frame” parts made of alloy B93

Heat treatment mode	Tempering	First stage of aging	Second stage of aging
Mode No. 1 (1933)	T = 470°C, starting point temperature — 455°C, holding time — 250 min., cooling medium — water, t_{water} = 75–85°C	T = 110°C, holding time — 24 h., cooling medium — air	T = 180°C, holding time — 10–12 h., cooling medium — air
Mode No. 2 (1933)	T = 470°C, starting point temperature — 455°C, holding time — 250 min., cooling medium — water, t_{water} = 75–85°C	T = 110°C, holding time — 12 h., cooling medium — air	T = 180°C, holding time — 6 h., cooling medium — air
Mode No. 1 (B93)	T = 460°C, starting point temperature — 445°C, holding time — 180 min., cooling medium — water, t_{water} = 75–85°C	T = 120°C, holding time 8 h., cooling medium — air	T = 170°C, holding time — 8 h., cooling medium —air
Mode No. 2 (B93)	T = 460 ºC, starting point temperature — 445 ºC, holding time — 180 min., cooling medium — water, t_{water} = 75–85°C	T = 120°C, holding time — 10 h., cooling medium — air	T = 175°C, holding time — 10 h., cooling medium — air

Table 4 shows the results of evaluating the mechanical properties after the studied modes and heat treatment options for alloy 1933. Mode No. 2 (1933), presented in Table 3, allows you to obtain the required mechanical properties corresponding to RD, and this mode can also be used as a repeated heat treatment to eliminate negative results after processing according to Mode No. 1 (1933) — an unacceptably low level of alloy strength in the longitudinal and transverse (width) direction of fiber.

Table 4

Results of mechanical properties tests after hardening heat treatment of the "traverse" part made of alloy 1933

Heat treatment mode	Mechanical properties			
	$\sigma_в$, MPa	$\sigma_{0,2}$, MPa	δ, %	HB
Longitudinal direction of fiber				
Mode No. 1 (1933)	430	370	10.1	129
Mode No. 2 (1933) (in re-processing option)	480	430	12.2	–
Mode No. 2 (1933) (in option of replacing Mode No. 1)	480	400	16.1	138
RD requirement	440–530	380–480	Not less than 7.0	Not less than 110
Transverse direction of fiber (in width)				
Mode No. 1 (1933)	420	370	13.2	129
Mode No. 2 (1933) (in re-processing option)	470	450	11.3	–
Mode No. 2 (1933) (in option of replacing Mode No. 1)	480	410	11.1	138
RD requirement	430–530	370–470	Not less than 4.0	Not less than 110
Transverse direction of fiber (in thickness)				
Mode No. (1933)	430	–	16.3	129
Mode No. 2 (1933) (in re-processing option)	480	–	16.2	–
Mode No. 2 (1933) (in option of replacing Mode No. 1)	460	–	10.4	138
RD requirement	420–500	–	Not less than 2.5	Not less than 110

Table 5 shows the results of evaluating the mechanical properties after the studied modes and heat treatment options for B93pch alloy.

Table 5

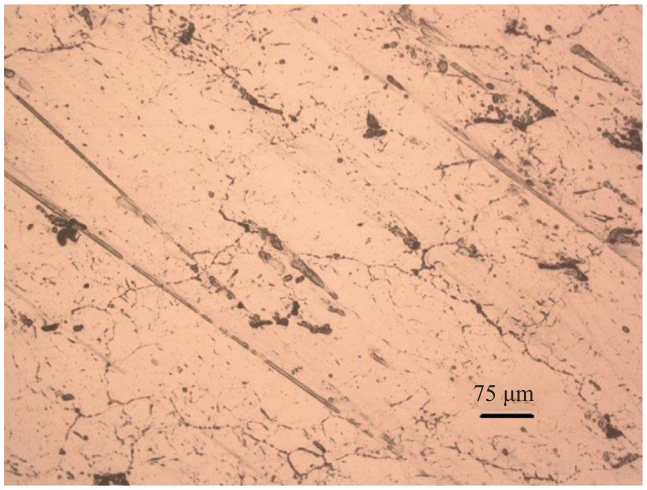
Results of mechanical properties test after hardening heat treatment of the "frame" part made of B93pch alloy

Heat treatment mode	Mechanical properties		
	$\sigma_в$, MPa	δ, %	HB
Longitudinal direction of fiber			
Mode No. 1 (B93)	510	12.4	163
Mode No. 2 (B93) (in re-processing option)	450	15.5	121
Mode No. 2 (B93) (in option of replacing Mode No. 1)	480	13.0	143
RD requirement	440–500	Not less than 7.0	Not less than 110
Transverse direction of fiber (in width)			
Mode No. 1 (B93)	510	7.2	163
Mode No. 2 (B93) (in re-processing option)	440	13.5	121
Mode No. 2 (B93) (in option of replacing Mode No. 1)	480	8.0	143
RD requirement	430–500	Not less than 4.0	Not less than 110
Transverse direction of fiber (in thickness)			
Mode No.1 (B93)	490	4.0	163
Mode No. 2 (B93) (in re-processing option)	431	9.0	121
Mode No. 2 (B93) (in option of replacing Mode No. 1)	480	8.0	143
RD requirement	420–500	Not less than 3.0	Not less than 110

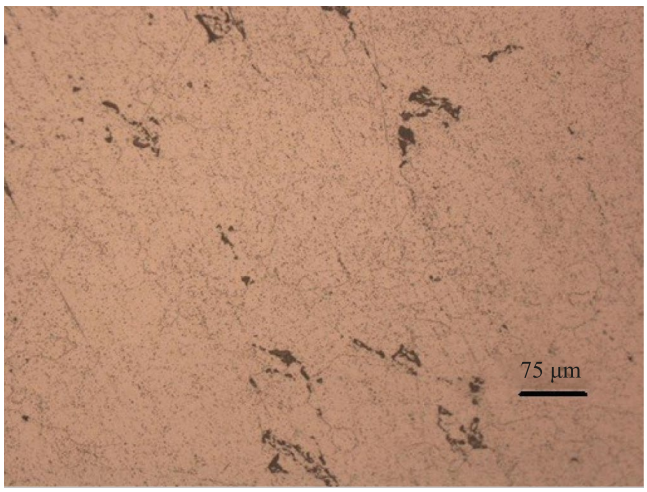
As it can be seen from the presented data, Mode No. 1 (B93) does not provide the required level of strength properties in the longitudinal and transverse (in width) directions of the fiber of the part. The level of properties is overestimated. At the same time, Mode No. 2 (B93) allows you to achieve the necessary property values when it is implemented both in the re-processing option and in the replacement option of Mode No. 1.

Thus, the longitudinal and transverse (in width) directions of fiber are the most sensitive to the influence of heat treatment modes in large-sized products made of alloys of the Al-Zn-Mg-Cu system. It is possible to achieve the required level of strength properties by correcting the aging modes of alloys — either by reduction (alloy 1933) or by increase (alloy B93pch) of duration.

The performed microstructural studies confirmed the absence of signs of burnout after quenching during processing in all modes and variants of heat treatment. Figure 4 shows the microstructure of the studied alloys after hardening heat treatment according to Mode No. 2 (1933) and Mode No. 2 (B93pch) (in options of replacing Mode No. 1). Since significantly longer aging was used during heat treatment of alloy B93pch, dispersed particles of strengthening phases are detected in the microstructure.



a)



b)

Fig. 4. Structure of alloys after hardening heat treatment according to the modes:
a — Mode No. 2 (1933); *b* — Mode No. 2 (B93pch) (in options of replacing Mode No. 1)

The authors conducted studies on electrical conductivity of alloys 1933 and B93pch after different modes and variants of heat treatment. Based on the results of these studies, it was possible to evaluate the P.1.22 extent of decomposition of the supersaturated solid solution under different aging conditions, as well as the corrosion resistance of the alloy, according to TU 1-804-475-2008. According to the RD requirements, in order to confirm satisfactory corrosion resistance on semi-finished products made of alloy 1933 in the T2 and T3 states, electrical conductivity index (ϒ) should be at least 22.5 mSm/m in the T2 state and at least 23.5 mSm/m in the T3 state; for alloy B93pch, the electrical conductivity index should be within the range of 21–25 mSm/m. Electrical conductivity measurements were carried out by the device on the most massive parts of the part (indicated by arrows in Fig. 2). In the state of delivery, the electrical conductivity of alloy B93pch was 22.7–23.8 mSm/m. The measurement results are presented in Table 6.

Table 6

Values of electrical conductivity at various stages of hardening heat treatment of alloys 1933 and B93pch

Heat treatment mode	Condition of the workpiece during heat treatment	Electrical conductivity, mSm/m
Mode No. 1 (1933) Mode No. 1 (B95)	After tempering	18.5–18.6
	After the 1st stage of aging	19.6–19.8
	After the 2nd stage of aging	25.1–25.9 23.5–23.6
Mode No. 2 (1933) Mode No. 2 (B95) (in re-processing option)	After tempering	18.5–18.6
	After the 1st stage of aging	19.6–19.7
	After the 2nd stage of aging	25.1–25.7 24.2–25.0
Mode No. 2 (1933) Mode No. 2 (B95) (in option of replacing Mode No. 1)	After tempering	18.5–18.7
	After the 1st stage of aging	19.6–19.7
	After the 2nd stage of aging	25.2–25.7 24.3–25.0

As follows from the above data, as the processes of decomposition of a supersaturated solid solution develop during aging, there is an increase in the electrical conductivity of the alloy, which is associated with a decrease in supersaturation of a crystal lattice with atoms of alloying elements. At the same time, despite the shortened duration of aging in the first and second stages, when implementing Mode No. 2 (1933), the values of electrical conductivity practically coincide with the values after Mode No. 1 (1933). This indicates a sufficiently high degree of decomposition of the supersaturated solid solution at the stages of aging during treatment according to Mode No. 2 (1933). The values of electrical conductivity of the alloy confirm its sufficient CC resistance. The electrical conductivity of alloy B93pch also meets the RD requirements.

Discussion and Conclusion. During hardening heat treatment of SSJ-NEW and TU 214 aircraft parts made from large-sized forgings of the 1933 alloy and stamped blanks of the B93pch alloy, cases of inconsistency of strength properties in the longitudinal and transverse (in width) directions of fiber of the parts were revealed.

It is shown that, depending on the configuration and dimensions of parts, the levels of the required characteristics of mechanical properties of aging stages duration should be assigned differentially. The modes and options of heat treatment of parts using a shortened (for alloy 1933) or increased (for alloy B95pch) holding time at aging stages are proposed, which allows you to ensure the necessary level of mechanical properties and resistance to corrosion cracking of large-sized products.

The studies conducted to investigate the effect of implementing different heat treatment stages on the electrical conductivity of the 1933 alloy have confirmed the achievement of an adequate level of decomposition of the supersaturated solid solution with the use of a shortened aging period for this alloy. This approach provides the necessary strength and corrosion resistance levels. By extending the aging time for the B93pch alloy, a higher level of electrical conductivity can be achieved.

References

1. *Mechanical Engineering. Non-Ferrous Metals and Alloys. Composite Metal Materials.* Encyclopedia. In 40 vol. Vol. II–3. Moscow: Mashinostroenie; 2001. 880 p. (In Russ.)

2. Kablov EN. Strategical Areas of Developing Materials and Their Processing Technologies for the Period up to 2030. *Aviation Materials and Technologies.* 2012;(S):7–17. (In Russ.)

3. Kablov EN, Antipov VV, Odolodkova YuS, Odolodkov MS. Experience and Application Prospects of Aluminum-Lithium Alloys in Aircraft and Space Technology. *Metallurg.* 2021;(1):62–70. URL: https://library.bmstu.ru/Publications/Home/AuthorPublications/c00e1744-db59-4d2f-9f79-1e9e757d5105 (accessed: 29.04.2024). (In Russ.)

4. Fridlyander IN. *Memories of the Creation of Aerospace and Nuclear Technology from Aluminum Alloys*. 2-nd ed. Moscow: Nauka; 2006. 275 p. URL: https://elib.biblioatom.ru/text/fridlyander_vospominaniya_2006/p12/ (accessed: 29.04.2024). (In Russ.)

5. Antipov VV, Senatorova OG, Tkachenko EA, Vakhromov PO. Aluminium Wrought Alloys. *Aviation Materials and Technologies.* 2012;(S):167–182. (In Russ.)

6. Antipov VV, Senatorova OG, Sidelnikov VV, Popov VI, Blinova NE. Development and Application of High-Strength Alloys of the Al-Zn-Mg-Cu-Zr System for Aviation and Rocket Technology. In: *Proceedings of the International scientific and technical conference "Development of the fundamentals of materials science of light alloys and composite materials based on them for the creation of aerospace and nuclear engineering products".* Moscow: All-Russian Scientific Research Institute of Aviation Materials of the National Research Center "Kurchatov Institute"; 2013. P. 51. (In Russ.)

7. Kablov EN. Quality Control of Materials is a Guarantee of the Safety of Aviation Equipment Operation. *Aviation Materials and Technologies.* 2001:(1);3–8. (In Russ.)

8. Senatorov OG, Antipov VV, Bronz AV, Somov AV, Serebrennikova NYu. High-Strength and Super High-Strength Conventional Al-Zn-Mg-Cu System-Based Alloys, Their Role in Engineering and Possibility of Development. *Tekhnologiya legkikh splavov.* 2016;4:43–49. (In Russ.)

9. Kai Wen, Yunqiang Fan, Guojun Wang, Longbin Jin, Xiwu Li, Zhihui Li, et al. Aging Behavior and Precipitate Characterization of a High Zn-Containing Al–Zn–Mg–Cu Alloy with Various Tempers. *Materials & Design.* 2016;101:16–23. http://doi.org/10.1016/j.matdes.2016.03.150

10. Kablov EN. Innovative Developments of FSUE "VIAM" SSC of RF on Realization of "Strategic Directions of the Development of Materials and Technologies of Their Processing for the Period until 2030". *Aviation Materials and Technologies*. 2015;1(34):3–33. URL: https://journal.viam.ru/ru/system/files/uploads/pdf/2015/2015_1_1_1.pdf (accessed: 29.04.2024). (In Russ.)

11. Antipov VV. Prospects for Development of Aluminium, Magnesium and Titanium Alloys for Aerospace Engineering. *Aviation Materials and Technologies.* 2017;(S):186–194. https://doi.org/10.18577/2071-9140-2017-0-S-186-194 (In Russ.)

12. Kablov EN. New Generation Materials and Technologies for Their Digital Processing. *Herald of the Russian Academy of Sciences.* 2020;90(4):331–334. https://doi.org/10.31857/S0869587320040052 (In Russ.)

13. Fridlyander IN. Modern Aluminum, Magnesium Alloys and Composite Materials Based on Them. *Metallovedenie i termicheskaya obrabotka metallov.* 2002;(7):24–29. (In Russ.)

14. Nechaykina TA, Blinova NE, Ivanov AL, Kozlova OYu, Kozhekin AE. Research of the Effect of Homogenization and Quench Hardening Modes on the Structure and Mechanical Properties of Retail Rings From Alloy B95o.ch.-T2. *Proceedings of VIAM.* 2018;10(70):27–36. https://doi.org/10.18577/2307-6046-2018-0-10-27-36 (In Russ.)

15. Senatorova OG, Serebrennikova NYu, Antipov VV, Ivanov AL, Popov VI. Investigation of the Structure and Properties of an 80 mm Thick Plate Made of B95 p.chT2 Alloy. *Tekhnologiya legkikh splavov.* 2016;(2):37–42. (In Russ.)

16. Nechaikina TA, Oglodkov MS, Ivanov AL, Kozlova OYu, Yakovlev SI, Shlyapnikov MA. Features of Quenching of Wide Cladding Clad Sheets Made of Aluminum Alloy B95p.ch on a Continuous Heat Treatment Line. *Proceedings of VIAM.* 2021;(11(105)):25–33. https://doi.org/10.18577/2307-6046-2021-0-11-25-33 (In Russ.)

17. Ovsyannikov BV. Beware of Grain Refinement. *Materials Science Forum.* 2014;794–796:143–148. http://dx.doi.org/10.4028/www.scientific.net/MSF.794-796.143

18. Leonov VV, Nikiforov AG, Kovaleva AA. Identification of Correlations between Physical Properties of Aluminum Alloys. *Fundamental research.* 2017;(7):44–48. URL: https://elibrary.ru/item.asp?id=29771980&ysclid=lxeg34pp2m868169526 (In Russ.)

About the Authors:

Vladimir S. Muratov, Dr. Sci. (Eng.), Professor of the Department of Metallurgy, Powder Metallurgy, Nanomaterials, Samara State Technical University (244, Molodogvardeyskaya St., Samara, 443100, RF), SPIN-code: 1341–1718, ORCID, ResearcherID, muratov1956@mail.ru

Nikolai S. Yakimov, Cand. Sci. (Eng.), Leading Engineer of Aviaagregat JSC (55, Zavodskoe highway, Samara, 443009, RF), SPIN-code: 7371-3706, ORCID, ResearcherID, andrej.bakin2013@yandex.ru

Claimed Contributorship:

VS Muratov: academic advising, research results analysis, text revision, conclusions correction.

NS Yakimov: formulation of the basic concept, goals and objectives of the study, conducting tests, text preparation, conclusions formulation.

Conflict of Interest Statement: **the authors do not have any conflict of interest.**

All authors have read and approved the final manuscript.

Об авторах:

Владимир Сергеевич Муратов, доктор технических наук, профессор кафедры металловедения, порошковой металлургии, наноматериалов Самарского государственного технического университета (443100, Российская Федерация, г. Самара, ул. Молодогвардейская, 244), SPIN-код: 1341-1718, ORCID, ResearcherID, muratov1956@mail.ru

Николай Сергеевич Якимов, кандидат технических наук, ведущий инженер АО «Авиаагрегат» (443009, Российская Федерация, г. Самара, Заводское шоссе, 55), SPIN-код: 7371-3706, ORCID, ResearcherID, andrej.bakin2013@yandex.ru

Заявленный вклад авторов:

В.С. Муратов: научное руководство, анализ результатов исследований, доработка текста, корректировка выводов.

Н.С. Якимов: формулирование основной концепции, целей и задач исследования, проведение испытаний, подготовка текста, формулирование выводов.

Конфликт интересов: **авторы заявляют об отсутствии конфликта интересов.**

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 29.05.2024
Revised / Поступила после рецензирования 13.06.2024
Accepted / Принята к публикации 17.06.2024

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

UDC 621.762
https://doi.org/10.23947/2541-9129-2024-8-3-88-96

Original Empirical Research

Influence of Chemical Composition of Abrasive Materials and Strength of Interlayer Boundaries on Impact and Abrasive Wear Resistance of Layered Composite Materials

Markiz A. Ismailov
Platov South-Russian State Polytechnic University (NPI), Novocherkassk, Russia
✉ al_myalim@mail.ru

EDN: ZNNPJE

Abstract

Introduction. Parts of machines and mechanisms that operate in various conditions and come into contact with abrasive particles can quickly wear out and fail. This is especially true for the hydraulic block of a drilling pump, which, due to intense wear, must be replaced after only 5–10 hours of use when pumping heavy drilling fluids. The analysis of scientific literature and experience with drilling pump operation shows that current methods for increasing the wear resistance of structural steels against abrasive and impact-abrasive forces are ineffective. Thus, it is an urgent task to enhance these properties through improved design and manufacturing techniques for drilling pump components, which would reduce the cost of production, repairs, and maintenance. The aim of this work is to study the effect of chemical composition of abrasive particles and the strength of the interlayer boundaries of "wear-resistant steel — rubber" on the impact and abrasive wear resistance of layered composite materials.

Materials and Methods. Layered composite materials (LCMs) consisted of: a wear-resistant layer of 40X steel and a rubber layer of BK-1675N butyl rubber. The impact and abrasive wear resistance of the LCMs was studied in accordance with GOST 23.207–79 on a special installation. A mixture of silicon oxide and aluminum was used as an abrasive material. The microstructure of the SCMs surface, as well as the chemical and phase composition of the abrasive particles, were analyzed using equipment from the Common Use Center "Nanotechnology" of Platov South-Russian State Polytechnic University (NPI). The adhesive strength between the layers of the LCMs was determined using a custom-built installation.

Results. The results of the study revealed that the wear resistance of the LCMs was several times higher than that of steels used for manufacturing parts resistant to abrasive particles. During the wear process, solid particles of aluminum and silicon oxides actively embed in the surface of the LCMs, increasing the intensity of wear. In contrast, less solid particles of magnesium and calcium aluminates were destroyed and fixed in formed defects on the LCM surface, slightly reducing wear intensity. It was also found that, when SCM layers were joined by hot vulcanization under pressure with a copper concentration of 25–30% in sintered P40X steel, adhesive strength increased to 0.93 MPa.

Discussion and Conclusion. The developed SCMs make it possible not only to increase the abrasive and impact-abrasive wear resistance, but also to use cheaper grades of steels as a wear-resistant layer. The proposed method of joining the SCM layers from sintered steels eliminates the need for additional surface machining and the use of special adhesives. Such SCMs can be used in the assemblies of machine parts and mechanisms that are operated in conditions of abrasive and shock-abrasive wear.

Keywords: impact and abrasive wear resistance, layered composite material, drilling pumps, elastic-dissipative substrate, adhesive strength

Acknowledgements. The author 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. Ismailov MA. Influence of Chemical Composition of Abrasive Materials and Strength of Interlayer Boundaries on Impact and Abrasive Wear Resistance of Layered Composite Materials. *Safety of Technogenic and Natural Systems.* 2024;8(3):88–96. https://doi.org/10.23947/2541-9129-2024-8-3-88-96

Оригинальное эмпирическое исследование

Влияние химического состава абразива и прочности межслойных границ на ударно-абразивную износостойкость слоистых композиционных материалов

М.А. Исмаилов
Южно-Российский государственный политехнический университет имени М.И. Платова, г. Новочеркасск, Российская Федерация
✉ al_myalim@mail.ru

Аннотация

Введение. Детали машин и механизмов, эксплуатируемые в различных условиях, при контакте с абразивными частицами быстро изнашиваются и выходят из строя. Например, при перекачке тяжелых буровых растворов из-за интенсивного изнашивания детали гидравлического блока бурового насоса через 5–10 часов работы необходимо менять. Анализ научных публикаций и опыт эксплуатации буровых насосов указывают на то, что существующие способы повышения износостойкости конструкционных сталей при абразивном и ударно-абразивно воздействии малоэффективны. Поэтому актуальной задачей является повышение этих свойств в результате совершенствования конструкции и технологии изготовления деталей буровых насосов, что позволит снизить затраты на производство их комплектующих, ремонт и обслуживание. Целью данной работы является исследование влияния химического состава абразивных частиц и прочности межслойных границ «износостойкая сталь — резина» на ударно-абразивную износостойкость слоистых композиционных материалов.

Материалы и методы. Слоистые композиционные материалы (СКМ) состояли из износостойкого слоя стали 40Х и резинового слоя бутилкаучука марки БК-1675Н. Ударно-абразивную износостойкость СКМ рассматривали в соответствии с ГОСТ 23.207–79 на специальной установке. В качестве абразивного материала была взята смесь оксида кремния и алюминия. Изучение микроструктуры поверхности СКМ, химического и фазового состава абразивного порошка проводили на оборудовании ЦКП «Нанотехнологии» ЮРГПУ (НПИ). Адгезионную прочность межслойных границ СКМ исследовали на разработанной для этой цели установке.

Результаты исследования. В результате исследований СКМ на ударно-абразивный износ выявлено, что их износостойкость в несколько раз выше, чем у сталей, используемых для изготовления деталей, устойчивых к воздействию абразивных частиц. Выявлено, что в процессе изнашивания твердые частицы оксидов алюминия и кремния активно внедряются в поверхность СКМ, увеличивая интенсивность износа, тогда как менее твердые частицы алюминатов магния и кальция при ударе разрушаются и закрепляются в образовавшихся дефектах на поверхности СКМ, незначительно снижая интенсивность износа. Установлено, что при соединении слоев СКМ методом горячей вулканизации под давлением и концентрации меди 25–30 % в спеченной стали П40Х адгезионная прочность повышается до 0,93 МПа.

Обсуждение и заключение. Разработанные СКМ позволяют не только повысить абразивную и ударно-абразивную износостойкость, но и в качестве износостойкого слоя использовать более дешевые марки стали. Предложенный способ соединения слоев СКМ из спеченных сталей исключает необходимость в дополнительной механической обработке поверхности и в использовании специальных клеящих составов. Такие СКМ могут использоваться в узлах деталей машин и механизмов, которые эксплуатируют в условиях абразивного и ударно-абразивного износа.

Ключевые слова: ударно-абразивная износостойкость, слоистый композиционный материал, буровые насосы, упруго-диссипативная подложка, адгезионная прочность

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

Для цитирования. Исмаилов М.А. Влияние химического состава абразива и прочности межслойных границ на ударно-абразивную износостойкость слоистых композиционных материалов. *Безопасность техногенных и природных систем.* 2024;8(3):88–96. https://doi.org/10.23947/2541-9129-2024-8-3-88-96

Introduction. The main reason for the decrease in the operational reliability of parts and mechanisms in mining [1], oil and gas [2], construction, road and processing industries [3] is the impact of various types of wear, such as abrasive, shock-abrasive, corrosive, and fatigue and others [4]. For example, scientific research and operational experience with drilling pumps have shown that the hydraulic block components are more susceptible to abrasive and shock-abrasive wear.

The analysis of scientific publications has shown that materials developed for operation in impact and abrasive wear conditions must have high hardness, viscosity and wear resistance [5]. However, the experience of operating drilling pumps [6] indicates that one of the reasons for the decrease in the operational reliability of valve parts is the low impact and abrasive wear resistance of structural steels [7] and sealing elastic elements [8]. Therefore, an urgent task is to develop a technology for producing layered composite materials in which one of the layers is made of a wear-resistant material, and the other is made of an elastic-dissipative one, for example, based on rubber mixtures, which allows absorbing part of the impact energy acting on the part.

Materials and Methods. Layered samples were made for testing, one layer of which was made of wear-resistant steel (Fig. 1, pos. 1), and the other, elastic layer was made of BK-1675N butyl rubber (Fig. 1, pos. 2). As wear-resistant steel, we used:

– rolled steel 40X, which was subjected to heat treatment — quenched at 860°C with oil cooling and tempered at 200 and 570°C with air cooling;

– sintered and hot-formed steel P40X.

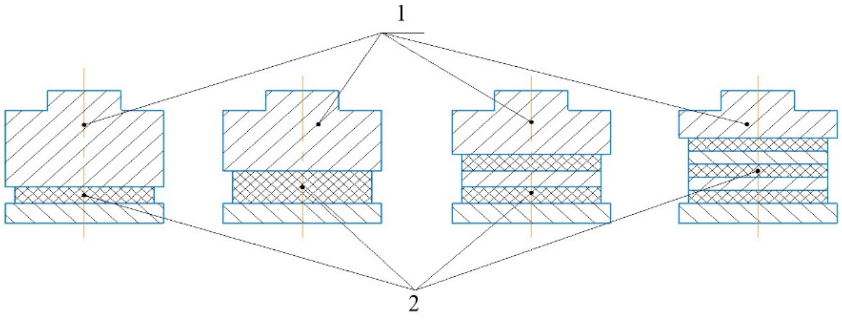


Fig. 1. Samples of LCMs for testing for impact and abrasive wear resistance:
1 — wear-resistant material; 2 — elastic-dissipative substrate

The impact and abrasive wear resistance of layered samples was tested in accordance with GOST 23.207-79[1] on a special installation [9]. The principle of operation of the installation was based on the forced impact of the sample on the counterbody through a layer of abrasive. The wear of the samples was estimated by the lost mass after 1000 strokes on analytical scales OHAUS Pioneer PA [10].

GOST 23.207–79 “Ensuring of wear resistance of products. Testing of engineering materials for impact abrasive wear” recommends to use silicon carbide as an abrasive to compare the abrasive and impact-abrasive wear resistance of various materials. However, in relation to the specific operating conditions of machines and mechanisms, GOST allows the use of an appropriate abrasive material. For example, to increase the density of drilling fluids, various weights are used, the choice of which will depend on the specific drilling conditions. In the case where weights with greater abrasiveness are required, various abrasive materials are used [11]. Therefore, a mixture of silicon and aluminum oxides was used as an abrasive when testing for impact and abrasive wear resistance.

Microstructure of the LCMs surface after testing for impact and abrasive wear resistance, X-ray studies and qualitative phase analysis of the abrasive powder were carried out at the Common Use Center “Nanotechnology” of Platov South-Russian State Polytechnic University (NPI).

To study the adhesive strength, the samples of rolled steel 40X, sintered and hot-deformed steel P40X were glued to rubber in two ways: with an adhesive based on chloroprene rubber and by hot vulcanization under pressure at a temperature of 160°C for 20 minutes without glue [12]. The adhesive strength of the interlayer boundaries of LCMs was studied using the installation developed for this purpose [13].

Results. Tests with impact energy from 3 to 23 J showed that 40X steel samples wear significantly more after improvement than samples after low tempering (Fig. 2, curves 1 and 3). At the same time, the use of elastic-dissipative substrate (UDS) reduced wear by 1.5–2 times (Fig. 2, curves 2 and 4), compared with samples that were tested without a substrate (Fig. 2, curves 1 and 3).

[1] GOST 23.207-79. *Ensuring of wear resistance of products. Testing of engineering materials for impact abrasive wear.* URL: https://docs.cntd.ru/document/1200010682 (accessed: 22.05.2024). (In Russ.)

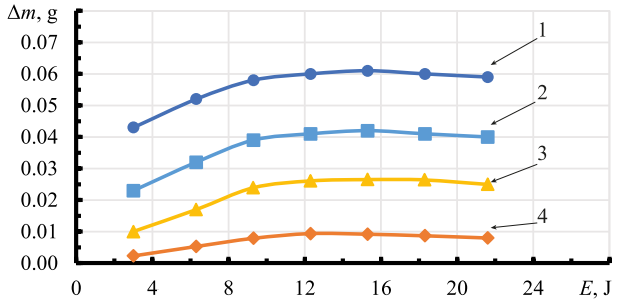
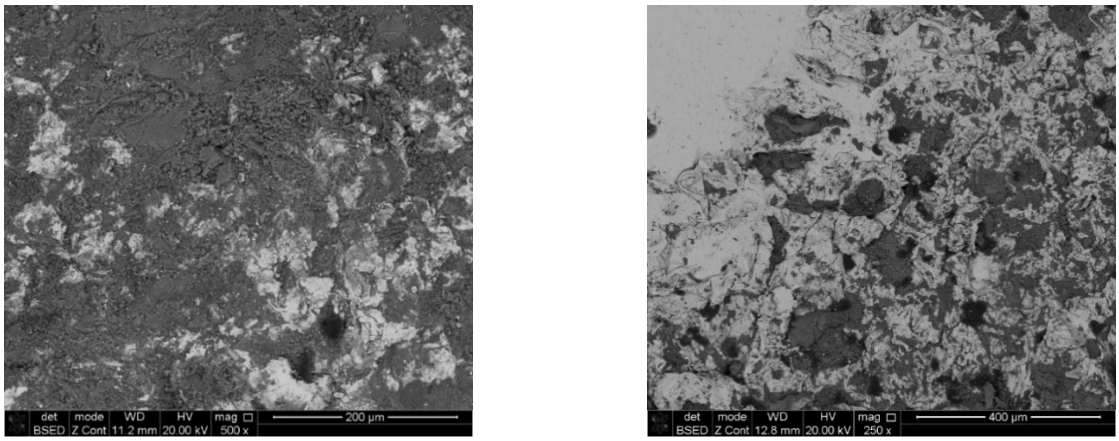


Fig. 2. Dependence of wear (Δm) on impact energy (E) without (1, 3) and with a rubber substrate (2, 4) LCMs with a working layer of 40X steel after improvement (1, 2) and low tempering (3, 4)

In Figure 2, it can be seen that with an increase in the impact energy, the wear intensity of the samples changed, and two sections could be distinguished. At the first stage, with an increase in the impact energy to 12 J, the wear of the samples increased as a result of the introduction of abrasive particles into their surface (Fig. 3 *a*) and into the grain boundaries (Fig. 3 *b*), which contributed to intensive chipping of micro-volumes of metal. In the second section, with a further increase in the impact energy, as a result of plastic deformation, the upper layer of the sample was strengthened, and abrasive particles, collapsing, loaded its surface, resulting in a slight slowdown in the intensity of wear.



a) *b)*

Fig. 3. Microstructure of the working layer surface made of improved 40X steel:
a — in the steady state of wear; *b* — at the stage of intensive wear

X-ray phase analysis showed that the abrasive powder mainly consisted of aluminum and silicon oxides, magnesium and calcium aluminates (Fig. 4). Phase composition of the abrasive did not change after wear resistance tests.

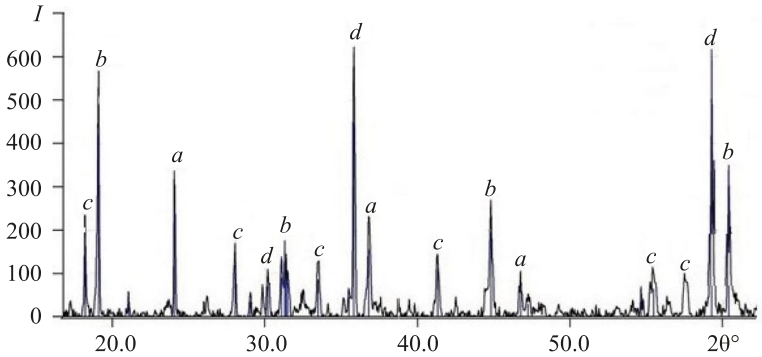
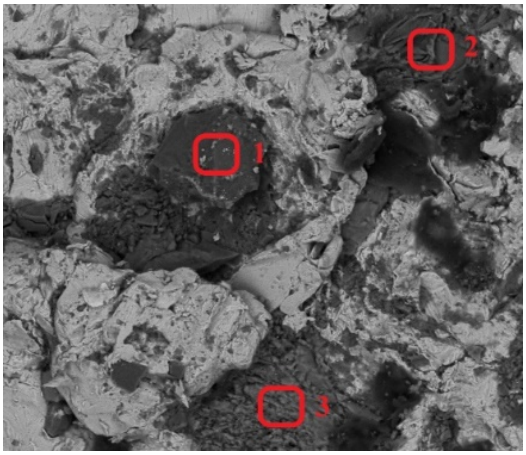


Fig. 4. Phase composition of the abrasive powder used in tests for impact and abrasive wear:
a — SiO_2; *b* — $MgAl_2O_4$; *c* — $CaAl_2O_4$; *d* — Al_2O_3

After the impact resistance test, there were areas with particles of silicon and aluminum oxides on the surface of 40X steel rings, which, penetrating into the surface of the sample, formed wells and activated the destruction process at the initial stage (Fig. 5 *a*). Magnesium aluminate particles (Fig. 5 *a*, pos. 2) due to the lower hardness (Mohs scale hardness 7.5–8), compared with aluminum oxide particles (Mohs scale hardness 9), with increasing impact energy, partially penetrated into the surface of the sample, and most of them were destroyed. Calcium aluminate particles

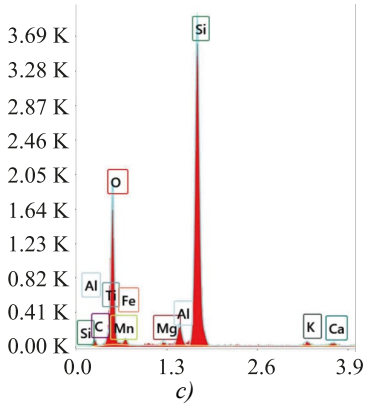
(Fig. 5 *a*, pos. 3) due to low hardness, at all values of the impact energy, actively loaded the LCMs surface (Fig. 3 *a*). Figures 5 *b–g* provide chemical composition of the test surface in the abrasive particles area.



a)

Element	Weight %	MDL	Atomic %	Error %
C K	3.4	2.30	5.8	31.7
O K	45.8	0.35	59.5	10.3
Mg K	0.7	0.15	0.6	17.0
Al K	2.7	0.13	2.1	8.9
Si K	38.1	0.11	28.2	5.1
K K	1.0	0.25	0.5	19.3
Ca K	0.9	0.24	0.5	21.2
Ti K	1.0	0.34	0.4	18.2
Mn K	0.8	0.38	0.3	29.0
Fe K	5.6	0.41	2.1	7.1

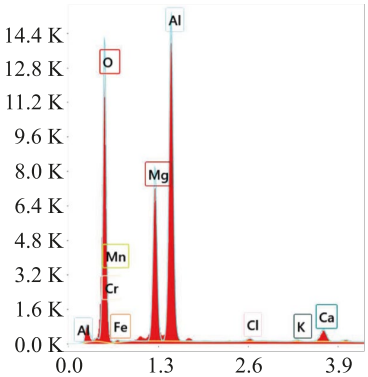
b)



c)

Element	Weight %	MDL	Atomic %	Error %
O K	42.8	0.08	57.0	9.2
Mg K	15.4	0.06	13.5	7.0
Al K	31.9	0.07	25.2	6.7
Cl K	0.4	0.08	0.2	19.7
K K	0.3	0.10	0.1	21.8
Ca K	2.1	0.11	1.1	5.5
Cr K	4.6	0.16	1.9	4.2
Mn K	0.3	0.20	0.1	35.0
Fe K	2.2	0.19	0.8	6.5

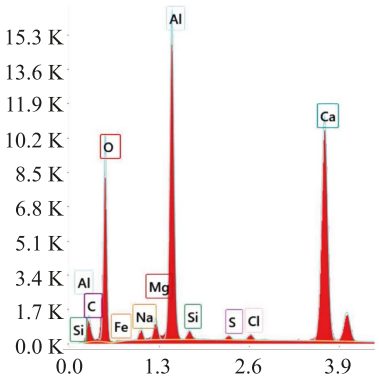
d)



e)

Element	Weight %	MDL	Atomic %	Error %
C K	6.1	0.34	10.5	12.7
O K	45.5	0.12	58.8	10.5
Na K	1.4	0.09	1.3	11.4
Mg K	1.5	0.05	1.2	9.1
Al K	18.6	0.05	14.2	6.3
Si K	0.6	0.05	0.4	10.6
S K	0.3	0.05	0.2	15.7
Cl K	0.4	0.05	0.3	11.4
Ca K	24.7	0.07	12.7	2.4
Fe K	0.9	0.12	0.3	8.7

f)



g)

Fig. 5. Microstructure (*a*) and distribution of components in abrasive particles on the surface of improved 40X steel at the stage of intensive wear: *b, c* — silicon oxide; *d, e* — magnesium aluminate; *f, g* — calcium aluminate

Studies showed that the operational reliability of LCMs was significantly affected by the adhesive strength of the interlayer boundaries. The adhesive strength of the interlayer boundaries of LCMs "steel — rubber" bonded with glue based on chloroprene rubber (Fig. 6, *1*) and hot vulcanization (Fig. 6, *2*) differed significantly.

Figure 6 shows that LCMs bonded with glue had greater adhesive strength with rubber than LCMs connected by hot vulcanization under pressure. The adhesive strength of the samples made of P40X steel with rubber was almost the same when using both bonding methods and amounted to 0.21 and 0.2 MPa, respectively (Fig. 6 *c* and Fig. 6 *d*).

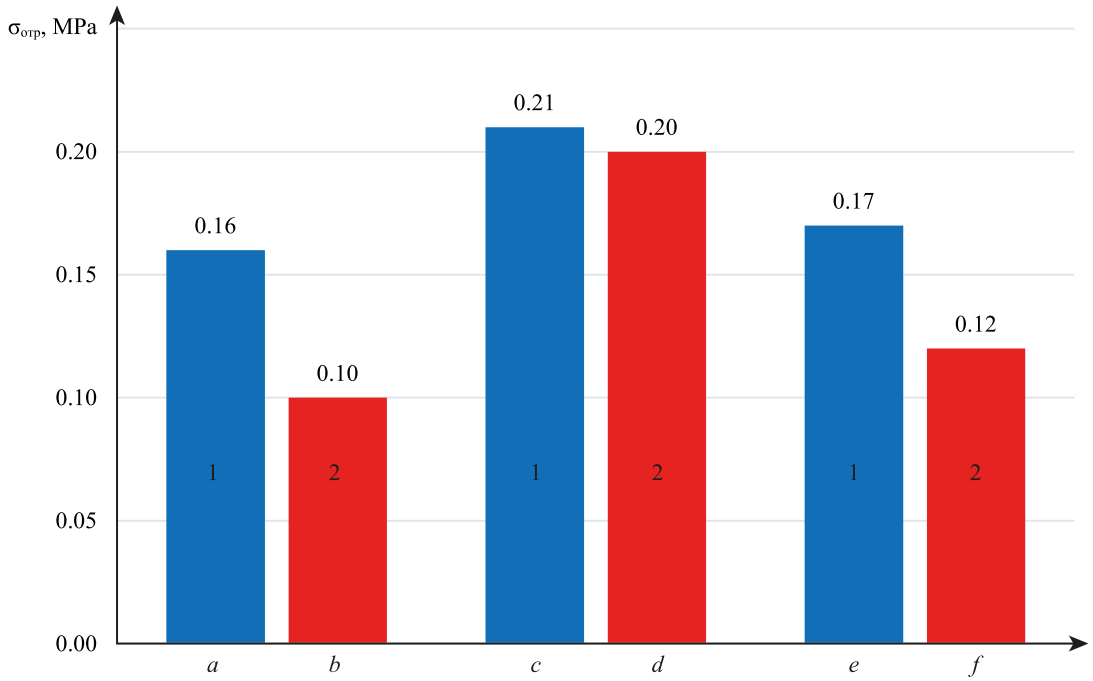


Fig. 6. Dependence of the adhesive strength of LCMs on the technology of obtaining steel samples:
a, b — rolled 40X; *c, d* — sintered P40X; *e, f* — hot-deformed P40X

When tested for impact and abrasive wear resistance, LCMs bonded with glue were destroyed due to overstress along the metal-rubber boundary, due to their significantly different stiffness, degree of deformation and the complex stress state that occurred as shear deformations developed [14].

Therefore, further research was aimed at increasing the adhesive strength of sintered P40X steel with rubber connected by hot vulcanization. One of the ways to increase the adhesive strength was to add copper to the charge (Fig. 7), which, when sintered above its melting point, spread over the free surface of the particles and interparticle boundaries under the influence of surface tension forces. This helped to increase the surface porosity of the compacts.

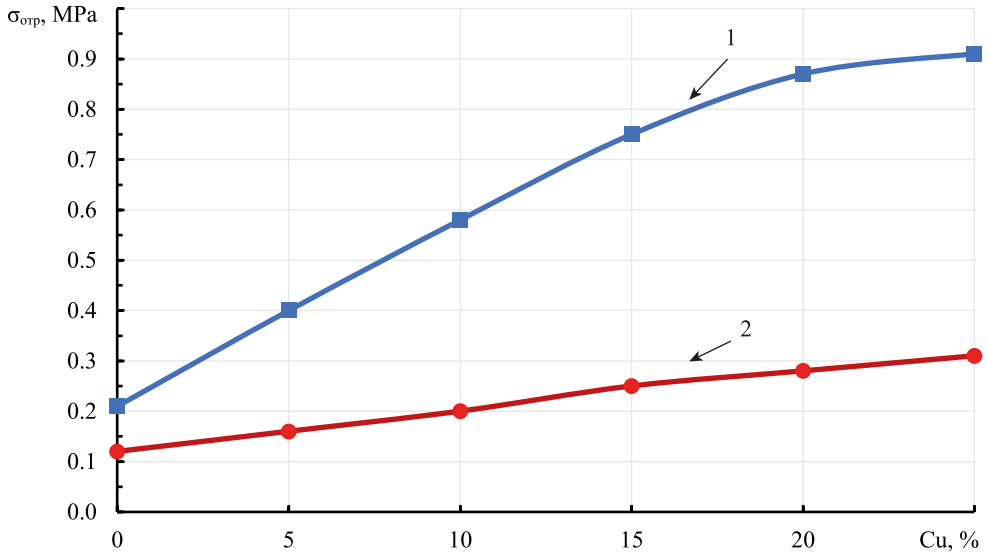


Fig 7. Effect of copper on the adhesive strength of LCMs made of sintered (1) and hot-deformed steel P40X (2)

Figure 7 shows that an increase in the concentration of copper in sintered P40X steel led to an increase in the adhesive strength of LCMs from 0.1 to 0.93 MPa, while the strength of the interlayer boundaries of LCMs with hot-formed steel increased slightly (from 0.05 to 0.3 MPa) due to the fact that during dynamic hot pressing, the surface was smoothed and most pores closed.

During hot vulcanization under pressure, crude rubber was pressed into the pores on the surface of sintered steel P40X (Fig. 8 *a*) and copper and iron sulfidation occurred in the process, and intermediate copper sulfide films of nonstoichiometric composition of Cu_xS type were formed between copper particles and rubber [15], which increased the adhesion of rubber to the matrix of sintered steel.

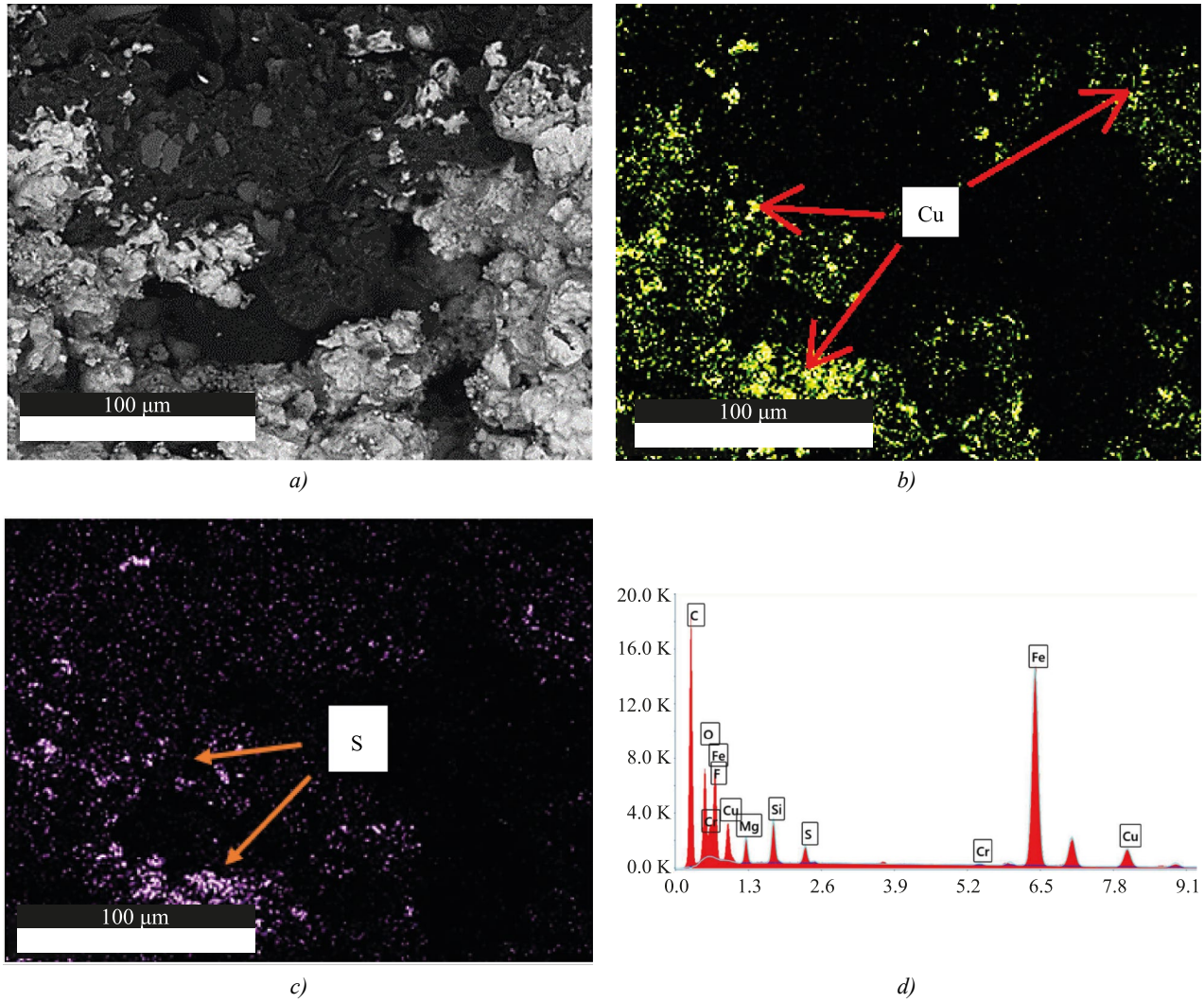


Fig. 8. Microstructure of the LCM transition zone:
a — sintered steel — rubber; *b* — distribution of copper; *c* — sulfur; *d* — other elements

The analysis of the results of mapping the interlayer boundary of the sintered steel—rubber LCM revealed the distribution zones of copper (Fig. 8 *b*) and sulfur (Fig. *8 c*) elements. Thus, in the areas enriched with copper, due to the formation of copper sulfides, the concentration of sulfur increased, which led to an increase in the LCMs adhesion.

Discussion and Conclusion. The studies have shown that the intensity of impact-abrasive wear depends on the structure of 40X steel, the impact energy and the chemical composition of abrasive particles. It was found that with an increase in the impact energy from 3 to 9 J, the intensity of abrasive wear of 40X steel samples increases and does not depend much on the type of heat treatment. This is due to the fact that at these values of impact energy, abrasive solids are actively embedded in the surface of the sample, triggering the mechanism of impact-abrasive wear. An increase in the impact energy from 9 to 22 J leads to a decrease in the intensity of wear due to the fact that solid abrasive particles of silicon and aluminum oxide, magnesium aluminate, without having time to penetrate into the surface of the sample, break down into smaller parts and form smaller wells, and calcium aluminate particles actively break down, fixing themselves in the formed wells, micropores and other defects.

It was found that when adding from 5 to 20% of copper to the charge, the adhesive strength of the interlayer boundaries of the steel—rubber LCM increased by 3–4 times as a result of the spreading of copper under the influence of surface tension forces over the free surface of particles and interparticle boundaries, as well as the formation of Cu_xS copper sulfides during hot vulcanization under pressure.

References

1. Gusev AI, Kozyrev NA, Usoltsev AA, Kryukov RE, Mikhno AR. Improving the Reliability and Durability of Mining Equipment Parts Operating under Conditions of Intense Impact and Abrasive Wear by Surfacing. *Naukoemkie tekhnologii razrabotki i ispol'zovaniya mineral'nykh resursov.*2021;(7):199–204. (In Russ.)

2. Abdyukova RYa, Bagautdinov NYa. The Analysis of Drilling Pump Clack Valves Failures. *Problems of Gathering, Treatment and Transportation of Oil and Oil Products.* 2012;(4):65–70. https://doi.org/10.17122/ntj-oil-2012-4-65-70 (In Russ.)

3. Gadalov VN, Kutepov SN, Petrenko VR, Kalinin AA. Assessment of Damage to Pump Parts of Drilling Equipment in Their Operation Mode. *News of the Tula State University. Technical Sciences.* 2022;(10):492–499. https://doi.org/10.24412/2071-6168-2022-10-492-499 (In Russ.)

4. Babaev SG, Gabibov IA, Melikov RKh. *Fundamentals of the Theory of Reliability of Oilfield Equipment.* Baku: Azerbaijan State Oil Academy; 2015. 400 p. URL: https://www.anl.az/el_ru/kniqi/2015/Ap2015-51.pdf (accessed: 22.05.2024). (In Russ.)

5. Bratkovskiy EV, Shapovalov AN, Dema RR. Increasing the Shock-Abrasive Resistance of Steels. *Vestnik mashinostroeniya*. 2019;(3): 64–67. (In Russ.)

6. Gadalov VN, Gubanov OM, Filonovich AV. Assessment of Damage to Pump Parts Drilling Equipment in Their Operation Mode. *Spravochnik. Inzhenernyi Zhurnal*. 2023;6(315):22–27. https://doi.org/10.14489/hb.2023.06.pp.022-027 (In Russ.)

7. Gasanov BG, Sirotin PV. Powder Materials for Components Operating Under Impact-Abrasive Wear Conditions. *Metallurg*. 2011;(3):61–64. (In Russ.)

8. Kwiatkowski K, Nachman M. The Abrasive Wear Resistance of the Segmented Linear Polyurethane Elastomers Based on a Variety of Polyols as Soft Segments. *Polymers*. 2017;9(12):705. http://doi.org/10.3390/polym9120705

9. Gasanov BG, Sirotin PV, Efimov AD. *Installation for Testing the Impact-Abrasive and Impact-Waterjet Wear of Structural and Special Materials.* Patent RF, No. 2434219. 2011. URL: https://allpatents.ru/patent/2434219.html (accessed: 22.05.2024). (In Russ.)

10. Gasanov BG, Sirotin PV. A Unit for Studying the Impact-Abrasive and Impact-Hydroabrasive Wear. *Industrial Laboratory. Diagnostics of Materials.* 2010;76(11):60–63. (In Russ.)

11. Kuharev AS, Gilaev GG. The Composition and Parameters of Drilling Fluids Required for the Development of Oil And Gas Fields. Environmental Protection when Working with Drilling Mud. In: *Proceedings of the II International Scientific and Practical Conference.* Krasnodar: Publishing House — Yug; 2022. P. 56–62. (In Russ.)

12. Sirotin PV, Gasanov BG, Ismailov MA. Installation for Determination of the Elastic and Damping Characteristics of Powder Materials with an Elastic-Dissipative Substrate. *Industrial laboratory. Diagnostics of materials.* 2021;87(6):63–69. https://doi.org/10.26896/1028-6861-2021-87-6-63-69 (In Russ.)

13. Sirotin PV, Ismailov MA. *Bench for Static Tests of Composite Multilayer Materials (Versions).* Patent RF, № 2725530. 2020. URL: https://patents.s3.yandex.net/RU2725530C1_20200702.pdf (accessed: 22.05.2024). (In Russ.)

14. Gasanov BG, Ismailov MA, Kharchenko EV. Increasing the Adhesive Strength in the Interlayer Boundaries of Powdered Iron-Copper Alloys with Rubber. *Bulletin PNRPU. Mechanical engineering, materials science*. 2022;24(4):26–34. https://doi.org/10.15593/2224-9877/2022.4.03 (In Russ.)

15. Nikiforova NA, Sheryshev MA. Ways to Increase the Adhesive Strength at the Rubber — Metal Cord Boundary. *Uspekhi v khimii i khimicheskoi tekhnologii*. 2011;25(3(119)):24–28. (In Russ.)

About the Author:

Markiz A. Ismailov, Senior Lecturer of the Department of Automobiles and Transport and Technological Complexes, Platov South-Russian State Polytechnic University (NPI) (132, Prosveshcheniya Str., Novocherkassk, 346428, RF), SPIN-code: 9370-9816, ORCID, al_myalim@mail.ru

Conflict of Interest Statement: **the author declares no conflict of interest.**

The author has read and approved the final manuscript.

Об авторе:

Маркиз Азизович Исмаилов, старший преподаватель кафедры автомобили и транспортно-технологические комплексы Южно-Российского государственного политехнического университета (НПИ) имени М.И. Платова (346428, Российская Федерация, г. Новочеркасск, ул. Просвещения, 132), SPIN-код: 9370-9816, ORCID, al_myalim@mail.ru

Конфликт интересов: **автор заявляет об отсутствии конфликта интересов.**

Автор прочитал и одобрил окончательный вариант рукописи.

Received / Поступила в редакцию Received 24.06.2024
Revised / Поступила после рецензирования 18.07.2024
Accepted / Принята к публикации 28.07.2024