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PHYSICS

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КАРАГАНДИНСКОГО
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BULLETIN
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ФИЗИКА сериясы

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ҚҰРМЕТТІ ОҚЫРМАН!

Сіздерге «Қарағанды университетінің хабаршысы» журналының 100-ші мерекелік санын ұсынып отырмыз. «Қарағанды университетінің хабаршысы» ғылыми мерзімді басылымы Қазақстан және басқа елдер ғалымдарының әр түрлі ғылым салаларындағы зерттеулерінің нәтижелерін ашық баспасөзде жариялауға бағытталған. Журналдың мақсаты — халықаралық ғылыми қауымдастықты жаңа әдістер және идеялармен таныстыра отырып, маңызды ғылыми және білім беру ақпараттарымен алмасуға тиімді жағдай жасау. Журнал ғылыми қызметтің негізгі нәтижелерін жариялау үшін ҚР БҒМ ғылым және білім саласындағы бақылау бойынша комитетпен ұсынылған басылымдар тізіміне енгізілген.

Журнал 1996 жылы алғашында екі серия («Гуманитарлық ғылымдар сериясы» және «Жаратылыстану ғылымдар сериясы») бойынша жарық көрді. 2004 жылдан бастап «Математика», «Физика», «Химия», «Биология. Медицина. География», «Экономика», «Педагогика», «Филология», «Тарих. Философия. Құқық» сияқты сегіз серия бойынша материалдар жарияласа, 2010 жылы «Құқық» өз алдына бөлек серия ретінде шығарылып, жалпы саны тоғызға жетті.

2015 жылдан бастап «Қарағанды университетінің хабаршысы» журналының «Химия», «Физика», «Математика» бағытындағы сериялары Web of Science Core Collection халықаралық базасының «Emerging Sources Citation Index (ESCI)» платформасына енді. Қазіргі уақытта «Қарағанды университетінің хабаршысы» журналында отандық ғалымдардың өзекті мәселелер бойынша ғылыми зерттеулерінен басқа, ТМД елдері және Германия, Польша, Қытай, Египет, Түркия Үндістан, Пәкістан секілді әлемдік ғылыми ортада 9 серия бойынша ғылыми жұмыс нәтижелерін жариялайтын беделді басылымға айналып отыр. Журналдың халықаралық талаптарға сәйкес келетін 3 тілдегі жеке сайтында редакциялық алқа саясаты, онлайн мақала жіберу мен онлайн рецензиялау талаптары көрсетілген. Журналда жарияланған барлық мақалаларға цифрлік объект идентификаторы беріледі. Журнал алдыңғы қатарлы отандық және шетелдік кітапханалық жүйелермен және дереккорлармен ынтымақтастық жасап, қазақстандық дәйексөздер базасы бойынша импакт факторға ие. Бұл өз кезегінде жарияланған материалдарға жылдам және ашық қол жеткізуге мүмкіндік береді.

Тәуелсіз еліміздің ғылымы мен білімінің дамуында айшықты қолтаңбамыз қалыптасты. Осындай абырой биігіне көтерілу ұзақ жылғы қажыр-қайраттың, үздіксіз ізденудің, талмай алға ұмтылудың нәтижесі деп білемін. Адамзат алдында тұрған аса ділгір мәселелерді шешуді өзінің мәңгілік межесі, игі мақсатына айналдырған басылым әлі де соны ғылыми жаңалықтардың жаршысы бола беретініне бек сенімдімін. Журналдың ғылыми әлеуетінің артуына үлес қосқан барлық авторлар мен ғалым-зерттеушілерге ризашылығымызды білдіре отырып, 100-ші мерекелік басылымның шығуына орай баршаңызды шын жүректен құттықтаймын!

Редакциялық кеңестің төрағасы
ҚР ҰҒА корреспондент-мүшесі,
заң ғылымдарының докторы,
профессор Н.О. Дулатбеков

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Preparation of powder coatings on the surface of steel balls
by mechanochemical synthesis

This work presents the results of the study of tribological and corrosion properties of powder coatings based on VN, TiN, SiC and Cr_2N obtained by mechanochemical synthesis on the surface of steel balls ShKh15. The idea of this method is using the impact energy of moving balls to apply coatings on metal surfaces. Based on the conducted research, it was proved using the method of mechanochemical synthesis possible to obtain a coating of VN, TiN, SiC, and Cr_2N on the surface of steel balls. The optimal parameters for coating were chosen: amplitude of the oscillation 3.5 mm; frequency of the oscillation 50 Hz; volume of filling of the chamber 50 %, the diameter of the ball 6 mm; ratio mass of the powder to the mass of the balls $m_p:m_b$=1:30, processing time by mechanochemical synthesis is 1 hour. It is established that the change in the characteristics of coatings directly depends on the stiffness and physical and mechanical properties of the source material (substrate) and surface roughness. The results of the tribological study showed that a wear-resistant coating was formed on the surface of the steel balls.

Keywords: mechanochemical synthesis, steel ShKh15, coating, coefficient of friction, wear resistance, corrosion, vibration stand, bearing.

Introduction

The machines longevity and mechanisms are mostly determined by the wear resistance used in their construction of bearing units. Wear of bearing units is followed by changes in the size of all components of their construction the rubbing detail. Feature of the work friction bearing units is the impact of: working pressure, temperatures, changing speeds of relative sliding or rolling, environmental aggression which leads to a certain type of wear (fatigue, abrasive, water-abrasive, corrosion-abrasive, etc.) and as a result of decrease in performance and reduce the durability of the friction bearing unit. The wear resistance of friction bearing units is largely determined by the quality of the lubricant material, the parameters of the contact surfaces of the details (shape deviation, waviness, roughness), and the physical-mechanical properties of the surface layer, which are formed during production and change during exploitation.

The application of the mechanical alloying (MA) method to obtain coatings on the metal surface is a new direction of surface treatment. Special attention is paid to the surface treatment of steel balls using the MA method. Steel bearing balls used in mechanical engineering, construction, etc. are exposed to rapid wear under various loads and have a negative impact on production. A significant role is played by improving the physical and mechanical properties of the surface by applying various powders to the surface of steel balls [1–4]. Methods such as electrochemical, ion implants, chemical and physical coatings, and electron beams,

which are widely used in practice, always do not give good results. Therefore, in this direction, it is more effective to increase the surface properties of the material by using MA. This process has been the object of intensive research confirming the importance of its application in various industries. Recently, processes activated by mechanical action (mechanochemical synthesis, mechanical activation, mechanical alloying) have become the subject of intensive research in connection with their prospective application in various industries, as they provide the creation of new non-traditional, ecologically pure and less expensive technologies compared to existing methods of coating metal surfaces such as chemical and physical vapor deposition, self-propagating high-temperature synthesis, thermal spraying, sol-gel method, etc. Exists needs to develop new methods of deposition coating the surface of metals and alloys [5–9]. In this regard, the aim of this work is to obtain coatings on the surface of the ShKh15 steel balls by method of mechanochemical synthesis.

Methods and materials

A thin coating of Cr_2N was obtained on the surface of the bearing balls made of ShKh15 steel by the method of mechanochemical synthesis on the vibration stand IV-50. The optimal parameters for coating were selected: amplitude of the oscillation 3.5 mm; frequency of the oscillation 50 Hz; volume of filling of the chamber 50 %, the diameter of the ball 6 mm; ratio mass of the powder to the mass of the balls m_p:m_b=1:30, processing time by mechanochemical synthesis is 1 hour. Figure 1 shows a scheme of the MA method. The essence of this method is that steel balls and powder of a specific chemical composition are placed in a chamber, and in a particular range of frequency form a coating on the surface of the material processed under the influence of the shock energy of the balls, exposing the mechanical vibration accelerator to vibration in a specific frequency range. The frequency of mechanical vibration is determined by the composition of the applied mixture and in accordance with the mechanical properties of the treated material.
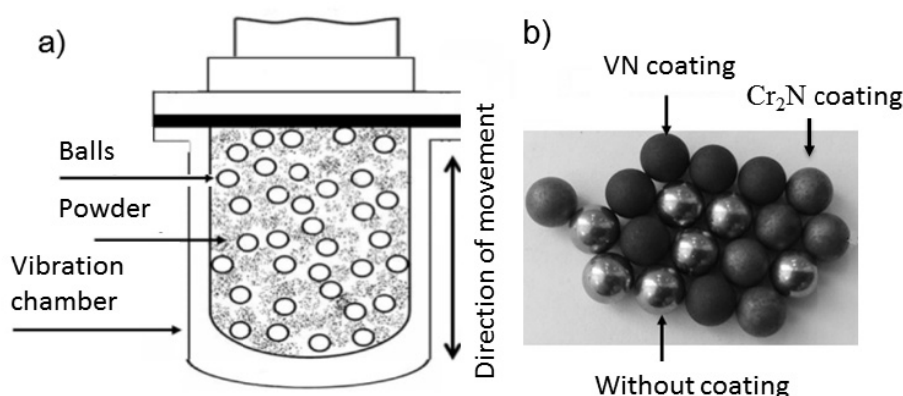
a — scheme the method of mechanical synthesis; *b* — steel balls with coating

Figure 1. Vibration stand IV-50 for the obtained coatings

VN, TiN, SiC, Cr_2N coatings obtained by MA method on the surface of steel ShKh15 was selected as the object of research. The diameter of the ball is 6 mm, the fraction of selected powders is 20–40 mμ. The mass of the balls (m_b=36 g) and the powder (m_p=12 g) which placed in the chambers were stable. The volume filling of the chamber with balls was about 80–85 %, depending on the size of balls It was selected that the distance between the surface of the ball layer and the treated material was close to the value of the oscillation span (two amplitudes) to obtain the maximum impact force of the balls. It should be noted that by varying the filling volume of the vibration chamber with balls, possible changes character of the impact on the treated material. At low filling coefficients, the movement of the balls occurs at the maximum speed, but the interaction of the balls with each other and the treated surface is minimal, which leads to low values of the intensity of the bringing energy. With an increase in the filling volume the chamber with balls, the frequency of collisions increases significantly, but due to the reduction in the length of the free path, the balls do not have time to accelerate to high speeds.

Turning medium unbalanced vibration stand relative to the two extremes unbalanced was adjusted working amplitude oscillation 3.5 mm. Considering the technical characteristics of the installation, the set value of the amplitude provides a sufficient intensity of the bringing mechanical energy of the impact of the

balls for coating. A significant increase in the amplitude (about 5 mm) with a high degree of loading leads to a sharp rise in the consumption of energy. On this basis, an excessive increase in the amplitude is not always effective, in addition, it influenced the construction of the used installation.

The oscillation frequency of the three-phase asynchronous motor (5A80MA2UZ) was regulated by the frequency Converter MG.02.C2.50-VLT (Danfoss). Using the tachometer TCh10-P, the oscillation frequency was measured by direct connection to the asynchronous engine. At a nourishing frequency of 50 Hz, the oscillation frequency of the asynchronous engine was equal to 2688 ± 69 rpm.

Results and discussion

The tribological properties of the balls are determined on the TRB[3] tribometer. The rotation radius is 5 mm, the speed is 5 cm/s, the installed load is 15 N, the path length is 75 m. Figure 2 shows the coefficient of friction of coatings VN, TiN, SiC, Cr_2N applied to steel balls ShKh15. The friction coefficient of steel ShKh15 is $\mu_{ShKh15} = 0.488$, for $\mu_{VN} = 0.416$, $\mu_{TiN} = 0.562$, $\mu_{SiC} = 0.563$, $\mu_{Cr2N} = 0.476$ (Table 1). A thin and strong coating is formed on the surface of the balls by using MA. According to the tribological research, the greatest friction coefficient was observed with TiN and SiC balls. Based on the results of the study of the wear intensity by weight loss, we can say that balls with TiN and Cr_2N coatings have a high wear resistance.
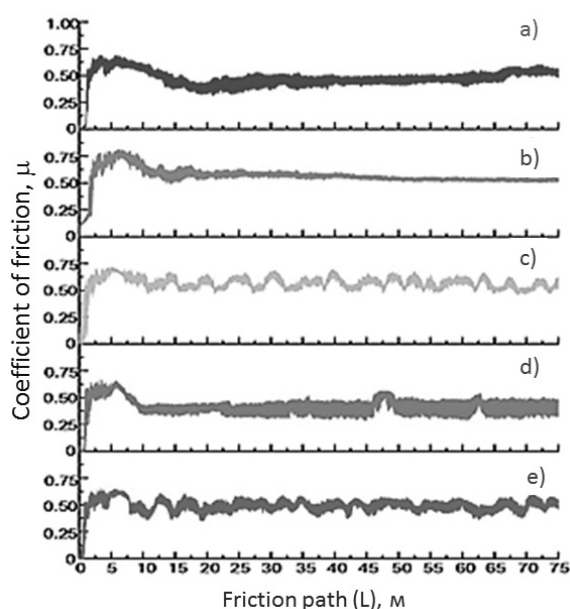
a — Steel ShKh15; *b* — VN coating; *c* — TiN coating; *d* — SiC coating; *e* — Cr_2N coating

Figure 2. The friction coefficient of the samples

T a b l e 1

The results of tribological research of steel ShKh15 and coatings

Samples	Steel ShKh15	VN coating	TiN coating	SiC coating	Cr_2N coating
the middle of the friction coefficient, $\mu_{mid.}$	0,488	0,416	0,562	0,563	0,476
Standard deviation	0,064	0,071	0,070	0,083	0,081

With a view to improve the durability and reliability of gas turbine engine bearings by increasing their corrosion resistance, various methods are being developed to extend the service life of bearings in situations when may occur lubricating oil pollution with the salt water. If water or aggressive environments penetrates in the bearing to such an extent that lubricants cannot protect the steel surfaces and corrosion occurs. In work [10], the influence of heating on the corrosion properties of TiN and CrN coated steels was investigated. The results of the research showed that samples coated with Cr_2N showed better anti-corrosion properties than TiN-coated steels. The corrosion of steel ShKh15 before and after the application of a thin film coating Cr_2N

by mechanochemical alloying was determined by the method of potentiometric. The method of potentiometry is based on the dependence of the concentration/activity of ions in a solution with an electrode on the equilibrium electrode potential, i.e. the EDS of a reversible galvanic cell consisting of electrodes immersed in the test solution was measured, where the potential depended on the concentration of the determining ions. Corrosion tests were performed on a potentiostat-galvanostat P150, in a 4 % solution of nitric acid (HNO$_3$). The corrosion test results of samples are shown in Table 2.

T a b l e   2

Corrosion test results of samples

Sample	S, cm^2	E$_{corr}$, mV	lg(I)	M, g/mol	n, g/mol	t, s	p, g/cm^3	i$_{corr}$, A	j$_{corr}$, A/cm^2	m, g	l, cm	R$_{corr}$, cm/year
Shh15 initial	0.45	−926	−2.32	56	56	3.15E+07	7.8	0.0047	1.06E-02	1.563	0.445	0.445
ShKh15 with Cr$_2$N coating	0.45	−1098	−3.11	118	60	3.15E+07	5.8	0.0008	1.72E-03	0.498	0.191	0.191

The corrosion behavior of samples was estimated by the size of their electrode potentials, by measuring and regulating the currents and voltages at the working electrode during electrochemical research. The test results showed that after applying the Cr$_2$N coating, the corrosion rate was 0.191 cm / year, which is twice as less as that of uncoated steel ShKh15.

Conclusion

Tribological and corrosion characteristics of chromium-based thin-film coatings applied by mechanochemical method on the surface of steel balls were researched. It is established that the mechanical alloying of nitride coatings depends on the process parameters that determine the flow of energy bringing. The growth rate of the coating is determined by the processing time and the intensity of the energy brought, the latest depends on the size and mass of the balls. The thickness of the coatings, uniformity and structure can be adjusted widely by changing the process parameters. The thickness of the coatings, uniformity and structure can be adjusted widely by changing the process parameters. The developed method of mechanochemical alloying allows obtaining VN, TiN, SiC, Cr$_2$N coatings on bearing balls at room temperature, in a short processing time and with minimal energy expenditure. The improvement of tribological and corrosion characteristics of ShKh15 steel was identified after applying thin-film coatings based on TiN and Cr$_2$N applied by mechanochemical method..

References

1   Torosyan A.R. A New Mechanochemical Method for Metal Coating / A.R. Torosyan, R.T. Jonathan, A.M. Korsunsky, S.A. Barseghyan // Journal of Metastable and Nanocrystalline Materials. — 2002. — Vol. 13. — P. 251–256. DOI: 10.4028/msf.386–388.251

2   Boytsov O. Correlation between milling parameters and microstructure characteristics of nanocrystalline copper powder prepared via a high energy planetary ball mill / O. Boytsov, A.I. Ustinov, E. Gaffet, F. Bernard // Journal of Alloys and Compounds. — 2007. — Vol. 432. — P. 103–110. doi.org/10.1016/j.jallcom.2006.05.101

3   Zadorozhnyy V. Formation of intermetallic Ni–Al coatings by mechanical alloying on the different hardness substrates / V. Zadorozhnyy, S. Kaloshkin, V. Tcherdyntsev, M. Gorshenkov, A. Komissarov, M. Zadorozhnyy // Journal of Alloys and Compounds. — 2014. — Vol. 586. — P. 373–376.

4   Бутягин П.Ю. Кинетика и энергетический баланс в механохимических превращениях / П.Ю. Бутягин, А.Н. Стрелецкий // Физика твердого тела. — 2005. — Т. 47, Вып. 5. — С. 830–836. doi.org/10.1016/j.jallcom.2006.04.045

5   Joardar J. Milling criteria for the synthesis of nanocrystalline NiAl by mechanical alloying / J. Joardar, S.K. Pabi, B.S. Murty // Journal of Alloys and Compounds. — 2007. — Vol. 429. — P. 204–210. doi.org/10.1016/j.jallcom.2006.04.045

6   Dashtbayazi M.R. Artificial neural network modeling of mechanical alloying process for synthesizing of metal matrix nanocomposite powders / M.R. Dashtbayazi, A. Shokuhfar, A. Simchi // Materials Science and Engineering. — 2007. — Vol. 466. — P. 274–283. doi.org/10.1016/j.msea.2007.02.075

7   Ipus J.J. An equivalent time approach for scaling the mechanical alloying processes / J.J. Ipus, J.S. Blázquez, V. Franco, M. Millán, A. Conde, D. Oleszak, T. Kulik // Intermetallics. — 2008. — Vol. 16. — P. 470–478. doi.org/10.1016/j.intermet.2007.12.011

8   Xianjin J. Mechanical alloying and reactive milling in a high energy planetary mill / J. Xianjin, M.A. Trunov, M. Schoenitz, N.D. Rajesh, E.L. Dreizin // Journal of Alloys and Compounds. — 2009. — Vol. 478. — P. 246–251. doi.org/10.1016/j.jallcom.2008.12.021

9   Tjong S.C. Nanocrystalline materials and coatings / S.C. Tjong, H. Chen // Materials Science and Engineering R: Reports. — 2004. — Vol. 45. — P. 1–88.

10 Ürgen M. The effect of heating on corrosion behavior of TiN- and CrN-coated steels / M. Ürgen, A.F. Çakir // Surface and Coatings Technology. — 1997. — Vol. 96. — P. 236–244. DOI: 10.1016/j.mser.2004.07.001

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Механохимиялық синтез әдісімен болат шарлардың бетіне ұнтақ жабындарын алу

Мақалада ШХ15 болат шарларының бетінде механохимиялық синтез әдісімен алынған VN, TiN, SiC және Cr_2N негізіндегі ұнтақ жабындарының трибологиялық және коррозиялық қасиеттерін зерттеу нәтижелері келтірілген. Бұл әдістің негізі — соқтығысқан шарлар энергиясын пайдалана отырып, металл беттеріне жабындар жағу. Жүргізілген зерттеулер негізінде механохимиялық синтез әдісін қолдана отырып, болат шарлардың бетіне VN, TiN, SiC, Cr_2N жабындысын алуға болатындығы дәлелденді. Жабын алу үшін оңтайлы параметрлер таңдалды: тербеліс амплитудасы 3,5 мм; тербеліс жиілігі 50 Гц; камераны толтыру дәрежесі 50 %, шардың диаметрі 6 мм; ұнтақ массасының шарлардың массасына қатынасы $m_\text{ұ}$:$m_\text{ш}$ = 1:30, механохимиялық синтез әдісімен өңдеу уақыты 1 сағ. Жабындардың сипаттамаларының өзгеруі бастапқы материалдың (субстраттың) қаттылығы мен физикалық-механикалық қасиеттеріне және бетінің кедір-бұдырына тікелей байланысты екендігі анықталды. Трибологиялық зерттеудің нәтижелері болат шарлардың бетінде тозуғатөзімді жабын пайда болғанын көрсетті.

Кілт сөздер: механохимиялық синтез, ШХ15 болаты, жабын, үйкеліс коэффициенті, тозуғатөзімділік, коррозия, дірілді стендтер, подшипник.

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Получение порошковых покрытий на поверхности стальных шаров методом механохимического синтеза

В статье приведены результаты исследования трибологических и коррозионных свойств порошковых покрытий на основе VN, TiN, SiC и Cr_2N, полученных методом механохимического синтеза на поверхности стальных шаров ШХ15. Идея данного метода состоит в использовании энергии ударов движущих шаров для нанесения покрытий на металлические поверхности. На основании проведенных исследований было доказано, что, с использованием метода механохимического синтеза, можно получить покрытия VN, TiN, SiC, Cr_2N на поверхности стальных шаров. Оптимальными параметрами для нанесения покрытий были выбраны амплитуда колебания 3,5 мм; частота колебания 50 Гц; степень заполнения камеры 50 %, диаметр шара 6 мм; отношение массы порошка к массе шаров $m_\text{п}$:$m_\text{ш}$ = 1:30; время обработки методом механохимического синтеза составляло 1 ч. Установлено, что изменение характеристик покрытий напрямую зависит от жесткости и физико-механических свойств исходного материала (подложки) и шероховатости поверхности. Результаты трибологического исследования показали, что на поверхности стальных шаров образовалось износостойкое покрытие.

Ключевые слова: механохимический синтез, сталь ШХ15, покрытие, коэффициент трения, износостойкость, коррозия, вибрационный стенд, подшипник.

References

1   Torosyan, A.R., Jonathan, R.T., Korsunsky, A.M., & Barseghyan, S.A. (2002). A New Mechanochemical Method for Metal Coating. *Journal of Metastable and Nanocrystalline Materials, 13*, 251–256.

2   Boytsov, O., Ustinov, A.I., Gaffet, E., & Bernard, F. (2007). Correlation between milling parameters and microstructure characteristics of nanocrystalline copper powder prepared via a high-energy planetary ball mill. *Journal of Alloys and Compounds, 432*, 103–110.

3   Zadorozhnyy, V., Kaloshkin, S., Tcherdyntsev, V., Gorshenkov, M., Komissarov, A., & Zadorozhnyy, M. (2014). Formation of intermetallic Ni–Al coatings by mechanical alloying on the different hardness substrates. *Journal of Alloys and Compounds, 586*, 373–376.

4   Butyagin, P.Yu., & Streletskiy, A.N. (2005). Kinetika i enerheticheskii balans v mekhanokhimicheskikh prevrashcheniiakh [Kinetics and energy balance in mechanochemical transformations]. *Fizika tverdoho tela — Solid state physics, 47*(5), 830–836 [in Russian].

5   Joardar, J., Pabi, S.K, & Murty, B.S. (2007). Milling criteria for the synthesis of nanocrystalline NiAl by mechanical alloying. *Journal of Alloys and Compounds*, *429*, 204–210.

6   Dashtbayazi, M.R. Shokuhfar, A., & Simchi, A. (2007). Artificial neural network modeling of mechanical alloying process for synthesizing of metal matrix nanocomposite powders. *Materials Science and Engineering, 466*, 274–283.

7   Ipus, J.J., Blázquez, J.S., Franco, V., Millán, M., Conde, A., Oleszak, D., & Kulik, T. (2008). An equivalent time approach for scaling the mechanical alloying processes. *Intermetallics, 16*, 470–478.

8   Xianjin J., Trunov, M.A., Schoenitz, M., Rajesh, N.D., & Dreizin, E.L. (2009). Mechanical alloying and reactive milling in a high energy planetary mill. *Journal of Alloys and Compounds, 478*, 246–251.

9   Tjong, S.C., & Chen, H. (2004). Nanocrystalline materials and coatings. *Materials Science and Engineering R: Reports*, *45*, 1–88.

10   Urgen, M., & Cakir, A.F. (1997). The effect of heating on corrosion behavior of TiN- and CrN-coated steels. *Surface and Coatings Technology*, *96*, 236–244.

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Experimental characterization of firebrand ignition of some wood building materials

Paper presents investigation on behaviour of wood construction material samples (plywood, oriented strand board, chipboard) in laboratory conditions as a result of a heat flux effect from naturally occurring flaming and glowing firebrands. The data of comparing ignition delay time of pine wood and wood-based construction materials (plywood, oriented strand board, chipboard) depending on the size and quantity of firebrands, initial temperature of samples, as well as the presence of air flow in firebrands falling zone is obtained. Ignition probability and conditions of wood construction materials as a result of the thermal effect of flaming and glowing pine firebrands are also studied. The obtained data allowed one to judge that according to chosen experimental parameters, the ignition time decreased with increasing air flow, as well as with an increase in the size and number of particles. It was experimentally confirmed that particle size plays a significant role in igniting of building structure. If the characteristic particle size is less than a certain characteristic value, which can be defined as the ratio of its volume to the surface area in contact with wood, then ignition mode with an abrupt maximum of temperature near phase boundary is not appear.

Keywords: firebrands, fire exposure, wood construction materials, ignition.

Introduction

Wildfires are one of the most serious problems of the world. The scale of the damage caused by wildfires around the world is catastrophic [1]. It can be the cause of wooden bridges, oil product depots, buildings in cities ignition. Flaming and glowing firebrands, which are formed due to the burning of forest combustible materials, cause particular interest. These firebrands can be carried away over long distances by falling into a convective column that forms above the fire zone and lead to a new fire. Moreover, in flight they burn in flameless conditions [2]. Thus, one of the damaging factors of wildfires is the burning elements of forest combustible material, which can be also carried away to a territory of urban environment [3]. This problem is actively researched in Australia, USA, Canada, Portugal, and Greece.

Large-scale wildland and wildland-urban interface (WUI) fires have happened more frequently in recent years. Direct flame contact, radiant heat, and burning firebrands (or embers) have been identified as three principal ways that cause fire spread in the wildland and WUI [4–7]. However, only burning firebrands can initiate a new spot fire at distances further than 60-m away from the main fire front [8]. Spotting due to firebrands also referred as the firebrand phenomenon can overpower fire suppression efforts and becomes the dominant fire spread mechanism [9]. The spotting process includes three phases: firebrand generation, transportation, and ignition of the recipient fuel.

The ability of a firebrand to travel far way and start a new fire is a function of its physical properties and the environmental parameters [10]. Primary physical properties of a firebrand include mass, size (aerodynamic) shape, surface temperature, heat flux, and the heat of combustion of the fuel. The shape and dimensions are critical factors in firebrand transport. The mass and heat of combustion determine the total available heat energy from the firebrand. Surface temperature and heat flux play an important role in heat transfer from the firebrand to the recipient fuel. Environmental conditions influence all three phases of the firebrand phenomena. Key parameters include relative humidity, environmental temperature, wind speed, terrain conditions, and the condition of the recipient fuel. Among the environmental parameters, wind speed is critical effecting breakage of burning fuel leading to the generation of firebrands, transport mechanism (e.g., travel distance) and the burning behavior. Softwood is usually used in construction as a load-bearing structure, and hardwood is used as a finishing material. One of the factors determining fire hazard of wood [11] is its capacity to ignite and to stimulate fire propagation. Aim of this work is to study behaviour of wood building material samples in laboratory conditions as a result of heat exposure from a point source.

Experimental

The following laboratory setup was used to study the ignition probability of wood construction materials from flaming and glowing firebrands (Fig. 1).

a

b
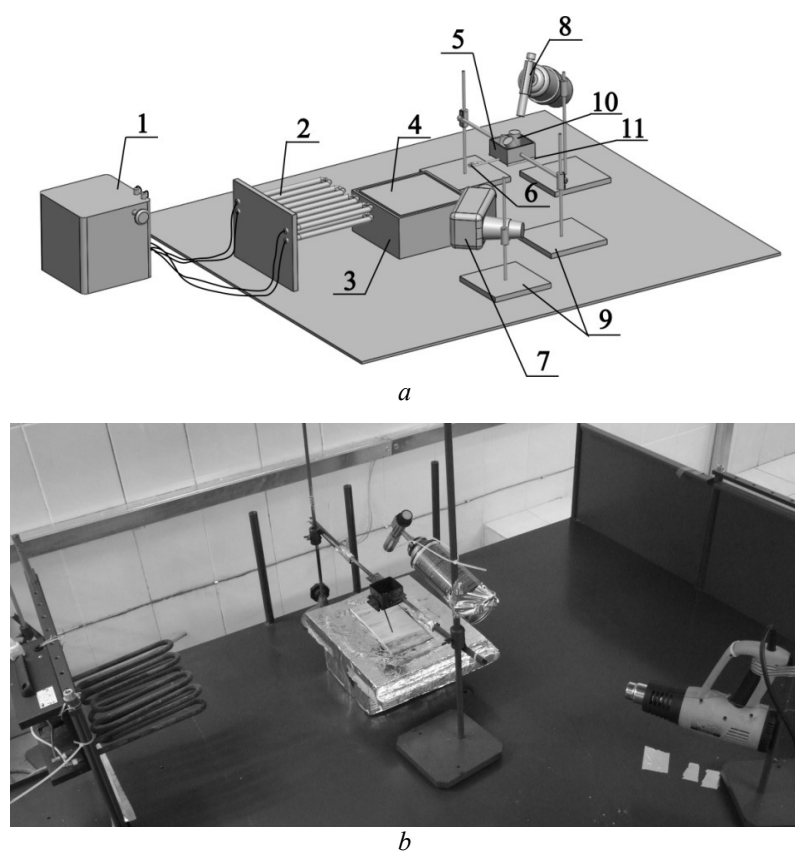
1 — laboratory autotransformer; *2* — heating element; *3* — pallet; *4* — wood sample; *5* — cell;
6 — stopper; *7* — heat gun; *8* — burner; *9* — tripods; *10* — particle samples; *11* — bracket

Figure 1. Scheme (*a*) and photo (*b*) of the experimental setup

Experimental equipment involves the following devices: a scientific infrared camera JADE J530SB equipped with an optical filter whose operating wavelength is 3.1–3.3 μm which allows one to record the temperature in the range of 300–800 ℃; a video camera Canon HF R88 applied for estimating the ignition delay for considered samples made of wood construction materials; a moisture content analyzer AND MX-50 for controlling moisture content of the studied samples; AND HL 100 scales to control the initial particle mass and the mass of wood sample.

The wood sample was preheated with a heating element to a temperature of 200–220 ℃ for 4 minutes [12]. Thus, the conditions were simulated when a wooden structure is exposed to heat flux from an approaching front of wildfire [13, 14]. Concurrently, particles were placed in the cell 5 mounted on the tripods 9, which had openings in the base sufficient for uniform heating of the particles, but excluding the possibility of particles falling out during the experiments. The volume of cell allowed one to place single particles in it, as well as groups of particles. Particles fell onto the wood sample when the sliding bottom of the cell was opened. Bottom parts were attached to the cell walls with hinges and were fixed in a horizontal position by a stopper 6. Two halves of the bottom fell under their own weight and firebrand fell when the latch was pulled out.

Particles were ignited and carried to a smoldering state with two gas burners 8. One burner was placed under the cell 5, and the other above it (Fig. 2) for uniform heating. After reaching the required temperature on the surface of sample, the substrate with sample was moved under the cuvette with particles preheated using gas burners, and they were discharged.

Plywood, chipboard and oriented strand board (OSB) are used as the samples of wood construction materials which are popular in the market.

The main parameters of samples are presented in Table 1.

Sample parameters of construction materials

	Plywood	OSB	Chipboard
Size, [mm]	150×150	150×150	150×150
Thickness [mm]	21	18	18
Density, [kg / m^3]	650÷690	570÷590	570÷590

The samples were isolated from the environment with a heat-insulating material so that one of the surfaces remained exposed to heat from falling particles. A photo of the sample before the experiment is shown in Figure 3.

Figure 2. Photo of the flame effect on particles   Figure 3. Photo of the sample before the experiment

The temperature during heating on the wood surface was controlled using an infrared camera. Figure 4 shows the thermogram of a wood sample as a result of heating by tubular heating element and the minimum (441 K), maximum (505 K), and average (479 K) temperatures on the surface of sample (in selected area 1 in the thermogram) obtained using Altair software. Previously in [17], it was found that firebrands of bark and branches were formed more often in a large wildfire. In current experiment, we used rectangular laths as particles that coincide in size with the typical particle sizes determined during field experiments [15]. Photos of the samples are shown in Figure 5.
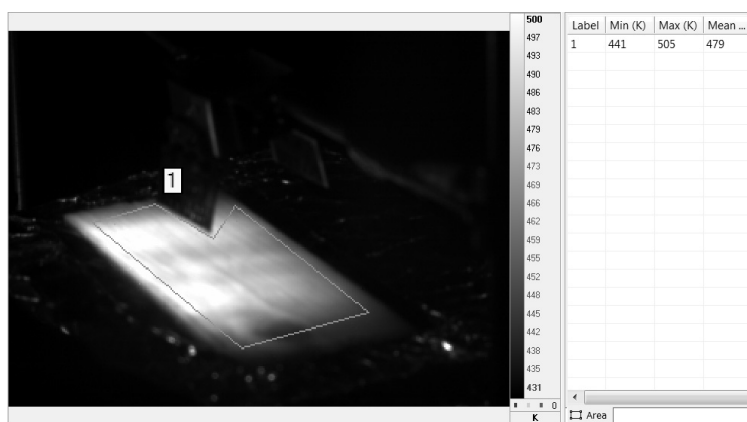
Figure 4. Thermogram of a wood sample after heating   Figure 5. Model particles

The particle length in this experiment was: (20±2; 40±2; 60±2) mm. The moisture content of particles did not exceed 10 %, for samples of wood construction materials it was 6–8 %.

Glowing firebrands, which effects the surface of sample, are of particular interest in current research. The case when glowing firebrands that form during a wildfire can accumulate on the roof and in corners of buildings, fences, or find a way to get inside premises and ignite it is simulated in these experiments.

The optimal particle ignition time was preliminarily selected (Table 2), at which the particle smoldering phase was achieved [18–19]. Particle burner time depended on particle size and quantity. Particle temperature was monitored using a JADE J530SB infrared camera.

Under natural conditions, the effect of firebrands on various wooden structures is accompanied by a number of natural factors, in particular, the action of a heated air stream from the front of a wildfire. Glowing firebrands discharged in the experiments onto wood samples were blown using a heat gun, Interskol FE2000-E brand, with a stream of heated air at a speed of 1.5 m/s, 2 m/s and 2.5 m/s with corresponding temperatures of 40 ºC, 60 ºC, and 110 ºC. An air flow was directed to the surface of the wood sample into the particle discharge region using a nozzle. The ignition moment was recorded using a Canon LEGRIA HF R86 video camera.

T a b l e 2

Exposure time depended on particle size

	Length, [mm]	Exposure time, [s]
Rectangular slats	20	15
	40	20
	60	25

A series of experiments began with one glowing firebrand, then two and so on up to 10 particles, thereby simulating the ignition of wood from one particle, as well as in the case of «fire rain». Three repetitions were performed for each experiment. If ignition occurred in at least one of the three cases, it was believed that the wood sample ignited. Ignition was understood as the appearance of a flame on the surface of samples of wood construction materials with subsequent steady burning.

Results and discussion

It was found that ignition of the samples was not observed in the range of wind speeds of 0÷1 m/s.

The probability of ignition of a preheated surface of plywood, chipboard, and OSB samples depending on the size of flaming and glowing firebrands and their amount interacting with this surface at various wind speeds was estimated as a result of a series of experiments (Fig. 6).
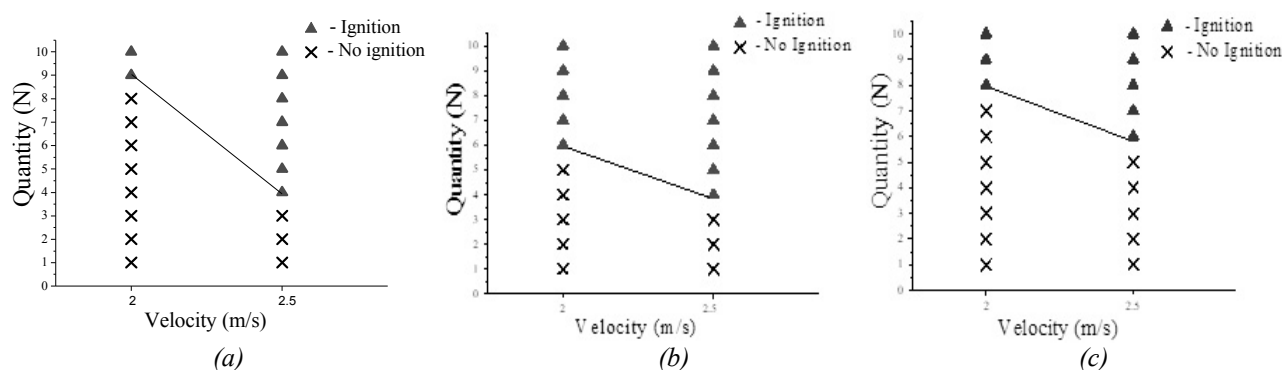
Figure 6. The dependence of wood samples ignition of construction materials on the size and quantity of glowing firebrands at air flow rates of 2 m/s and 2.5 m/s, where *a* is plywood, *b* is oriented strand board, *c* is chipboard

Analysis of the graphs shows that with increasing wind speed; the probability of wood ignition by particles of the same size increases. In particular, with an increase of wind speed from 2 to 2.5 m/s, the minimum number of particles with a length L = 40 mm, sufficient to ignite the wood, decreases from 7 to 3 particles. The number of particles also affects the ignition process of wood.

Figure 7 shows a typical group of images on particle ignition of a chipboard sample, on the surface of which glowing firebrands of length 40 mm in the amount of 6 pieces were discharged. The air flow rate was 2 m/s. It should be noted that the transition of particles from the glowing phase to the flame occurs due to the

influx of the oxidizing agent from the heat gun. In particular, the transition occurred already at the 8th second in this case (Fig. 7), which subsequently led to the burning of chipboard over the surface.

8 sec.

40 sec.

1 min.

1 min. 30 sec.

1 min. 50 sec.

2 min. 10 sec.
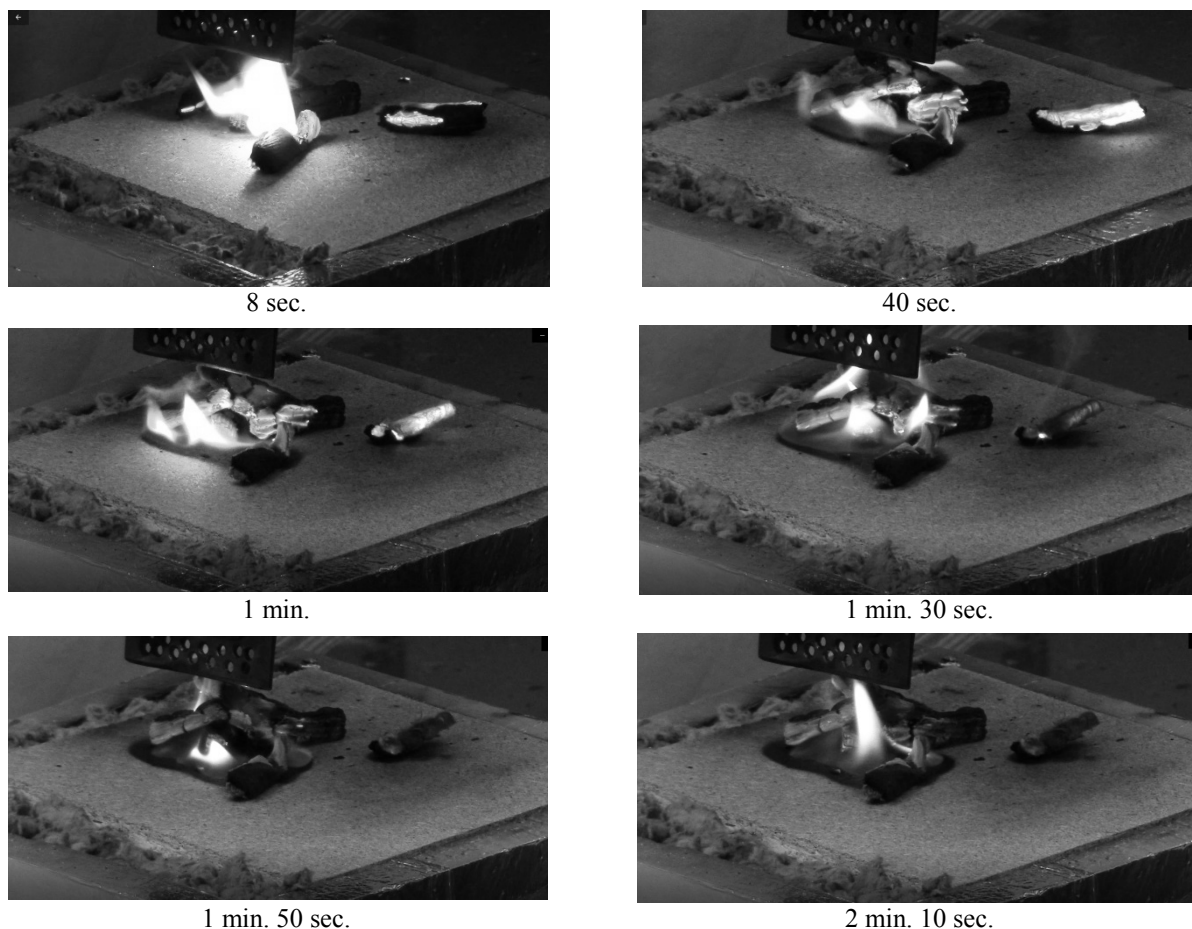
Figure 7. A group of images on the effect of particles on a chipboard sample

Previously in [18–19], the experiment was conducted on the ignition of wood samples from a pine construction board as a result of exposure to flaming and glowing firebrands of pine bark. The experimental technique is similar. It was concluded that the probability of ignition of wood samples increases with increasing particle size, as well as with increase in air flow rate. The size of rectangular slats (40 mm long) was chosen based on this, which is close in size to particles of pine bark, which has the highest incendiary potential for the chosen experimental parameters (30×30 mm and 5 mm thick).

Figure 8 shows graphs comparing the ignition delay times of pine wood and construction materials (plywood, OSB, and chipboard) depending on the number of particles at air flow rates of 1.5 m/s, 2 m/s and 2.5 m/s.
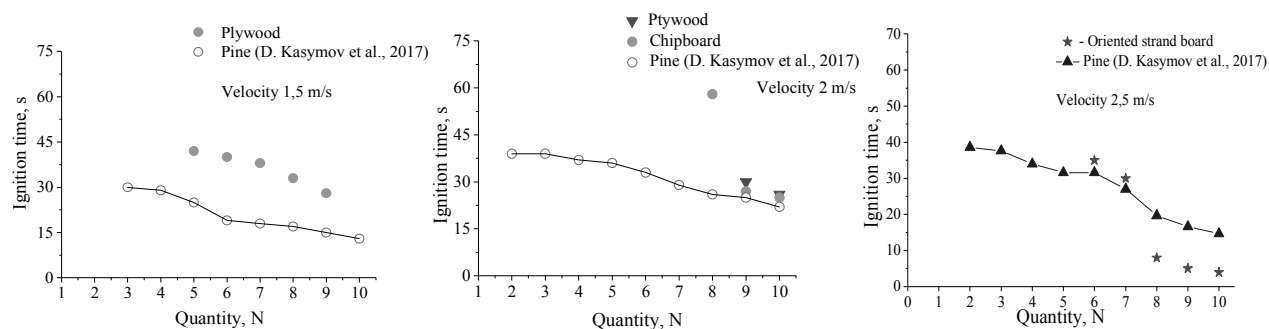
Figure 8. The ignition delay times of pine wood and construction materials

There is a tendency to decrease the ignition time of samples with an increase in the number of particles according to the analysis of graphs (Fig. 8). It can be seen that in the cases with plywood and chipboard samples, the ignition times are close to the times of pine wood ignition in the case of bark particles, and in the case with OSB, a large number of particles (8–10 particles) are observed, the ignition time is significantly reduced, more than 2 times compared to a similar experiment with pine. The obtained data allows one to judge that, at the chosen experimental parameters, the ignition time decreased with increasing air flow, as well as with an increase in the number of particles.

Conclusion

The behavior of samples of wood construction (plywood, OSB, chipboard) was studied as a result of heat exposure from flaming and glowing firebrands.

It was found that ignition of the samples was not observed in the range of wind speeds of 0÷1 m/s. The considered construction materials from wood (plywood, OSB, chipboard) were more resistant to ignition with the chosen experimental parameters. Apparently, this is due to the composition of studied samples, which contains additional binding components (synthetic resins). In addition, the presented construction materials have a lower surface roughness, unlike a standard building board.

The use of IR diagnostics made it possible to estimate the temperature on the samples surface and to select the optimal heating time. Moreover, this made possible to control the phase of glowing firebrands before discharge.

References

1   Yool S.R. Describing the brush fire hazard in southern California / S.R. Yool // Annals of the Association of American Geographers. — 1985. — Vol. 75, No. 3. — P. 417–430.

2   Filkov A. Experimental investigation of surface litter ignition by bark firebrands / A. Filkov, D. Kasymov, V. Zima, O. Matvienko // AIP Conference Proceedings. — 2016. — Vol. 1698, No. 060004. — P. 1–6. DOI: 10.1063/1.4937859.

3   Castro R. Modeling Forest Fire Danger from Geographic Information System / R. Castro, E. Chuvieco // Geocarto International. — 1998. — Vol. 13. — P. 15–23.

4   Clements H.B. Lift-off of Forest Firebrands / H.B. Clements // Forest Service, U.S. Dept. of Agriculture, Southeastern Forest Experiment Station. — Asheville, 1977. — P. SE-159.

5   Maranghides A. A Case Study of a Community Affected by the Witch and Guejito Wildland Fires / A. Maranghides, W. Mell // Fire Technology. — 2011. — Vol. 47. — P. 379–420.

6   Koo E. Modelling firebrand transport in wildfires using HIGRAD/FIRETEC / E. Koo, R.R. Linn, P.J. Pagni, C.B. Edminster // International Journal of Wildland Fire. — 2012. — Vol. 21. — P. 396–417.

7   Caton S.E. Review of Pathways for Building Fire Spread in the Wildland Urban Interface Part I: Exposure Conditions / S.E. Caton, R.S.P. Hakes, D.J. Gorham, A. Zhou, M.J. Gollner // Fire Technology. — 2017. — Vol. 53. — P. 429–473.

8   Cohen J. The wildland-urban interface fire problem / J. Cohen // Forest History Today. — 2008. — Vol. 11. — P. 20–26.

9   Koo E. Firebrands and spotting ignition in large-scale fires / E. Koo, P.J. Pagni, D.R. Weise, J.P. Woycheese // International Journal of Wildland Fire. — 2010. — Vol. 19, No. 7. — P. 818–843.

10 Tohidi A. Statistical description of firebrand size shape distribution from coniferous trees for use in metropolis Monte Carlo simulations of firebrand flight distance / A. Tohidi, N. Kaye, W. Bridges // Fire Safety Journal. — 2015. — Vol. 77. — P. 21–35.

11 Pantoli M.R.L. Performance Monitoring of Wood Construction Materials by Means of Integrated Sensors / M.R.L. Pantoli, M. Muttillo, V. Annibaldi // Key Engineering Materials. — 2018. — Vol. 792. — P. 195–199.

12 Babrauskas V. Charring rate of wood as a tool for fire investigations / V. Babrauskas // Fire Safety Journal. — 2005. — Vol. 40. — P. 528–554.

13 Cohen J.D. Preventing disaster: Home ignitability in the wildland-urban interface / J.D. Cohen // Journal of Forestry. — 2000. — Vol. 3, No. 98. — P. 15–21.

14 Rehm R.G. Community-scale fire spread / R.G. Rehm, A. Hamins, H.R. Baum // Proceedings of the California's 2001 Wildfire Conference, California. — 2001. — P. 126–139.

15 Filkov A.I. Investigation of firebrand production during prescribed fires conducted in a pine forest / A.I. Filkov, S.A. Prohanov, E. Mueller, D.P. Kasymov et. al. // Proceedings of the Combustion Institute. — 2017. — Vol. 36, No. 2. — P. 3263–3270.

16 Toregldin M.M. Protection against dust explosions in coal mines using shale barriers / M.M. Toregldin, O.B. Seldyugaev, N.K. Tanasheva // Bulletin of the University of Karaganda-Physics, 2019. — Vol. 2, No. 94. — P. 73–81.

17 Nussupbekov B.R. The technology for the intensification of the process of bioethanol production / B.R. Nussupbekov, A.K. Khassenov, M. Stoev, D.Z. Karabekova, A.Z. Beysenbek // Bulletin of the University of Karaganda-Physics, 2017. — Vol. 1, No. 85. — P. 60–66.

18 Kasymov D.P. Studying the resistance to fire of wood under the different type of thermal impact while forest fires / D.P. Kasymov, M.V. Agafontsev, V.V. Perminov, V.A. Tarakanova // Proceedings of 24th International Symposium on Atmospheric and Ocean Optics, Atmospheric Physics SPIE 10833. — 2018. — P. 1083356. DOI: 10.1117/12.2504454.

19 Kasymov D. Effect of a fire retardant on the ignition of pine wood exposed to smoldering particles of pine bark / D. Kasymov, A. Paletsky // EPJ Web of Conferences. — 2017. — Vol. 159. — P. 00026. DOI: 10.1051/epjconf/201715900026.

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Кейбір ағаш құрылыс материалдарының тұтануының эксперименттік сипаттамасы

Мақалада зертханалық шарттарда табиғи жағдайларда жану және бықсу бөлшектерінің жылулық әсерінің салдарынан ағаш құрылыс материалдары үлгілерінің (фанера, жоспарлы түрде алынған жоңқа тақтасы, сүрек-жоңқа тақтасы) беталысы бойынша зерттеу жүргізілген. Жанып жатқан бөлшектердің мөлшері мен санына, үлгілердің бастапқы температурасына, сондай-ақ бөлшектердің құлау аймағында ауа ағынының болуына байланысты қарағай мен ағаш құрылыс материалдарының (фанера, жоспарлы түрде алынған жоңқа тақтасы, сүрек-жоңқа тақтасы) тұтану уақытын салыстыру деректері алынды. Сондай-ақ, өртену жағдайлары және қарағайдың жанған, бықсыған бөлшектерінің жылу әсерінен ағаштан жасалған құрылыс материалдарының тұтану ықтималдығы зерттелді. Алынған мәліметтер эксперименттің таңдалған параметрлерінде ауа ағынының жоғарылауымен, сондай-ақ бөлшектердің мөлшері мен санының артуымен тұтану уақыты төмендегенін бағалауға мүмкіндік береді. Бөлшектердің мөлшері құрылыс құрылымын тұтандыруда маңызды рөл атқаратындығы эксперименталды түрде расталды. Егер оның көлемінің ағашпен жанасатын бетінің ауданына қатынасы ретінде анықтауға болатын бөлшектің тән мөлшері белгілі бір мәннен аз болса, онда фазалық шекараның жанындағы температураның күрт максимумымен тұтану режимі орындалмайды. Мұны жылу фенінен келетін және химиялық реакциялар нәтижесінде пайда болатын жылу мөлшерімен салыстырғанда жылудың сыртқы ортаға таралуы арқылы түсіндіруге болады. Бөлшектердің тән мөлшері мәселенің нақты тұжырымына және материалдың түріне, оның жылу өткізгіштік коэффициентіне байланысты болады.

Кілт сөздер: жанып жатқан бөлшектер, жылу әсері, ағаш құрылыс материалдары, тұтану.

В.А. Тараканова, Д.П. Касымов, О.В. Гальцева, Н.В. Чичерина

Экспериментальная характеристика воспламенения некоторых древесных строительных материалов

В статье проведено исследование в лабораторных условиях по поведению образцов древесных строительных материалов (фанера, ориентированно-стружечная плита, древесно-стружечная плита) в результате теплового воздействия от горящих и тлеющих частиц природного происхождения. Были получены данные сравнения времени задержки зажигания древесины сосны и древесных строительных материалов (фанера, ориентированно-стружечная плита, древесно-стружечная плита) в зависимости от размера и количества горящих частиц, начальной температуры образцов, а также от наличия воздушного потока в зоне падения частиц. Также исследованы условия зажигания и вероятность воспламенения строительных материалов из древесины в результате теплового воздействия горящих и тлеющих частиц сосны. Полученные данные позволяют судить о том, что при выбранных параметрах эксперимента время зажигания снижалось с увеличением воздушного потока, а также с увеличением размера и количества частиц. Экспериментально подтверждено, что существенную роль в воспламенении строительной конструкции играет размер частиц. Если характерный размер частицы, который можно определить как отношение ее объема к площади поверхности, соприкасающейся с древесиной, меньше некоторой характерной величины, то режим зажигания с резким максимумом температуры возле границы раздела фаз не реализуется. Это можно объяснить превалирующим отводом тепла во внешнюю среду по сравнению с количеством тепла, поступающим от теплового фена и возникающим в результате химических реакций. Характерный размер частиц будет зависеть от конкретной постановки задачи и типа материала, его коэффициента теплопроводности.

Ключевые слова: горящие частицы, тепловое воздействие, древесные строительные материалы, воспламенение.

References

1 Yool, S.R. (1985). Describing the brush fire hazard in southern. *California Annals of the Association of American Geographers, 75*(3), 417–430.

2 Filkov, A., Kasymov, D., Zima, V., & Matvienko, O. (2016). Experimental investigation of surface litter ignition by bark firebrands. *AIP Conference Proceedings, 1698*(060004), 1–6, Doi: 10.1063/1.4937859.

3 Castro, R., & Chuvieco, E. (1998). Modeling Forest Fire Danger from Geographic Information System. *Geocarto International, 13,* 15–23.

4 Clements, H.B. (1977). Lift-off of Forest Firebrands. *Forest Service, U.S. Dept. of Agriculture, Southeastern Forest Experiment Station, Asheville*, SE-159.

5 Maranghides, A., & Mell, W. (2011). A Case Study of a Community Affected by the Witch and Guejito Wildland Fires. *Fire Technology*, *47*, 379–420. DOI: 10.1007/s10694–010–0164-y.

6 Koo, E., Linn, R.R., Pagni, P.J., & Edminster, C.B. (2012). Modelling firebrand transport in wildfires using HIGRAD/FIRETEC. *International Journal of Wildland Fire, 21*, 396–417. DOI: 10.1071/WF09146.

7 Caton, S.E., Hakes, R.S.P., Gorham, D.J., Zhou, A., & Gollner, M.J. (2017). Review of Pathways for Building Fire Spread in the Wildland Urban Interface Part I: Exposure Conditions. *Fire Technology, 53*, 429–473. DOI: 10.1007/s10694–016–0589-z.

8 Cohen, J. (2008). The wildland-urban interface fire problem. *Forest History Today, 11*, 20–26.

9 Koo, E., Pagni, P.J., Weise, D.R., & Woycheese, J.P. (2010). Firebrands and spotting ignition in large-scale fires. *International Journal of Wildland Fire, 19*(7), 818–843. DOI: 10.1071/WF07119.

10 Tohidi, A., Kaye, N., & Bridges, W. (2015). Statistical description of firebrand size shape distribution from coniferous trees for use in metropolis Monte Carlo simulations of firebrand flight distance. *Fire Safety Journal, 77*, 21–35. DOI: 10.1016/j.firesaf.2015.07.008.

11 Pantoli, M.R.L., Muttillo, M., & Annibaldi, V. (2018). Performance Monitoring of Wood Construction Materials by Means of Integrated Sensors. *Key Engineering Materials, 792*, 195–199.

12 Babrauskas, V. (2005). Charring rate of wood as a tool for fire investigations. *Fire Safety Journal, 40,* 528–554, DOI: 10.1016/j.firesaf.2005.05.006.

13 Cohen, J.D. (2000). Preventing disaster: Home ignitability in the wildland-urban interface. *Journal of Forestry, 3*(98), 15–21.

14 Rehm, R.G., Hamins, A., & Baum, H.R. (2001). Community-scale fire spread. *Proceedings of the California's 2001 Wildfire Conference,* California, 126–139.

15 Filkov, A.I., Prohanov, S.A., Mueller, E., & Kasymov, D.P. (2017). Investigation of firebrand production during prescribed fires conducted in a pine forest. *Proceedings of the Combustion Institute, 36*(2), 3263–3270, DOI: 10.1016/j.proci.2016.06.125.

16 Toregldin, M.M., Seldyugaev, O.B., & Tanasheva, N.K. (2019). Protection against dust explosions in coal mines using shale barriers. *Bulletin of the University of Karaganda-Physics, 2*(94), 73–81.

17 Nussupbekov, B.R., Khassenov, A.K., Stoev, M., Karabekova, D.Z., & Beysenbek, A.Z. (2017). The technology for the intensification of the process of bioethanol production. *Bulletin of the University of Karaganda-Physics, 1*(85), 60–66.

18 Kasymov, D.P., Agafontsev, M.V., Perminov, V.V., & Tarakanova, V.A. (2018). Studying the resistance to fire of wood under the different type of thermal impact while forest fires. *Proceedings of 24th International Symposium on Atmospheric and Ocean Optics, Atmospheric Physics SPIE 10833,* 1083356. DOI: 10.1117/12.2504454.

19 Kasymov, D., & Paletsky, A. (2017). Effect of a fire retardant on the ignition of pine wood exposed to smoldering particles of pine bark. *EPJ Web of Conferences, 159*, 00026. DOI: 10.1051/epjconf/201715900026.

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Obtaining functional gradient coatings based on Al$_2$O$_3$ by detonation spraying

The article deals with the phase composition and hardness of Al$_2$O$_3$ coatings obtained by detonation spraying. It was found that a decrease in the delay time between shots is leading to an increase in the hardness and elastic module of Al$_2$O$_3$ coatings. It was found based on X-ray diffraction analysis that the main reason for the increase in hardness with a decreasing in the delay time between shots is associated with increases in the volume fraction of α- Al$_2$O$_3$ phase. A high content of the more ductile γ-Al$_2$O$_3$ phase at the substrate-coating interface leads to an increase in adhesion characteristics, and a high content of the α-Al$_2$O$_3$ phase on the coating surface provides high hardness and wear resistance. The studies of X-ray diffraction presented that the highest phase content is achieved when the coatings are formed with a delay time between shots of 0.25 s. It was found that increase in the volume fraction of the α-Al$_2$O$_3$ phase is caused by the secondary recrystallization γ → α, which occurs due to the heating of particles during coating formation, i.e. due to increase in temperature above 1100 ºC in single spots of the coating when they are put each other.

Keywords: detonation spraying, gradient coating, aluminum oxide, structure, hardness, wear resistance, phase, temperature.

Introduction

Currently, methods of applying powder coatings are the effective remedy of increasing the reliability and durability of structural materials for machine parts, equipment, technological and tooling [1]. The restoration and enhancing of machine parts using powder coatings has given rise to a whole family of so-called gas thermal technological processes [2]. The current trend of increasing the adhesion properties of gas thermal coatings is directed to improving the speed of sprayed particles. Therefore, there is much interested in high-speed technologies for coating deposition, which are characterised by high performance, universality, simplicitÿ of automation, and almost unlimited sizes of the surfaces to be coated. Geothermal high-speed methods for obtaining coatings include methods of detonation, high-velocity air-oxygen fuel (HVAOF) and high-velocity oxygen fuel (HVOF) spraying [3–5]. Among them, prospective is detonation spraying [6–9]. However, widely used the detonation method for strengthening components and equipment parts for the oil and gas industry, shipbuilding, metallurgy, gas turbine engineering, etc. requires a significant increase in the properties of the obtained coatings. It is related to the components and parts of the above equipment operate under the simultaneous influence of various environments and loads, the values of which in many cases exceed the maximum permissible values for existing detonation coatings. Significantly increase the properties of detonation coatings can be achieved by spraying various materials (powders) in several layers, which allows you to obtain coatings with special characteristics. This is also possible when using gradient coatings of the same material, which structure and properties change in the depth of the coatings. Such coatings have the necessary specified properties of the outer layers that are exposed to the direct impacts on the external environment. Besides, compared to a multi-layer coating, they reduce the difference between the physical and mechanical characteristics of the coating and the base. Therefore, the stress jump occurs when loading at the border of the interface layers is reduced.

In connection with, the task was in this work to obtain and study functional gradient coatings based on aluminium oxide obtained on a single-barrel detonation unit by changing the technological parameters during spraying with the use of only one dispenser, i.e. one type of powder.

Methods and materials

Stainless steel 12Kh18N10T was chosen as the substrate. Before coating, the samples were exposed to sandblasting. For the obtain coatings of zirconium oxide was used powders of corundum (α-Al$_2$O$_3$). Powder

particle size is 22–45 mμ. Detonation coatings were obtained by a new generation of CCDS2000 (Computer Controlled Detonation Spraying) computerized detonation spraying system [10]. Table 1 shows the modes for obtaining functional gradient coatings based on Al_2O_3.

Technological parameters for obtaining functional gradient coatings Al_2O_3

Ratio of O_2/C_2H_2	Filling volume of the barrel, %	Spray distance, mm	Number of shots fired	Delay time between shots, s
1.856	63	250	20	1.00–0.25

The general view and schematic diagram of the detonation spraying process are shown in Figure 1. The channel inside the gun barrel is filled with gases using a high-precision gas distribution system, which is controlled by a computer. The process begins with filling the channel with a carrier gas. After that, a particular portion of the explosive mixture is fed in such a way that a layered gas medium is formed, consisting of an explosive charge and a carrier gas. Using a carrier gas stream for the powder is injected into the barrel (using a computer-controlled feeder) and forms a cloud. The substrate is allocated at a certain distance from the output from the barrel. After some of the gunpowder is injected, the computer sends a signal to initiate detonation. is is realized by an electric spark. The duration of the explosive charge combustions is about 1 ms. In the explosive mixture, a detonation wave is formed, which in the carrier gas passes into a shockwave. The detonation products (heated to 3500–4500 K) and the carrier gas (heated by the shockwave to 1000–1500 K) move at supersonic speed. The interaction time of gases with the sprayed particles is 2–5 ms. The particle speed can reach 800 ms^{-1} [11].
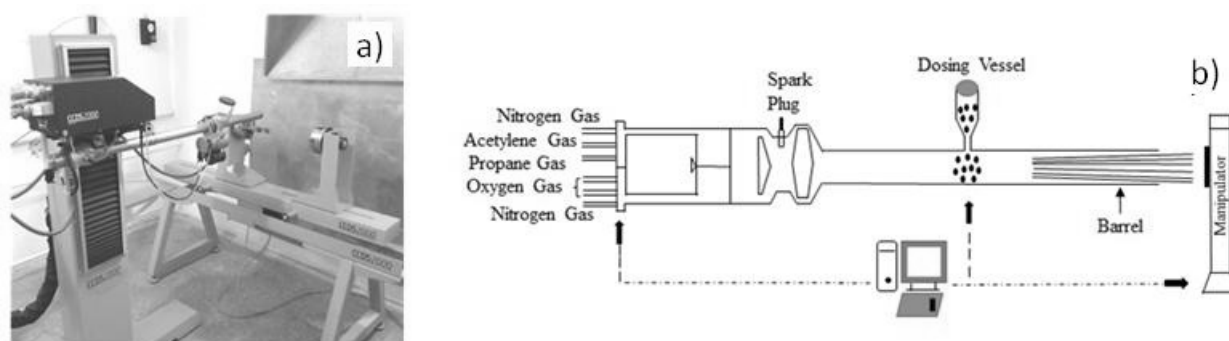
Figure 1. Computerized detonation complex CCDS2000 (*a*) and its schematic diagram (*b*)

The phase composition of the samples was studied by X-ray diffraction analysis on an X'pert Pro diffractometer using CuKα-radiation. The measurement of hardness and modulus of elasticity was determined by indenting on a nano hardness «NanoScan-4D compact» by state standard R 8.748–2011 and ISO 14577. The tests were performed at a load of 100 mN. Tribological tests for sliding friction were performed on a high-temperature tribometer TRB[3] using the standard «ball-disk» method (international standards ASTM G 133–95 and ASTM G 99). As a counterbody was used a 3.0 mm diameter ball made of SiC-coated steel. The tests were performed at a load of 10 N and a linear velocity of 3 cm/s, with a wear radius of 4 mm, and a friction path of 81 m. Tribological characteristics of the modified layer were characterized by wear intensity and friction coefficient. All types of experimental studies were performed at the Scientific Research Center «Surface Engineering and Tribology» of the Non-limited profit company Sarsen Amanzholov East Kazakhstan University.

Results and discussion

In work [12], was studied the effect of the detonation spraying mode on the structure and properties of Al_2O_3 coatings. Determined, a decrease in the delay time between shots brings to an increase in the hardness and elastic modulus of Al_2O_3 coatings. Based on X-ray phase analysis was found, the main reason for the increase in hardness with a decrease in the delay time between shots is associated with an increase in the volume fraction of the α-Al_2O_3 phase. X-ray phase analysis showed the highest content of the α-phase is achieved when coatings are formed with a delay between shots of the order of 0.25 s. It was found, the in-

crease in the volume fraction of the α-Al_2O_3 phase is caused by secondary recrystallization of $\gamma \rightarrow \alpha$, which occurs due to the warming of the particles during the coating formation, i.e., due to an increase in the temperature above 1100 ºC in individual coating spots when they overlap each other. In this regard, we studied the possibility of obtaining functional gradient coatings, which the gradient of structure and properties is based on a gradual increase in the volume fraction of the α-Al_2O_3 phase from the substrate to the outer layer.

Figure 2 shows the diffractograms of a multilayer gradient coating obtained by a gradual decrease in the delay time between shots during spraying. Multilayer coating consists of four layers. All coating layers are contained the γ-Al_2O_3 and α-Al_2O_3 phases.
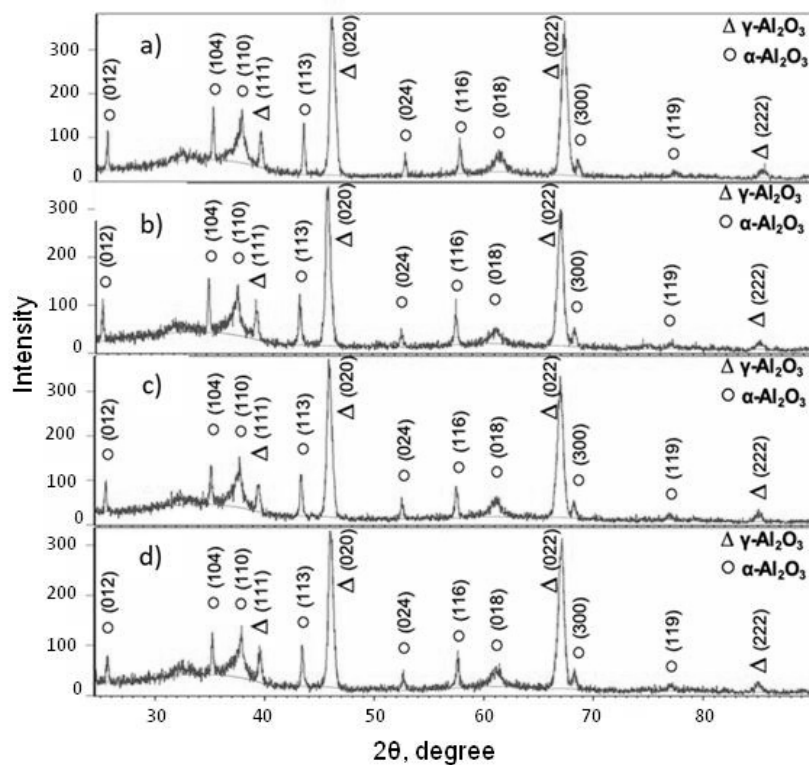
a — fourth layer; *b* — third layer; *c* — second layer; *d* — first layer

Figure 2. Diffractogram of the coating

Herewith, there is a gradual increase in the intensity of the α-Al_2O_3 phase reflexes from the substrate to the surface. The results of the quantitative analysis showed that the volume fraction of the α-Al_2O_3 phase from the substrate to the outer layer gradually increases. The volume fraction of the α-Al_2O_3 phase in the first layer is 24 %, in the second layer 30 %, in the third layer 31 %, in the fourth layer, i.e. on the coating surface the volume fraction of the α-Al_2O_3 phase is 34 %.

Figure 3 shows a graph of the microhardness distribution over the thickness of gradient coatings. The graph of the dependence of microhardness on the depth of the gradient coating Al_2O_3 shows an unequal distribution of microhardness: the coating near the transition layer has a lower microhardness value, indifference the upper part of the coating. Herewith, there is a uniform increase in microhardness from the substrate to the surface of the coating.

A layer-by-layer analysis was performed of the functional gradient coating of Al_2O_3. After spraying each layer, was studied the structure and tribological characteristics of the coatings. Table 2 shows data of layers of functional gradient coating Al_2O_3 the structure and tribological characteristics. Experimental data clearly illustrates the correlation between the structural and tribological characteristics of layers of Al_2O_3 functionally gradient coating.

The generalized data given in the Table 2, the dependence of the wear intensity, hardness, and friction coefficient of the Al_2O_3 coating layers on its structural and phase states is clearly traced. The wear resistance of the first, second and third layers (delay time between shots 1 s) is significantly lower than that of the fourth layer (delay time between shots 0.25 s). The fourth layer, consisting of γ-Al_2O_3 (66 %) and α-Al_2O_3

(34 %), showed high tribological characteristics. The effects of increasing hardness and wear resistance are directly related to the volume fraction of the α-Al$_2$O$_3$ phase, which are formed during the spraying process due to heating of the coating surface.
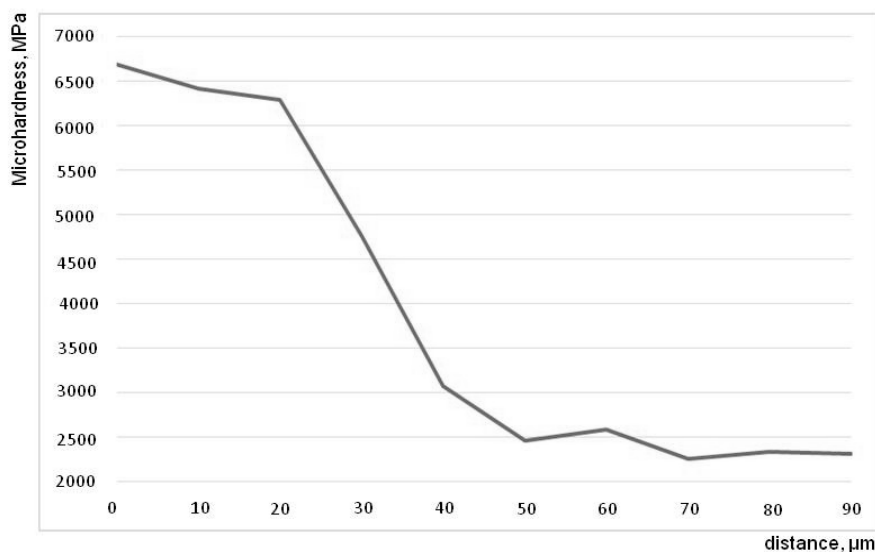
Figure 3. Graph of hardness distribution by depth of gradient coatings Al$_2$O$_3$

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**Experimental data on the structure and tribological characteristics
of functional gradient coating layers Al$_2$O$_3$**

Coating layer	Phase composition	Nanohardness, GPa	Young modulus, GPa	Coefficient of friction	Wear intensity, mm^3/(m·N)
First layer	γ-Al$_2$O$_3$ (76 %) and α-Al$_2$O$_3$ (24 %)	10.87	207.70	0.42	3.83·10^{-5}
Second layer	γ-Al$_2$O$_3$ (70 %) and α-Al$_2$O$_3$ (30 %)	11.03	159.97	0.48	4.16·10^{-5}
Third layer	γ-Al$_2$O$_3$ (69 %) and α-Al$_2$O$_3$ (31 %)	11.72	206.48	0.41	3,73·10^{-5}
Fourth layer	γ-Al$_2$O$_3$ (66 %) and α-Al$_2$O$_3$ (34 %)	16.33	270.64	0.37	1,60·10^{-5}

Conclusion

A method for obtaining multilayer gradient coatings based on Al$_2$O$_3$ with various modifications, varying the technological modes of detonation spraying has been developed. The developed method allows obtaining gradient coating structures on a single barrel detonation installation with a unique dispenser by changing the delay time between shots. It is determined that a decrease in the delay time between shots leads to an increase in the hardness, modulus of elasticity and wear resistance of Al$_2$O$_3$ coatings. Based on X-ray phase analysis, it was found that the main reason for the increase in hardness with a decrease in the delay time between shots is associated with an increase in the volume fraction of the α-Al$_2$O$_3$ phase. A high content of the more plastic γ-Al$_2$O$_3$ phase at the substrate-coating border leads to an increase in the adhesion characteristics, and a high content of the α-Al$_2$O$_3$ phase on the coating surface provides high hardness and wear resistance. Therefore, we obtained a functional gradient coating in which the gradient of structure and properties is based on a gradual increase in the volume fraction of the α-Al$_2$O$_3$ phase from the substrate to the outer layer.

References

1 Погребняк А.Д. Получение и исследование структуры и свойств плазменно-детонационных покрытий из Al$_2$O$_3$ / А.Д. Погребняк, Ю.Н. Тюрин, Ю.Ф. Иванов, А.П. Кобзев, О.П. Кульментьева, М.И. Ильяшенко // Письма в ЖТФ. — 2000. — Т. 26(21). — С. 53–60.

2 Gladish G. Physics of Laser Materials Processing: Theory and Experiment. Springer Series in Materials Science / G.G. Gladish, I. Smurov. — NY: Springer, 2011. — 552 p.

3 Ulianitsky V.Y. Detonation spraying behaviour of refractory metals: Case studies for Moand Ta-based powders / V.Y. Ulianitsky, I.S. Batraev, A.A. Shtertser, D.V. Dudina, N.V. Bulina, I. Smurov // Advanced powder Technology. — 2018. — Vol. 29(8). — P. 1859–1864.

4 Shaopeng N. A comparative study of La$_{0.6}$Sr$_{0.4}$Co$_{0.2}$Fe$_{0.8}$O$_3$ — δ oxygen transport membranes deposited on porous metal supports prepared by supersonic air-gas plasma spraying (SAPS) and low pressure plasma spraying-physical vapor deposition (PS-PVD) / N. Shaopeng, Zh. Kesong, X. Liping, D. Changguang, L. Min, M. Jie // Surface and Coatings Technology. — 2016. — Vol. 307(A). — P. 963–970.

5 Student M.M. Structure and Wear Resistance of VC–FeCr and VC–FeCrCo Coatings Obtained by Supersonic Flame Spraying / M.M. Student, H.V. Pokhmurs'ka, Kh.R. Zadorozhna // Materials Science. — 2018. — Vol. 54. — P. 22–29.

6 Rakhadilov B.K. Research of annealing influence on the hardness of detonation coatings from zirconium dioxide / B.K. Rakhadilov, D.N. Kakimzhanov, N. Kantai, P. Kowalewski, R.S. Kozhanova // Bulletin of the university of Karaganda-Physics. — 2020. — Vol. 2(98). — С. 75–82.

7 Buitkenov D. Impact of the detonation gas spraying mode on the phase composition and adhesional strength of Ti-Si-C coating / D.B. Buitkenov, B.K. Rakhadilov, W. Wieleba, M.K. Kylyshkanov, D. Yerbolatuly // Bulletin of the university of Karaganda-Physics. — 2020. — Vol. 1. — С. 59–64.

8 Hermanek F.J. What is Thermal Spray? For the International Thermal Spray Association (ITSA) [Electronic resource] / F.J. Hermanek. — 2014. — Retrieved from: www.thermalspray.org.

9 Rakhadilov B.K. Structure and properties of detonation coatings based on titanium carbosilicide / B.K. Rakhadilov, D.B. Buitkenov, B.T. Tuyakbaev, Zh.B. Sagdoldina, A.B. Kenesbekov // Key Engineering Materials. — 2019. — Vol. 821.— P. 301–306.

10 Ulianitsky V.Y. Computer-controlled detonation spraying: flexible control of the coating chemistry and microstructure / V.Y. Ulianitsky, D.V. Dudina, A. Shtertser, I. Smurov // Metals. — 2019. — Vol. 9(12). — P. 1244.

11 Buitkenov D. Influence of heat treatment on the phase composition and microhardness of coatings based on Ti$_3$SiC$_2$/TiC / D. Buitkenov, B. Rakhadilov, D. Erbolatuly, Zh. Sagdoldina // Key Engineering Materials. — 2019. — Vol. 839. — P. 137–143.

12 Rakhadilov B.K. The effect of detonation spraying on the phase composition and hardness of Al$_2$O$_3$ coatings / B.K. Rakhadilov, D.B. Buytkenov, D. Kakimzhanov, R.S. Kozhanova, G.S. Bektasova // Eurasian Journal of Physics and Functional Materials. — 2020. — Vol. 4(2). — P. 160–166.

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Детонациялық тозаңдату әдісімен Al$_2$O$_3$ негізінде функционалдық-градиенттік жабындарды алу

Мақалада детонациялық бүрку режимінің Al$_2$O$_3$ жабындарының құрылымы мен қасиеттеріне әсері зерттелді. Ату арасындағы кідіріс уақытының азаюы Al$_2$O$_3$ жабындарының қаттылығы мен серпімділік модулінің жоғарылауына әкелетіні анықталды. Рентгендік фазалық талдау негізінде кадрлар арасындағы кідіріс уақытының азаюымен қаттылықтың жоғарылауының негізгі себебі α-Al$_2$O$_3$ фазасының көлемдік үлесінің артуымен байланысты екендігі анықталды. Төсем мен жабын шекарасындағы пластикалық γ-Al$_2$O$_3$ фазасының неғұрлым көп мөлшері адгезиялық сипаттамаларының жоғарылауына әкеледі, ал жабындар бетіндегі α-Al$_2$O$_3$ фазасының көп мөлшері жоғары қаттылық пен тозуғатөзімділікті қамтамасыз етеді. Рентгендік фазалық зерттеу көрсеткендей, α фазасының ең көп мөлшері 0,25 с бүрку арасындағы кідіріспен жабындарды қалыптастыру кезінде қол жеткізіледі. Фазаның α-Al$_2$O$_3$ көлемдік үлесінің артуы γ → α-ның қайталамалы қайта кристалдануымен байланысты екендігі анықталды, бұл жабынды қалыптастыру кезінде бөлшектердің қызуы нәтижесінде пайда болады, яғни олар бір-біріне қабаттасқан кезде жабынның бір дақтарында температураның 1100 °C-тан жоғары көтерілуіне байланысты.

Кілт сөздер: детонациялық бүрку, градиентті жабын, алюминий оксиді, құрылым, қаттылық, тозуғатөзімділік, фаза, температура.

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Получение функционально-градиентных покрытий на основе Al₂O₃ методом детонационного напыления

В статье было изучено влияние режима детонационного напыления на структуру и свойства покрытий Al₂O₃. Определено, что уменьшение времени задержки между выстрелами приводит к повышению твердости и модуля упругости покрытий Al₂O₃. На основе рентгенофазового анализа установлено, что основная причина повышения твёрдости при уменьшении времени задержки между выстрелами связана с повышением объемной доли α-Al₂O₃ фазы. Большое содержание более пластичной γ-Al₂O₃-фазы на границе подложка–покрытие приводит к увеличению адгезионных характеристик, а большое содержание α-Al₂O₃-фазы на поверхности покрытий обеспечивает высокую твердость и износостойкость. Рентгенофазовое исследование показало, что наибольшее содержание α-фазы достигается при формировании покрытий с задержкой между выстрелами порядка 0,25 с. Установлено, что увеличение объемной доли α-Al₂O₃ фазы обусловливается вторичной перекристаллизацией γ → α, происходящей вследствие отогрева частиц при формировании покрытия, т.е. при возрастании температуры выше 1100 ℃ в единичных пятнах покрытия в результате их наложения друг на друга.

Ключевые слова: детонационное напыление, градиентное покрытие, оксид алюминия, структура, твердость, износостойкость, фаза, температура.

References

1 Pogrebnyak, A.D., Tyurin, Yu.N., Ivanov, Yu.F., Kobzev, A.P., Kulmentyeva, O.P., & Iliashenko, M.I. (2000). Poluchenie i issledovanie struktury i svoistv plazmenno-detonatsionnykh pokrytii iz Al₂O₃ [Preparation and investigation of the structure and properties of plasma-detonation coatings from Al₂O₃]. *Pisma v ZhTF — Letters to ZhTF, 26*(*21*), 53–60 [in Russian].

2 Gladish, G., & Smurov, I. (2011). *Physics of Laser Materials Processing: Theory and Experiment. Springer Series in Materials Science.* NY: Springer.

3 Ulianitsky, V.Y., Batraev, I.S., Shtertser, A.A., Dudina, D.V., Bulina, N.V., & Smurov, I. (2018). Detonation spraying behaviour of refractory metals: case studies for Moand Ta-based powders. *Advanced Powder Technology, 29,* 8, 1859–1864.

4 Shaopeng, N., Kesong, Zh., Liping, Xu., Changguang, D., Min, L., & Jie, M. (2016). A comparative study of La₀.₆Sr₀.₄Co₀.₂Fe₀.₈O₃ — δ oxygen transport membranes deposited on porous metal supports prepared by supersonic air-gas plasma spraying (SAPS) and low pressure plasma spraying-physical vapor deposition (PS-PVD). *Surface and Coating Technology, 307(A),* 963–970.

5 Student, M.M., Pokhmurs'ka, H.V., & Zadorozhna, Kh.R. (2018). Structure and wear resistance of VC–FeCr and VC–FeCrCo coatings obtained by supersonic flame spraying. *Journal of Materials Science, 54,* 22–29.

6 Rakhadilov, B.K., Kakimzhanov, D.N., Kantai, N., Kowalewski, P., & Kozhanova, R.S. (2020). Research of annealing influence on the hardness of detonation coatings from zirconium dioxide. *Bulletin of the university of Karaganda-Physics*, *2(98),* 75–82.

7 Buitkenov, D.B., Rakhadilov, B.K., Wieleba, W., Kylyshkanov, M.K., & Yerbolatuly, D. (2020). Impact of the detonation gas spraying mode on the phase composition and adhesional strength of Ti-Si-C coating. *Bulletin of the university of Karaganda-Physics*, *1,* 59–64.

8 Hermanek, F.J. (2014). *What is Thermal Spray? For the International Thermal Spray Association (ITSA). Thermalspray*. Retrieved from: www.thermalspray.org.

9 Rakhadilov, B.K., Buitkenov, D.B., Tuyakbaev, B.T., Sagdoldina, Zh.B., & Kenesbekov, A.B. (2019). Structure and properties of detonation coatings based on titanium carbosilicide. *Key Engineering Materials, 821,* 301–306.

10 Ulianitsky, V.Y., Dudina, D.V., Shtertser, A., & Smurov, I., (2019). Computer-controlled detonation spraying: flexible control of the coating chemistry and microstructure. *Metals, 12*, 1244.

11 Buitkenov, D., Rakhadilov, B., Erbolatuly, D., & Sagdoldina, Zh. (2020). Influence of heat treatment on the phase composition and microhardness of coatings based on Ti₃SiC₂/TiC. *Key Engineering Materials, 839,* 137–143.

12 Rakhadilov, B.K., Buytkenov, D.B., Kakimzhanov, D., Kozhanova, R.S., & Bektasova, G.S. (2020). The effect of detonation spraying on the phase composition and hardness of Al₂O₃ coatings. *Eurasian Journal of Physics and Functional Materials, 4(2),* 160–166.

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Normalization of reproducibility and suitability indexes
for assessment of products or production services quality

A technique is proposed for estimating the probability of the possible appearance of defective products (or the inconsistency of the production service) on the basis of the suitability and reproducibility indexes of the production process. The index of reproduction is recommended to be calculated on the basis of the standard deviation, which can be established by the average span of the control map and the limits of the tolerance field. At the same time, the production process must necessarily be in a state of statistical controllability. The suitability index can not be calculated on the basis of the control card characteristics, but is calculated solely on the basis of the total of the standard deviation, which is calculated on the basis of the Bessel formula and tolerance limits. The production process does not need to be statistically controllable. Conclusions on the suitability or insufficiency of the products (production services) are based on the value of the indexes of reproduction and suitability, which can take values less than or greater than one. On the basis of the obtained values of these indexes, the probability of production appearance or characteristics of the production process, that does not match the established requirements, is established.

Keywords: normalization, quality assessment, product quality, quality of manufacturing services, suitability index, reproducibility index, probability of defective product, production process.

Introduction

In order to ensure the competitiveness of enterprises products, manufacturers should apply a strategy of continuous improvement. For the implementation of a such strategy, product manufacturers or service providers need to constantly evaluate their products [1]. It is advisable to apply the methods recommended by the international standards of the ISO/TR 18532, ISO 13528 and ISO/TR 22514 [2–5]. For the successful implementation of actions to continually improve the quality of products or services, it is necessary to monitor the sources of the production process deviations and their stability.

In the conditions of competition for producers, not only the price of products or services should be important, but also the costs, that consumers will spend when using products (or services). Therefore, the purpose of any manufacturer should be to continuously reduce the deviations of the production process parameters (ensuring the stability of the production process), and not only compliance with established requirements. The strategy of continuous improvement will reduce the costs associated with failures, and will increase the sustainability of enterprise development in a competitive environment. In addition, reducing deviations will reduce control costs or reduce the frequency of selective control. Quantitative evaluation of deviations allows us to make conclusions about the suitability and conformity of the production process to the established requirements. For identification of deviations, the different methods, such as drawing up a flowchart and identifying inputs and outputs of a production process, using a causal diagram, etc. can be used.

Formulation of the problem

A number of international standards [1–5] recommend a variety of statistical methods that can be used to manage, control and improve the production process in order to analyze data and evaluate product quality indicators. Therefore, there is the actual problem of the development of mathematical models of the point evaluation of the reproducibility indexes and the suitability of the production process to confirm its statistical stability, as well as the establishment of the defective products probability appearance (or the proportion of units that do not match the requirements), which is the purpose of this article. The description of the mathematical models that can be used to evaluate the quality indexes on the basis of reproduction and suitability

indexes is an actual scientific task, since many manufacturers of products do not understand their differences and consequently incorrectly interpret the obtained results.

In order to achieve the set purpose of the article, it is necessary to develop methods for evaluating the quality indexes of products (services) on the basis of the indexes of reproducibility and suitability of the production process, as well as to formulate the criteria for normalization of reproduction and suitability indexes for decision-making on conformity (sufficient, satisfactory, good) or non-compliance of product quality indicators or production services to the established requirements.

Research results

Indicator of the reproducibility of a production process is a measure of its own change of the output characteristics of the production process, which is in a state of statistical control, and which enables to assess the ability of the process to maintain the output characteristics of the production process at the level of requirements set for it. This measure characterizes the variability that remains after eliminating all known causes. If the control of the production process is carried out using a control card, then the control card shows that the production process is in a controlled state [4, 6]. Reproducibility of the production process is often estimated by the number of products, the characteristics of which are within the tolerance field. Since the production process in a statistically controlled state can be described by the predicted distribution law, then the quantity of products which characteristics is beyond the tolerance field can be estimated. While the production process remains in a state of statistical control, the manufactured products have, on average, the same proportion of the defective products (products that do not match the established requirements).

The actions of the production process management, which are aimed to reducing the deviations caused by accidental causes, will make it possible to improve the conformity of the production process with the requirements of the quality management system. To do this, it is necessary: to determine the characteristics of the production process and the conditions of operation (if the conditions are changed, then new studies of the characteristics of the production process are necessary); to evaluate the parameters of short-term and long-term deviations in the form of percentages from full changes and to minimize them; maintain the stability of the production process and ensure its statistical control; to evaluate the own variability of the reproduction process; select the required parameter of the reproducibility of the production process.

Also, it is necessary to check the control card, the data of which had been used for statistical control, and the histogram data with all the established limits applied to it. In addition, it is necessary to check the normality of the distribution law by a valid criteria, for example, such as the Anderson-Darling criteria [7] or the χ^2-criteria [4]. These criteria are effective in detecting the deviation of the law of distribution from normality on the distribution tails, since this area is important in the evaluation of the indexes of reproduction and suitability of the production process. Also, an abnormal data explanation must be found and appropriate actions taken with the data to calculate the investigated parameter. Exclusion of data allocated to others is unacceptable. Such deviations can be very informative about the properties of the production process and should be investigated.

Reproducibility parameter of the production process may be a value that characterizes one or more properties of the distribution of the input characteristic in the conditions of the production process reproducibility. The general parameter of the distribution position is the mean (mathematical expectation) μ, but sometimes selective median $X_{50\%}$ is used. For a normal distribution law, the best position parameter is the median.

The best parameter characterizing the own variability of the production process is the standard deviation σ — index of reproducibility of the production process. It is recommended to evaluate it according to the average magnitude $\overline{R}$ obtained by the control card, when the production process is stable and is in a state of statistical control

$$\hat{\sigma} = \frac{\overline{R}}{d_2},$$
(1)

where d_2 is a constant corresponding to the sample size in the subgroup, its value is chosen from Table 1 [8].

Coefficients of the control card to estimate the standard deviation

Sample size (n)	d_2	c_4
2	1.128	0.7979
3	1.693	0.8862
4	2.059	0.9213
5	2.326	0.9400
6	2.534	0.9515
7	2.704	0.9594
8	2.847	0.9650
9	2.970	0.9693
10	3.078	0.9727

If we use the average standard deviation for controlling deviations within a subgroup, which is determined by the data of the control card, then the own standard deviation of the production process can be estimated by the formula

$$\hat{\sigma} = \frac{\overline{S}}{c_4}, \tag{2}$$

where S — average sampled standard deviation; c_4 — the constant corresponding to the sample size in the subgroup (n), its value is chosen from Table 1.

If for each subgroup it is possible to calculate the standard deviation of a subgroup, then a formula for assessing the standard deviation of the production process is recommended, which gives a more accurate estimate than formulas (1) and (2), which is described by formula

$$\hat{\sigma} = \sqrt{\frac{\sum_{j=1}^{m} S_j^2}{m}}, \tag{3}$$

were S_j — sampled standard deviation of j-th subgroup; m — is the number of subgroups with n observations in each subgroup.

It is also necessary to distinguish between the standard deviation, that characterizes only short-term changes in the production process, and the standard deviation that characterizes the long-term changes in the production process. And the data received over a long period of time have bigger value of standard deviation due to a more significant change in the production process. In this case, it is recommended to use the symbol σ_t to denote the standard deviation — the total (full) standard deviation.

If the data are obtained from the observation of a production process that is not in a state of statistical control or if control cards have not been used, then formula (1)–(3) should not be used to calculate the standard deviation, but it is necessary to apply the following formula

$$\hat{\sigma}_t = \sqrt{\frac{\sum_{i=1}^{N} \left(x_i - \overline{x} \right)^2}{N-1}}, \tag{4}$$

where N — total sample size; x_i — the i-th value in the sample; x — average arithmetic mean.

Equation (4) should be used when the production process has a change in the average value due to the presence of a systematic error [9], which can not be excluded, and this variability must be taken into account with along the random variability. This variation parameter is also suitable for use in the calculation of the suitability indexes of the production process.

With the normal distribution of the production process as an estimate of the reproducibility of the production process, an expression can be used

$$\overline{\overline{x}} \pm z_\alpha \cdot \hat{\sigma}_t, \tag{5}$$

where $\overline{\overline{x}} = \sum_{j=1}^{m} \overline{x}_j / m$ — the arithmetic average of several sample meanings; $\overline{x}_j$ — selective average of j-th subgroup; z_α is a quantile of a normalized normal distribution law.

The choice of the value of z_α depends on the used value of the reproducibility index of the production process in units of production of one million. Typically, z_α is assigned a value of 3, 4 or 5. If the reproducibility index of the production process matches the requirements, $z_\alpha = 3$ means an average of 2700 units of products per million beyond the requirements. Similarly, $z_\alpha = 4$ means an average of 64 units of products per million that do not match the established requirements, and $z_\alpha = 5$ means an average of 0.6 such items per million.

Reproducibility indexes of the production process are the point of estimation of their reference values. Using the reproducibility index of the production process allows us to characterize the state of the production process. The index of reproducibility of the production process is the ratio between the differences of the tolerance field to the length of reference interval

$$C_p = \frac{U - L}{X_{99.865\%} - X_{0.135\%}},$$ (6)

where L — lower limit of the tolerance field; U — the upper limit of the tolerance field; $X_{0.135\%}$ — the lower limit of the reference interval defined as the quantile of distribution at the level of 0.135 %; $X_{99.865\%}$ — the upper limit of the reference interval, which is defined as quantile of distribution at 99,865 %.

To estimate the index of reproducibility of the production process the reference interval $T = Y2 - Y1$ is used [4, 5], which includes 99.73 % of the production process characteristics values, which are in the state of statistical control. At the same time 0.135 % of each side of the distribution law is cut off [4, 5]. This interval is recommended to apply even in the case of a non-normal distribution law of the production process characteristics values [4, 10, 11]. For a normal distribution law, the length of the reference interval is six standard deviations (Fig. 1).

Control maps are usually used to evaluate reproducibility. If the control card shows weakened control lines or modified control lines, the actual standard deviation of the process will be greater than the standard deviation obtained from the control card with standard control lines. These features affect the reference interval, so it is important that the standard control lines were fixed in the evaluation of the reproducibility index of the production process.

A reproducible process is a production process with a reference interval T smaller than the tolerance field (L, U) for a certain value, as shown in Figure 1.
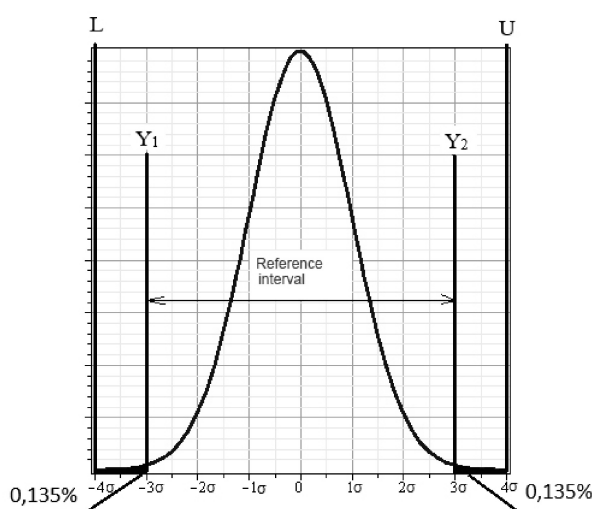
Figure 1. The length of the reference interval T and the lower L and the upper U limits of the tolerance field

It is also recommended by international standards [1, 3, 4] to use other indexes that characterize both the state and the variability of the production process, for example, the reproducibility index C_{pk}. If this index is smaller than a given value, then it can be assumed that in the manufacturing process there is a high probability of occurrence of defective products, that is, the characteristic of the production process goes beyond the tolerance field (L, U).

The reproducibility indexes C_{pk} can be defined as the ratio of difference between the tolerance field and the production process value to the difference between the corresponding limits of the production process value and the parameter of the production process:

$$C_{PkU} = \frac{U - X_{50\%}}{X_{99.865\%} - X_{50\%}},$$ (7)

$$C_{PkL} = \frac{X_{50\%} - L}{X_{50\%} - X_{0.135\%}},$$ (8)

where $X_{50\%}$ — the quantile of the distribution law of the production process at the level of 50 %.

These reproducibility indexes (C_{PkL}, C_{PkU}) provide information about how tightly the characteristics are routed around the centerline and whether product specification requirements may be violated. Even if the value of the index C_P is high, then the low values of the C_{Pk} indexes indicate that the production process is poorly concentrated around the central line, and the probability of the appearance of quality characteristics values beyond the established limits of the set requirements is high.

If the observed values are distributed according to the normal distribution law, the length of the reference interval is equal to $6\hat{\sigma}$, and the reproducibility index can be estimated by expression

$$\hat{C}_p = \frac{U - L}{6\hat{\sigma}}.$$ (9)

If the distribution of individual values is subject to the normal distribution law, then quantile $X_{50\%}$ is equal to the mathematical expectation μ, and the upper and lower indexes of the reproducibility C_{Pk} can be estimated from the expressions:

$$\hat{C}_{PkU} = \frac{U - \mu}{3\hat{\sigma}},$$ (10)

$$\hat{C}_{PkL} = \frac{\mu - L}{3\hat{\sigma}}.$$ (11)

Based on the evaluation of the lower $\hat{C}_{PkL}$ and upper $\hat{C}_{PkU}$ reproducibility indexes, for the final evaluation of the reproducibility index C_{Pk}, it is necessary to assume a lower reproducibility index

$$\hat{C}_{Pk} = \min\left(\hat{C}_{PkL}, \hat{C}_{PkU}\right).$$ (12)

In calculating the reproducibility index of the production process, it must be taken into account that the variability of the production process should correspond to the situation when the data has been obtained in a state of statistical control of the production process.

If the index of the reproducibility $C_P < 1$ (or $C_{Pk} < 1$), then the upper U and the lower L limits of the tolerance field are inside the reference interval T of the production process — this means that the production is not possible without a defect, and the production process is unsatisfactory (the probability of defective production is very high and may be higher than 0.27 %).

If the value $C_P = 1$ (or $C_{Pk} = 1$), then the upper U and the lower L limits of the tolerance field coincide with the reference interval T of the production process. In this case, if the process is centered and the distribution of quality indicators obeys the normal law, then the possible lack of products is 0.27 % (2700 defective products per 1 million manufactured goods). In this case, the production process is considered to be the minimum acceptable (satisfactory, it is recognized as reproducible).

If the value of the reproducibility index $C_P > 1$ (or $C_{Pk} > 1$), then the upper U and the lower L limits of the tolerance field are outside the reference interval T of the manufacturing process — this means that production is possible without defects, and the production process is considered to be satisfactory. If the value C_{Pk} (or C_P) lies within $1 < C_{Pk} < 1.33$, then the probability of occurrence of defective products will be in the range from 0.006 % to 0.27 %. If the value of the index of reproducibility is greater than 1.33 ($C_{Pk} > 1,33$), then the probability of occurrence of defective products is less than 0,006 %, and the production process is considered good.

The appropriateness of the production process regarding the quality of products is the achieved distribution of results. The only important difference between the suitability and reproducibility of the production

process is that for assessing the suitability of the production process there is no requirement for the presence in the production process of the state of statistical control and control cards.

In the analysis of the suitability of the production process:

a) all technical conditions, including requirements for the production environment, such as temperature and humidity requirements et al., must be established [12–15];

b) requirements for uncertainty of measurements must be established [9, 16–20];

c) an opportunity should be provided for the analysis of multi-factor and multi-level aspects of the production process;

d) data must be obtained and registered within a specified time period;

e) the frequency of sampling and the start and end of time of the data obtaining must match the requirements set by the quality management system [1];

f) the process may not be monitored by a control card;

g) the process may be statistically uncontrolled, in particular, previously obtained data, which sequence is unknown, can be used to assess the suitability of the production process.

The index of the suitability of the production process is a statistical indicator, which is determined by the output characteristic of the production process, which used to evaluate the production process, the location of which in the state of statistical control is not confirmed. The parameter of the suitability of the production process may be the quantities describing one or more properties of the quality characteristic distribution in terms of suitability. To estimate the suitability parameter, in contrast to the reproducibility parameter, under the normal distribution of the quality characteristic, we can only by expression (4). The index of the suitability of a production process is an index that reflects the stability of the production process to the specified field of tolerance.

If the values of the parameters under study are distributed according to the normal distribution law, then the length of the reference interval is equal to $6\hat{\sigma}$ [10, 11]. Therefore, the value of the index of fitness P_P can be calculated by expression

$$P_p = \frac{U - L}{6\hat{\sigma}_t}. \tag{13}$$

The upper P_{PkU} and lower P_{PkL} indexes of the suitability of the production process can be estimated by the expressions:

$$P_{pkU} = \frac{U - \overline{x}}{3\hat{\sigma}_t}, \tag{14}$$

$$P_{pkL} = \frac{\overline{x} - L}{3\hat{\sigma}_t}. \tag{15}$$

The indexes of the suitability of the production process P_{Pk} is assumed to be equal to the lower of the two values of P_{pkU} and P_{pkL}, i.e. $P_{Pk} = \min(P_{PkU}, P_{PkL})$. The lower the value of the index of suitability, the greater the probability of occurrence of defective products, and the production process will not match the established requirements.

As follows from expressions (13)–(15), the assessment of the indexes of suitability is similar to the evaluation of reproducibility indexes (6)–(12). The difference in the evaluation of suitability indexes from the reproducibility indices is that the production process does not necessarily have to be statistically controlled, and the standard deviation that characterizes the best indicator of the suitability of the production process can not be calculated based on the parameters of the control card.

The P_{Pk} suitability index characterizes the confirmed quality. If the production process is centered, that $P_{Pk} = P_P$, but when the process is shifted, the suitability index is shifted from its nominal value, and P_{Pk} becomes less than P_P. The high P_{Pk} index will only be the case when the goal is achieved with a minimum deviation from the average arithmetic value.

In case of noncentration of the production process, the P_P index can be adjusted by introducing a noncentral correction

$$P_{Pk} = (1 - k)P_P, \tag{16}$$

where k — a corrective coefficient that corresponds to the value of noncentration and is defined as the difference between the given reference value of the product characteristic and the average value of the production process parameter.

If the process is centered, then $k = 0$ and $P_{Pk} = P_P$. If the process is shifted relative to a given reference value, then k increases and the index P_{Pk} becomes smaller than the P_P index.

If the suitability indexes are equal ($P_{Pk} = P_P$), the production process is within the tolerance. If the index $P_P < 1$, then this means that the production process has low accuracy and the production process is unsatisfactory. The using of statistical methods [3–5] during the regulation will not give the necessary effect. In this case, it is necessary to improve the accuracy of the production process by replacing (or/and repairing) technical equipment and ensuring the quality of measurements (unity of measurements and accuracy of measurements) [21].

If the P_{Pk} suitability index is in the range from 1 to 1.33 ($1 \le P_{Pk} < 1.33$), the production process has sufficient accuracy — this means that the procedure for setting it up is correct. At the same time it is advisable to apply the acceptance control cards and to combine the procedure of manufacturing process regulation and the acceptance of products in one common procedure of the SPC (Statistical Process Control) [22].

If the index $P_P > 1.33$, then the production process is considered to be good (with high potential accuracy). If $P_P > 1$ and $P_{Pk} < 1$, then the production process is considered to have sufficient potential precision, but there are factors that shift the manufacturing process and remain unnoticed. In this case, it is recommended to use Shuhart's control cards to identify factors that may result in displacement of the manufacturing process center. If the index $P_P > 1.66$, then the production process is ideally configured [23, 24].

The main properties of the normal distribution law, on which the calculation of the defect fraction is based, are shown in Figure 2.
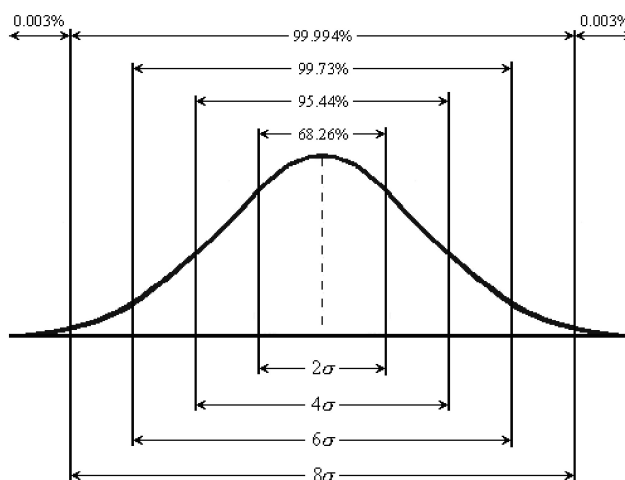
Figure 2. Properties of the normal distribution law, on which the calculation of the defect fraction is based

As it follows from Figure 2, in order to avoid a noticeable fraction of defective products or characteristics of the production process that deviates from the established requirements, the width of the tolerance field must be not less than 6σ.

Estimation of the values of $\hat{p}_t$ production process characteristic or the quality parameter of products that do not match the requirements under the normal distribution law can be found on the basis of the upper and lower parts of units that do not match the requirements:

$$\hat{p}_t = \hat{p}_L + \hat{p}_U = \Phi\left(\frac{L - \bar{x}}{\hat{\sigma}_t}\right) + \Phi\left(\frac{\bar{x} - U}{\hat{\sigma}_t}\right); \tag{17}$$

$$\hat{p}_L = 1 - \Phi\left(3\hat{C}_{PkL}\right); \tag{18}$$

$$\hat{p}_U = 1 - \Phi\left(3\hat{C}_{PkU}\right), \tag{19}$$

where $\hat{p}_L$ — assessment of the lower part of the units that do not match the requirements — the part of units of the process or product characteristics distribution, which does not exceed the lower limit of the field of tolerance L; $\hat{p}_U$ — assessment of the upper part of the units that do not match the requirements — the part of units of the process or product characteristics distribution, that exceeds the upper limit of the tolerance field U; Φ — the function of a normalized normal distribution law.

In order to estimate the proportion of product units that do not match the requirements of the suitability of the production process, it is necessary to replace the reproducibility indexes and indexes of suitability in formulas (18) and (19), and thus common part of the values of the characteristics distribution of the production services (production process) that may go beyond the tolerance field.

Conclusions

The quality of products or services is largely determined by the effectiveness of the quality management system at the enterprise and the proper organization of the production process. The quality management system, built in accordance with the principles of overall quality management, involves continuous improvement of the marketing activities of the enterprise, improving the quality of products and ensuring of the needs of all interested parties, both customers and producers, through the establishment of appropriate management in the enterprise [25–30].

The application of indexes of reproducibility and suitability of the production process in the system of quality control allows us to visually estimate the possibility of reducing the percentage of defective products by reducing and eliminating the effects of non-random causes of the production process parameters deviation (ensuring the stability of the production process), as well as reducing the impact of the random reasons leading to deviations of the production process parameters. This will allow timely warning and corrective actions that will enable them to find reserves for improving product quality, reduce financial costs for defective repair, and increase the competitiveness of the enterprise.

The reproducibility index and suitability index are not related to the mean of the process. That is, when the entire distribution is shifted, the reproducibility index and the fitness index will not change, it will only respond to the variation of the spread or sweep. The reproducibility index and the suitability index will be equal to one when the variation of 6σ is equal to the tolerance. If the indices are greater than one, then the range is less than the tolerance, if the indices are less than one, then the variation is greater than the tolerance. It should be taken into account that since the indices are not related to the position of the mean, then when the mean is far beyond the tolerance, the value of the indices may be much greater than one.

The accuracy of the proposed estimation methodology of the reproducibility and suitability index, which includes the proposed mathematical apparatus, was estimated on the basis of the correctness index, the method of assessment of which is carried out in accordance with the international standard ISO 5725–2:2002 [6]. The measure of correctness of the proposed method is the combined uncertainty of type B, the relative value of which does not exceed 0.05 %, and the efficiency of the model is determined by the level of the methodological component of probability, which was estimated by the method given in, the value of which is not less than 95 %.

References

1   Quality management systems — Fundamentals and vocabulary: HOST R ISO 9000:2015. [effective from 2015-09-15]. — Geneva: ISO copyright office, 2015. — P. 57 (International Standard).

2   Guidance on the application of statistical methods to quality and to industrial standardization: ISO/TR 18532:2009. [effective from 2009-04-15]. — Geneva: ISO copyright office, 2009. — P. 204 (International Standard).

3   Statistical methods in process management — Capability and performance — Part 2: Process capability and performance of time-dependent process models: ISO 22514–2:2017. [effective from 2017-02-06]. — Geneva: ISO copyright office, 2017. — P. 21 (International Standard).

4   Statistical methods in process management — Capability and performance — Part 4: Process capability estimates and performance measures: ISO/TR 22514–4:2016. [effective from 2016-07-04]. Geneva: ISO copyright office, 2016. — P. 45 (International Standard).

5   Statistical methods for use in proficiency testing by interlaboratory comparisons: ISO 13528:2015 [effective from 2015-08-01]. Geneva: ISO copyright office, 2016. — P. 89 (International Standard).

6   Accuracy (trueness and precision) of measurement methods and results — Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method — Technical Corrigendum 1: ISO 5725–2:2003. [effective from 2003-06-01]. Geneva: ISO copyright office, 2003. — P. 23 (International Standard).

7 Stephens M. Anderson-Darling Test for Goodness of Fit / M. Stephens // Encyclopedia of Statistical Sciences. — 1982. — Vol. 1. — P. 81–85.

8 Control charts — Part 2: Shewhart control charts: ISO 7870–2:2013. [effective from 2013–04–25]. Geneva: ISO copyright office, 2013. — P. 44 (International Standard).

9 Vasilevskyi O. A new approach to assessing the dynamic uncertainty of measuring devices / O. Vasilevskyi, P. Kulakov, D. Kompanets, O.M. Lysenko, V. Prysyazhnyuk, Waldemar Wojcik, D. Baitussupov // Proceedings of SPIE — The International Society for Optical Engineering. — 2018. — P. 257–268. https://doi.org/10.1117/12.2501578.

10 Beckert S. Critical analysis of the acceptance criteria used in measurement systems evaluation / S. Beckert, W. Paim // Int. J. of Metrology and Quality Engineering. — 2017. — Vol. 8(23). — P. 1–9.

11 Vasilevskyi O.M. Vibration diagnostic system for evaluation of state interconnected electrical motors mechanical parameters / O.M. Vasilevskyi, P.I. Kulakov, I.A. Dudatiev, V.M. Didych, A. Kotyra, B. Suleimenov, A. Assembay, A. Kozbekova // Proceedings of SPIE — The International Society for Optical Engineering. — 2017. — 104456C. — P. 348–358; https://doi.org/10.1117/12.2280993.

12 Meng X. Effect of retro-reflective materials on building indoor temperature conditions and heat flow analysis for walls / X. Meng, T.Luo, Z.Y. Wang, W. Zhang, B. Yan, J.L. Ouyang, E.S. Long // Energy Build. — 2016. — Vol. 127. — P. 488–498.

13 Szeląg-Sikora A. Impact of Integrated and Conventional Plant Production on Selected Soil Parameters in Carrot Production / A. Szeląg-Sikora, J. Sikora, M. Niemiec, Z. Gródek-Szostak, J. Kapusta-Duch, M. Kuboń, M. Komorowska, J. Karcz // Sustainability. — 2019. — Vol. 11. — P. 1–13.

14 Kucheruk V. Measurement of the Number Servings of Milk and Control of Water Content in Milk on Stall Milking Machines / V. Kucheruk, P. Kulakov, N. Storozhuk // Advances in Intelligent Systems and Computing. — 2017. — Vol. 543. — P. 435–447. DOI: 10.1007/978-3-319-48923-0_46.

15 Kucheruk V. Optical method to determine the quantity of water in milk using the visible radiation range / V. Kucheruk, P. Kulakov, O. Vasilevskyi, D. Mostovyi, A. Kulakova, I.M. Kobylyanska, G. Karnakova, P. Kisala // Proceedings of SPIE — The International Society for Optical Engineering. — 2018, 10808, 108080Y. — P. 123–126.

16 Vasilevskyi O. Calibration method to assess the accuracy of measurement devices using the theory of uncertainty / O. Vasilevskyi // Int. J. of Metrology and Quality Engineering. — 2014. — Vol. 5(4). — P. 403(p1)–403(p9).

17 Kucheruk, V.Yu. Computer-measuring system of the induction motor's dynamical torque-speed characteristics / V.Yu. Kucheruk, I.P. Kurytnik, Ye.Z. Oshanov, P.I. Kulakov, A.A. Semenov, D.Zh. Karabekova, A.K. Khassenov // Bulletin of the university of Karaganda-Physics. — 2019. — № 2(94). — P. 92–100. DOI: 10.31489/2019Ph2/92–100

18 Vasilevskyi O. The method of translation additive and multiplicative error in the instrumental component of the measurement uncertainty / O. Vasilevskyi, V. Kucheruk, V. Bogachuk, K. Gromaszek, W. Wójcik, S. Smailova, N. Askarova // Proceedings of SPIE — The Int. Society for Optical Engineering. — 2016. — P. 125–132.

19 Kucheruk, V. Definition of dynamic characteristics of pointer measuring devices on the basis of automatic indications determination / V. Kucheruk, I.P. Kurytnik, P. Kulakov, R. Lishchuk, Y. Moskvichova, A. Kulakova // Archives of Control Sciences. — 2018. — Vol. 28(LXIV), No. 3. — P. 335–352. DOI: 10.24425/acs.2018.124709

20 Vasilevskyi O. Method of evaluating the level of confidence based on metrological risks for determining the coverage factor in the concept of uncertainty / O. Vasilevskyi, V. Didych, A. Kravchenko, M. Yakovlev, I. Andrikevych, D. Kompanets, Y. Danylyuk, W. Wójcik, A. Nurmakhambetov // Proceedings of SPIE — The international society for optical engineering. — 2018. Retrieved from: http://ir.lib.vntu.edu.ua/bitstream/handle/123456789/22915/48076.pdf; jsessionid=4C469153E21B74681C99 B368CB6A8F86? sequence=2

21 Accuracy (trueness and precision) of measurement methods and results — Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method: ISO 5725:2019. [effective from 2019-12-20]. London: BSI, 2019. — P. 78 (International Standard).

22 Guidelines for implementation of statistical process control (SPC) — Part 1: Elements of SPC: ISO 11462–1:2001. [effective from 2001-06-15]. Geneva: ISO copyright office, 2001. — P. 32 (International Standard).

23 Demchuk L. Combined usage of Theory of Constraints, Lean and Six Sigma in quality assurance of manufacturing processes / L. Demchuk, R. Baitsar // Key Engineering Materials. — 2015. — Vol. 637. — P. 21–26.

24 Demchuk L. Achievement Particularities of Application of Theory of Constraints, Lean and Six Sigma for Ensuring the Quality of Proucts and Processes / L. Demchuk, R. Baitsar // Intern. Journal Sustainable Development. — 2014. — Vol. 16. — P. 98–103.

25 Staniškis J.K. Unsustainability reduction in enterprises by incremental innovations implementation and management / J.K. Staniškisa, E. Katiliūtėb // Journal of Cleaner Production. — 2019. — Vol. 236. — P. 117542. https://doi.org/10.1016/j.jclepro.2019.07.017.

26 Medina Munroe M. Analyzing external environment factors affecting social enterprise development / M. Medina Munroe, C. Belanger // Soc. Enterp. J. — 2017. — Vol. 13. — P. 138–152. 10.1108/SEJ-06-2016-0021

27 Mazzej M. Different ways of dealing with tensions: practices of (re)negotiation in local social economies / M. Mazzej // Soc. Enterp. J. — 2017. — Vol. 13. — P. 299–314.

28 Chan A. Supported social enterprise: a modified social welfare organization / A. Chan, S. Ryan, J. Quarter // Nonprofit and Voluntary Sector Quarterly. — 2016. — Vol. 46(2). — P. 261–279.

29 Hullavarad S. Enterprise content management solutions-roadmap strategy and implementation challenges / S. Hullavarad, R. O'Hare, A.K. Roy // International Journal of Information Management. — 2015. — Vol. 35 (2). — P. 260–265.

30 An L. Modeling human decisions in coupled human and natural systems: review of agent-based models. / L. An // Ecol. Modell. — 2012. — Vol. 229. — P. 25–36.

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Өнімнің немесе көрсетілетін қызметтердің сапасын бағалау үшін қайта өндіру және жарамдылық индекстерін қалыпқа келтіру

Ақауы бар өнімнің (немесе өндірістік қызметтің сәйкес келмеуінің) өндірістік процестің жарамдылығы мен шығарылу индексі негізінде пайда болу мүмкіндігін бағалау әдістемесі ұсынылған. Репродуктивтілік индексін стандартты ауытқу негізінде есептеу ұсынылады, оны бақылау картасының орташа ауқымы мен төзімділік өрісінің шегі бойынша орнатуға болады. Бұл ретте өндірістік процесс міндетті түрде статистикалық басқарылу жағдайында болуы тиіс. Жарамдылық индексі бақылау картасының сипаттамалары негізінде есептелмейді, тек жалпы стандартты ауытқу негізінде есептеледі, ол Бессель формуласының көмегімен және төзімділік өрісінің шегі негізінде анықталады. Сонымен қатар, өндірістік процесс міндетті түрде статистикалық тұрғыдан басқарылмауы керек. Өнімнің (өндірістік көрсетілетін қызметтердің) жарамдылығы немесе жарамсыздығы туралы тұжырымдар бірліктен аз немесе одан да көп мәндерді қабылдауы мүмкін қайта өндіру және жарамдылық индекстерінің мәні негізінде жүзеге асырылады. Осы индекстердің алынған мәндерінің негізінде белгіленген талаптарға сәйкес келмейтін өнімнің немесе өндірістік процесс сипаттамаларының пайда болуының ықтимал үлесі белгіленеді.

Кілт сөздер: қалыпқа келтіру, сапаны бағалау, өнімнің сапасы, өндірістік қызметтердің сапасы, жарамдылық индексі, репродуктивтілік индексі, өнімнің ақаулану ықтималдығы, өндірістік процесс.

И. Стуглик, И.П. Курытник, О.М. Василевский, В.Ю. Кучерук,
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Нормализация индексов воспроизводимости и пригодности для оценки качества продукции или услуг

Предложена методика оценки вероятности возможного появления бракованной продукции (или несоответствия производственной услуги) на базе индексов пригодности и воспроизводимости производственного процесса. Индекс воспроизводимости рекомендуется рассчитывать на основе стандартного отклонения, которое может быть установлено по среднему размаху контрольной карты и пределам поля допуска. При этом производственный процесс обязательно должен быть в состоянии статистической управляемости. Индекс годности не может быть определен на основе характеристик контрольной карты, а рассчитывается исключительно из общего стандартного отклонения, которое определяется с помощью формулы Бесселя и пределов поля допуска. При этом производственный процесс не обязательно должен быть статистически управляемым. Выводы о пригодности или непригодности продукции (производственных услуг) осуществляются на основе значения индексов воспроизводимости и пригодности, которые могут принимать значения меньше или больше единицы. На основе полученных значений этих индексов устанавливается возможная доля появления продукции или характеристик производственного процесса, не соответствующих установленным требованиям.

Ключевые слова: нормализация, оценка качества, качество продукции, качество производственных услуг, индекс пригодности, индекс воспроизводимости, вероятность брака продукта, производственный процесс.

References

1   Quality management systems — Fundamentals and vocabulary. Switzerland (2015). *HOST R ISO 9000:2015* from 15th September 2015. Geneva: ISO copyright office.

2   Guidance on the application of statistical methods to quality and to industrial standardization. Switzerland (2009). *ISO/TR 18532:2009* from 15th April 2009. Geneva: ISO copyright office.

3   Statistical methods in process management — Capability and performance — Part 2: Process capability and performance of time-dependent process models. Switzerland (2017). *ISO 22514-2:2017* from 6th February 2017. Geneva: ISO copyright office.

4   Statistical methods in process management — Capability and performance — Part 4: Process capability estimates and performance measures (2016). *ISO/TR 22514–4:2016* from 4th July 2016. Geneva: ISO copyright office.

5   Statistical methods for use in proficiency testing by interlaboratory comparisons. Switzerland (2016). *ISO 13528:2015* from 1st August 2015. Geneva: ISO copyright office.

6   Accuracy (trueness and precision) of measurement methods and results — Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method — Technical Corrigendum 1. (2003). *ISO 5725-2:2003* from 1st June 2003. Geneva: ISO copyright office, 2003. — P. 23 (International Standard).

7   Stephens, M. (1982). Anderson-Darling Test for Goodness of Fit. *Encyclopedia of Statistical Sciences, 1*, 81–85.

8   Control charts — Part 2: Shewhart control charts (2013). *ISO 7870-2:2013* from 25th April 2013. Geneva: ISO copyright office.

9   Vasilevskyi, O. Kulakov, P., Kompanets, D., Lysenko, O.M., Prysyazhnyuk, V., & Waldemar Wojcik, et al. (2018). A new approach to assessing the dynamic uncertainty of measuring devices. Proceedings of SPIE — The International Society for Optical Engineering, 257–268. https://doi.org/10.1117/12.2501578.

10   Beckert, S., & Paim, W. (2017). Critical analysis of the acceptance criteria used in measurement systems evaluation. *Int. J. of Metrology and Quality Engineering, 8*(23), 1–9.

11   Vasilevskyi, O.M., Kulakov, P.I., Dudatiev, I.A., Didych, V.M., Kotyra, A., & Suleimenov, B. (2017). Vibration diagnostic system for evaluation of state interconnected electrical motors mechanical parameters. *Proceedings of SPIE — The International Society for Optical Engineering, 104456C*, 348–358; https://doi.org/10.1117/12.2280993.

12   Meng, X., Luo, T., Wang, Z.Y., Zhang, W., Yan, B., & Ouyang, J.L., et al. (2016). Effect of retro-reflective materials on building indoor temperature conditions and heat flow analysis for walls. *Energy Build, 127*, 488–498.

13   Szeląg-Sikora, A., Sikora, J., Niemiec, M., Gródek-Szostak, Z., Kapusta-Duch, J., Kuboń, M., et al. (2019). Impact of Integrated and Conventional Plant Production on Selected Soil Parameters in Carrot Production. *Sustainability, 11*, 1–13.

14   Kucheruk, V., Kulakov, P., & Storozhuk, N. (2017). Measurement of the Number Servings of Milk and Control of Water Content in Milk on Stall Milking Machines. *Advances in Intelligent Systems and Computing*, 2017, 543, 435–447. DOI: 10.1007/978–3–319–48923–0_46.

15   Kucheruk, V., Kulakov, P., Vasilevskyi, O., Mostovyi, D., Kulakova, A., & Kobylyanska, I.M., et al. (2018). Optical method to determine the quantity of water in milk using the visible radiation range. *Proceedings of SPIE — The International Society for Optical Engineering, 10808, 108080Y*, 123–126.

16   Vasilevskyi, O. (2014). Calibration method to assess the accuracy of measurement devices using the theory of uncertainty. *Int. J. of Metrology and Quality Engineering, 5*(4), 403(p1)-403(p9).

17   Kucheruk, V.Yu., Kurytnik, I.P., Oshanov, Ye.Z., Kulakov, P.I., Semenov, A.A., Karabekova, D. Zh., & Khassenov, A.K. (2019). Computer-measuring system of the induction motor's dynamical torque-speed characteristics. *Bulletin of the university of Karaganda-Physics, 2*(94), 92–100. DOI: 10.31489/2019Ph2/92–100

18   Vasilevskyi, O., Kucheruk, V., Bogachuk, V., Gromaszek, K., Wójcik, W., Smailova, S., & Askarova N. (2016). The method of translation additive and multiplicative error in the instrumental component of the measurement uncertainty. *Proceedings of SPIE — The Int. Society for Optical Engineering*, 125–132.

19   Kucheruk, V., Kurytnik, I.P., Kulakov, P., Lishchuk, R., Moskvichova, Y., & Kulakova, A. (2018). Definition of dynamic characteristics of pointer measuring devices on the basis of automatic indications determination. *Archives of Control Sciences, 28(LXIV), 3*, 335–352. DOI: 10.24425/acs.2018.124709

20   Vasilevskyi, O., Didych, V., Kravchenko, A., Yakovlev, M., Andrikevych, I., & Kompanets, D., et al. (2018). Method of evaluating the level of confidence based on metrological risks for determining the coverage factor in the concept of uncertainty. *Proceedings of SPIE — The international society for optical engineering*. 2018. Retrieved from: http://ir.lib.vntu.edu.ua/bitstream/handle/123456789/22915/48076.pdf; jsessionid=4C469153E21B74681C99B368CB6A8F86? sequence=2

21   Accuracy (trueness and precision) of measurement methods and results — Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method (2019). *ISO 5725:2019* from 20th December 2019. London: BSI.

22   Guidelines for implementation of statistical process control (SPC) — Part 1: Elements of SPC (2001). *ISO 11462–1:2001* from 15th June 2001. Geneva: ISO copyright office.

23   Demchuk, L., & Baitsar, R. (2015). Combined usage of Theory of Constraints, Lean and Six Sigma in quality assurance of manufacturing processes. *Key Engineering Materials, 637*, P. 21–26.

24   Demchuk, L., & Baitsar, R. (2014). Achievement Particularities of Application of Theory of Constraints, Lean and Six Sigma for Ensuring the Quality of Proucts and Processes. *Intern. Journal Sustainable Development, 16*, 98–103.

25   Staniškis, J.K., & Katiliūtėb, E. (2019). Unsustainability reduction in enterprises by incremental innovations implementation and management. *Journal of Cleaner Production, 236*, 117542. https://doi.org/10.1016/j.jclepro.2019.07.017.

26   Medina Munroe M., & Belanger, C. (2017). Analyzing external environment factors affecting social enterprise development. *Soc. Enterp. J., 13*, 138–152.

27   Mazzej, M. (2017). Different ways of dealing with tensions: practices of (re)negotiation in local social economies. *Soc. Enterp. J.,13*, 299–314.

28   Chan, A., Ryan, S., & Quarter, J. (2016). Supported social enterprise: a modified social welfare organization. *Nonprofit and Voluntary Sector Quarterly, 46*(2), 261–279.

29   Hullavarad, S., O'Hare, R., & Roy, A.K. (2015). Enterprise content management solutions-roadmap strategy and implementation challenges. *International Journal of Information Management, 35*(2), 260–265.

30   An, L. (2012). Modeling human decisions in coupled human and natural systems: review of agent-based models. *Ecol. Modell, 229*, 25–36.

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Interaction model of low-temperature plasma with a steel surface during electrolyte plasma nitriding in an electrolyte on the bases of carbamide

The features of the formation of low-temperature plasma and its interaction with a metal surface were studied in this work. A qualitative model of the interaction of low-temperature plasma with the steel surface during nitriding has been developed by summarizing the available research results and taking into account the specific features of the electrolyte plasma process. In accordance with this model, in the first moments of the interaction of low-temperature plasma with the steel surface in the near-surface layer, which accelerated formation of the $Fe_{\alpha(N)}$ solid solution occurs due to the action of directed bombardment of charged particles, which enhances the adsorption and diffusion of nitrogen into the interior of the material, then dispersed particles of nitride of alloying elements are formed as further saturation in places with an increased level of free energy (at lattice defects, at grain boundaries, etc.). Subsequently, transformations occur in the surface zone of the layer when the limiting solubility of nitrogen in iron is exceeded, which leading to the formation of nitrides of the γ'-phase (Fe_4N) and ε-phase ($Fe_{2-3}N$) in it. Thus, electrolyte plasma nitriding opens up many new possibilities, in particular: varying the nitriding temperature over a wide range (400–700 ºC), targeted production of a nitrided layer consisting only of a diffusion layer without a layer of compounds, while obtaining a diffusion layer with particles γ'-phase (Fe_4N) of plate form and with finely dispersed nitrides MN (CrN). The use of an electric discharge in an electrolyte (low-temperature plasma) makes it possible to increase the heating rate and diffusion saturation of the material surface. This work is of practical importance, since the studied method of electrolytic-plasma nitriding makes it possible to obtain a modified surface layer on steels with high physical and mechanical properties.

Keywords: plasma, electrolyte-plasma treatment, nitriding, saturation, electrolyte, steel, model, modified layer, phase.

Introduction

Plasma electrolyte treatment is based on the interaction of ions, electrons, excited atoms and other energetic particles obtained in low-temperature plasma with the surface of a solid [1, 2]. An electrolyte is used to create and maintain a low-temperature plasma in nitriding, which is a source of ions for carrying out the nitriding process: an aqueous solution of salts containing nitrogen ions, an aqueous solution of ammonia and other nitrogen-containing media. On the basis of experimental studies, it was found that the most effective and promising electrolyte for electrolyte-plasma nitriding of steels is an electrolyte from an aqueous solution containing 20 % carbamide and 10 % sodium carbonate [3]. In the developed electrolyte, the nitrogen-containing component is carbamide, and the component that ensures the electrical conductivity of the electrolyte is sodium carbonate [3–5]. Water is used as a solvent. The main advantage of this electrolyte is its exceptional low cost, since the initial components are produced in mass quantities and are widely used in the national economy. They also do not belong to highly toxic substances that require special safety measures.

The results obtained in work [3–5] showed that plasma electrolyte nitriding in an electrolyte from an aqueous solution containing 20 % carbamide and 10 % sodium carbonate makes it possible to obtain a modified surface layer consisting of nitrogenous martensite, carbides M_6C, MC and Fe_4N nitrides, CrN.

As is known [6, 7], nitriding by electrolyte-plasma heating not only shortens the time required to reach the required temperature of the part, but also accelerate the formation of diffusion layers. The reason for this is the positive effect of heating conditions and a saturating environment on some elementary nitriding processes.

It is necessary to study the features of the formation of low-temperature plasma and its interaction with a metal surface in order to gain a deeper understanding of the physical processes that determine the formation of the composition, structure and properties of the nitrided layer, during electrolyte-plasma nitriding.

Results and discussions

As it is known [8, 9], the interaction of the saturating medium with the surface of the metal being treated during CTT is usually divided into the following stages:

1. Formation of active substances in the environment or reaction volume.
2. Supply of a saturating substance to the metal surface.
3. Adsorption of active atoms or molecules by the metal surface.
4. Chemical reactions on the surface (layer growth due to chemical reaction or diffusion), as well as the formation of reaction products in an adsorbed state.
5. Desorption of reaction products.
6. Removal of reaction products from the interaction zone into the reaction volume or environment.

Based on this, we will consider the main stages of interaction of the saturating medium with the treated surface during the electrolyte-plasma treatment of steel in an electrolyte from an aqueous solution containing 20 % carbamide and 10 % sodium carbonate.

The workpiece is immersed in an open reactor (electrolytic cell) filled with electrolyte during the nitriding process. A rectified voltage is applied to the part (cathode) and solid electrode (anode). A gas-steam jacket with a thickness of about 100–120 μm is created near the surface of the part (Fig. 1) [10]. The gas-vapor shell enveloping the workpiece contains electrolyte ions and, accordingly, nitrogen ions. It is a low-temperature plasma and is an active saturating atmosphere for nitriding. This saturating medium is dense — the pressure in the reactor corresponds to atmospheric [11].
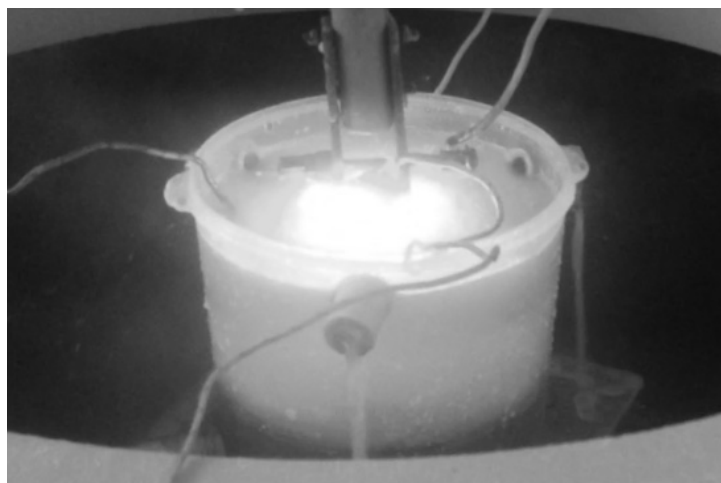
Figure 1. The process of electrolyte plasma nitriding of a steel sample

Thus, plasma electrolyte nitriding consists in processing products in a low-temperature plasma (vapor-gas shell) created between the electrolyte and the surface of the products.

Let us consider the features of the formation of active substances in a vapor-gas shell during nitriding of steels in an electrolyte from an aqueous solution containing 20 % carbamide and 10 % sodium carbonate.

Near the vapor-gas shell, the components of the aqueous solution enter into a reaction, with the release of a large amount of gases — ammonia, carbon dioxide and water vapor, which enters the vapor-gas shell:

$$2(NH_2)_2CO + Na_2CO_3 \rightarrow 2NaNCO + 2NH_3^\uparrow + CO_2^\uparrow + H_2O \tag{1}$$
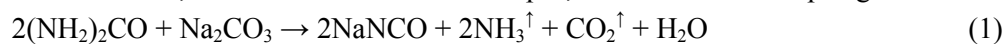
Sodium cyanate synthesized by fusion of carbamide with sodium carbonates is moderately soluble in water. In water and in water vapor, sodium cyanate hydrolyzes to Na_2CO_3, CO_2 и NH_3:

$$2NaNCO + 3H_2O \rightarrow Na_2CO_3 + CO_2^\uparrow + 2NH_3^\uparrow \tag{2}$$
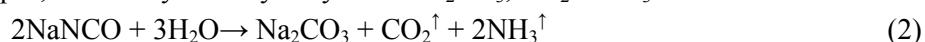
Hydrolysis intensifies at the boundary between the electrolyte and the vapor-gas shell, since the temperature in it is high.

In the course of the reaction at the boundary between the electrolyte and the vapor-gas shell, the released ammonia, entering the vapor-gas shell, decomposes with the release of atomic nitrogen:

$$2NH_3 \rightarrow 3H_2 + 2N\bullet \tag{3}$$

As a result, nitrogen is formed in the vapor-gas envelope, which is in an atomic state, and in this form is very chemically active.

It is necessary to maintain the composition of the vapor-gas shell in order to ensure stable formation of active ions of atomic nitrogen and saturation. This requires a constant supply of a saturating substance (electrolyte) to the vapor-gas shell (low-temperature plasma), thereby preserving the composition of the vapor-gas shell. It also provides a stable discharge in the vapor-gas envelope. Thus, the supply of the active medium to the metal surface and the removal of reaction products from the interaction zone are provided by the circulation of the electrolyte. The surface concentration of the element, which determines the thickness of the diffusion layer, depends on the ratio of the rates of delivery of active atoms to the surface and their diffusion into the metal. It is necessary that the rate of its adsorption exceeds the rate of diffusion to achieve a high concentration of the saturating component on the metal surface [12].

The initial stage of the diffusion process is the bombardment of the metal surface of the cathode with charged particles (H^+, N^+, Na^+), which leads to cleaning and heating of the surface at a distance of more than 100 μm, as well as to the initiation of vacancies and other defects in the crystal lattice, due to which the diffusion fraction increases through the crystal lattice of the metal. Avalanches of electrons arising during the development of a discharge in the electrolyte and forming well-conducting streamer channels, along which a current pulse runs at a high speed of $\sim 10^7$–10^8 m/s and a backward voltage wave propagates, make a large contribution to the heating of the metal. When the reverse voltage wave passes in the next period of time, with a duration of about 10^{-7} s, a large amount of energy is released in the channel. As a result, an abrupt increase in pressure occurs, and a cylindrical shock wave propagates into the space surrounding the channel, the temperature at the front of which is about 10^4 K. In this case, the ionization of the particles of the vapor-gas medium, the formation of additional branches of the channels with the involvement of charged ions in the avalanche [13].

Atomic nitrogen released in the vapor-gas envelope during chemical reactions is adsorbed by iron and diffuses deep into the material to form a solid solution of nitrogen in iron. In this case, the effect of directed bombardment of charged particles enhances the adsorption and diffusion of nitrogen. Since, during the process, there are mainly positive ions, excited atoms and electrons near the product, which is the cathode. These particles bombard the surface with an energy no less than the relaxation energy [14]. Since the electrolyte-plasma nitriding is carried out under conditions of excessive excitation of the metal surface and subsurface layers. An important factor influencing the growth rate of the nitrided layer and its structure during this process is the exclusion of the predominant role of boundary diffusion. Plasma, accelerating the directional mass transfer of ions to the sample surface, creates conditions for uniform adsorption of nitrogen atoms over the entire metal surface, rather than selectively along the grain boundaries, as is observed with conventional nitriding. The results of experiments carried out in [3, 5], in particular, the results of metallographic analysis, mapping and energy dispersive analysis showed a uniform distribution of the thickness of the diffusion layer and a more uniform distribution of nitrogen over the surface of the nitrided layer. The observed phenomenon of uniform adsorption and uniform growth of the nitrided layer should be explained by the appearance in the grain volume of a special defect substructure (dislocation-disclination structure of grains in the near-surface zone), which were observed in experimental studies of the fine structure carried out in [3]. The resulting defectiveness, apparently, approaches the defectiveness of grain boundaries. The possibility of forming such a grain substructure during nitriding is provided by:

− increased energy state of the surface and subsurface layers exposed throughout the treatment to bombardment with ions and neutral atoms of low-temperature plasma;
− the counter flow of metal atoms and alloying elements to the metal — saturating medium interface, due to their high affinity for nitrogen;
− phase hardening and periodic recrystallization;
− the simultaneous diffusion of nitrogen atoms and the formation of defects in the crystal structure.

Thus, the use of an electric discharge in an electrolyte (low-temperature plasma) makes it possible to increase the heating rate and diffusion saturation of the surface of materials. The large depth of the modified layer is due to the intensification of the process, and the intensification of the saturation process is associated with the formation of a defect substructure when exposed to low-temperature plasma.

We have characterized the main processes of the formation of low-temperature plasma and its effect on a metal surface. Nevertheless, for a complete understanding of the processes occurring in the surface layers of a metal, during electrolyte-plasma nitriding in low-temperature plasma, as well as maximum use of the potential capabilities of the technological process, it is necessary to have its model, which would most accu-

rately reflect the real essence of the phenomena. It is in this case that conditions are created for predicting the results of processing parts, as well as optimizing the technology.

According to its specific features, nitriding in an electrolyte plasma belongs to the technologies implemented using an electric discharge in a gas (vapor-gas shell) as an intensifier of the process. In the classical version, the part serves as a cathode. Several theoretical models of the interaction of a gaseous medium with a metal surface are known about this principle, which results in the creation of diffusion nitrogen-containing layers on the surface, modifying it in order to change its properties [15]. The theoretical provisions of the process are currently characterized by two main approaches.

The first of them was formed in solidarity by the scientists of the school of Yu.M. Lakhtin and the German school [16]. The essence of this model is demonstrated in Figure 2 [15, 17, 18], which has already become a classic in the theory of nitriding in a glow discharge.
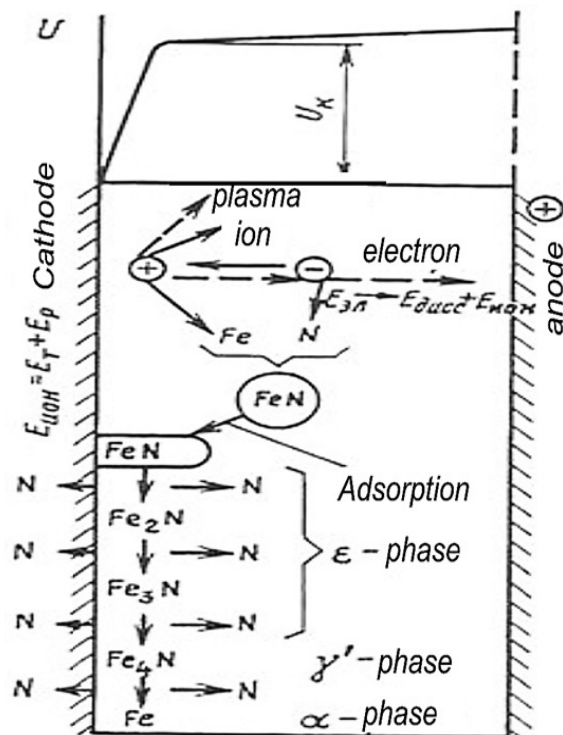
Figure 2. Scheme of plasma interaction with the cathode surface during nitriding in a glow discharge [15]

The initial premise of this model is the assumption that iron atoms in the glow discharge plasma combine with nitrogen, forming iron nitrides. They, in turn, under the influence of directed bombardment by charged particles, move in the direction of the cathode and are adsorbed by the surface. Then, already on the surface, the nitrides are transformed under the action of the surface bombardment by the incident flow, gradually transforming from the ε-phase into the γ′-phase, the atomic nitrogen released in this case forms a solid solution of the α-phase and diffusing into the depth of the surface. Thus, nitrogen enters the surface not only from the gas phase, but also as a result of the transformation of nitrides, and the driving force of the process is a high nitrogen concentration gradient.

The fundamental second model, the scientists of the school of Arzamasov BN, formulated a different principle of the process, which is demonstrated in Figure 3 [19]. According to this model, atomic nitrogen ions play the leading role in the nitriding process in a glow discharge. The intensity of the process is determined precisely by the number of atomic nitrogen ions. As a result of the bombardment of the surface, it can be sputtered, both in the form of neutral metal particles and its negative ions together with electrons. At the same time, a layer of adsorbed nitrogen particles forms on the surface as a result of the directed motion of particles in the field, recombination of ions directly on the surface, and also the release of some particles that have already penetrated into the surface at the gas-metal interface. Under the influence of the incident flow, the particles of the adsorbed layer can be sprayed or embedded into the surface, creating a solid solution.
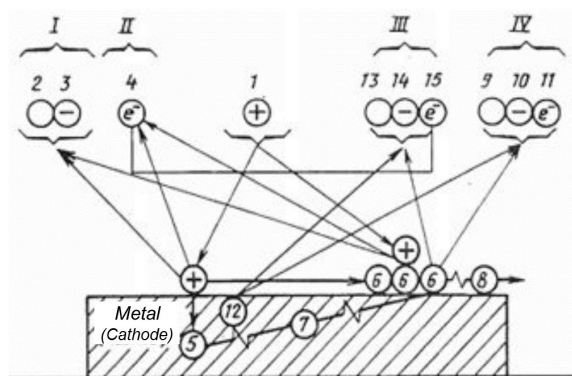
Figure 3. Scheme of the process of interaction of atomic particles with a metal in vacuum [15]

Thus, a fundamentally important difference between the above approaches is, first of all, the question of the primary formation of nitrides or a solid solution in the surface layers of the metal. According to the first model, nitrides are formed first, the transformation of which will lead to the formation of a solid solution. According to the second model, the excessive concentration of nitrogen in the solid solution, together with the energetic effect of the incident flow, promotes chemical transformations.

On the basis of these two models and the above-described processes occurring during nitriding, as well as the results obtained in [3, 5], it is possible to present a qualitative physical model of the interaction of low-temperature plasma created in a carbamide-based electrolyte with the steel surface, due to which, the formation of wear-resistant modified surface layers occurs. Since there is no unified model in the literature for the interaction of low-temperature plasma with a metal surface during nitriding.

Thus, summarizing the available research results and taking into account the specific features of the process, a qualitative model of the interaction of low-temperature plasma with the steel surface during nitriding has been developed. The essence of the developed model is shown in Figure 4.
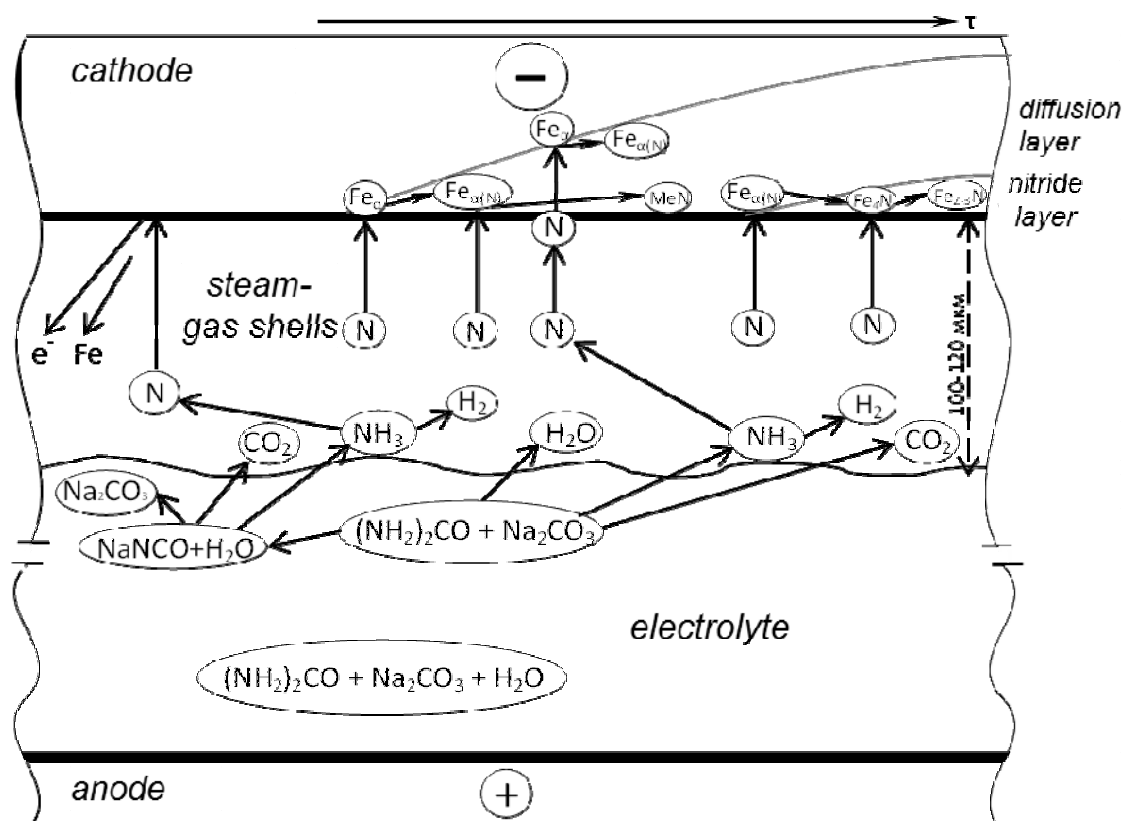
Figure 4. Model of the interaction of low-temperature plasma
with the surface of steel during electrolyte-plasma nitriding

In accordance with this model, in the first moments of the interaction of low-temperature plasma with the steel surface in the near-surface volume of steel, an accelerated formation of a $Fe_{\alpha(N)}$ solid solution occurs due to the action of directed bombardment of charged particles, which enhances the adsorption and diffusion of nitrogen into the interior of the material, then as further saturation in places with an increased level of free energy (at lattice defects, at grain boundaries, etc.), dispersed particles of nitrides of alloying elements are formed. Further, when the limiting solubility of nitrogen in α-iron is exceeded, transformations occur in the surface zone of the layer, leading to the formation of nitrides of the γ'-phase (Fe_4N) and ε-phase ($Fe_{2-3}N$) in it. And during cooling, excess γ'-nitride lamellar particles can form in the diffusion layer due to the formation of a highly supersaturated solid solution.

The developed model is formulated on the basis of experimental data and known regularities. So, in the first moments of the interaction of the vapor-gas shell (low-temperature plasma) with the surface of iron (steel), atomic nitrogen released in the vapor-gas shell during chemical reactions is adsorbed by the iron and diffuses deep into the material. In this case, the processes of adsorption and diffusion are enhanced by the action of directional bombardment of charged particles — positive ions and excited atoms. As a result of the bombardment of the surface, it can be sputtered in the form of neutral particles, negative metal ions and electrons. At the same time, a layer of adsorbed nitrogen particles forms on the surface as a result of the directed motion of particles in the field, recombination of ions directly on the surface, as well as the release of some particles that have already penetrated into the surface at the vapor-gas shell — metal interface. Under the influence of the incident flow, the particles of the adsorbed layer can be sprayed or embedded into the surface, creating a solid solution.

Penetrating into the crystal structure of steel, nitrogen can form not only solid solutions, but also chemical compounds — nitrides. The emergence of a new phase (nitrides) is accompanied by recrystallization of the system, which begins in places with an increased level of free energy (at lattice defects, at grain boundaries, etc.). There is an accumulation of diffusing elements, in particular nitrogen and the formation of a new crystal lattice — the nucleus of a new phase — is facilitated.

According to this model, solid solution of nitrogen in iron is the formed when iron is saturated with nitrogen, the primary result of the interaction of low-temperature plasma and the processed material. The formation of a chemical compound (nitrides) is a secondary process and occurs when the nitrogen content exceeds the maximum nitrogen concentration in a solid solution. So, Fe_4N nitride (γ'-phase) is formed when the limiting solubility of nitrogen in iron is exceeded and $Fe_{2-3}N$ nitride (ε-phase) is formed with a further increase in nitrogen concentration.

It should be noted that the process of diffusion saturation of the surface of materials and the formation of a diffusion layer occurs faster, since the rate of nitrogen diffusion in the γ'-phase is 25 times less, and in the ε-phase it is 60 times less than in the α-phase due to the gradual formation of a solid solution and a layer of compounds [20]. Also an important factor influencing the growth rate of the nitrided layer and its structure during this process is the exclusion of the predominant role of boundary diffusion. Since the electrolyte-plasma nitriding is carried out under conditions of excessive excitation of the metal surface and subsurface layers. Plasma, accelerating the directional mass transfer of ions to the sample surface, creates conditions for uniform adsorption of nitrogen atoms over the entire metal surface, rather than selectively along the grain boundaries, as is observed with conventional nitriding.

As is known, the following phases can form in the Fe–N system at nitriding temperatures: α–nitrogen solution in iron, an intermediate γ'-phase of variable composition with an FCC lattice (the formula Fe_4N is attributed to it), and an intermediate ε–phase with an HCP lattice and a wide region homogeneity (from 8.1 to 11.1 % N at room temperature). According to the proposed model, nitrogen initially diffuses into the α-phase with the formation of a solid solution of nitrogen in iron (nitrogenous martensite), with further saturation in places with an increased level of free energy (at lattice defects, at grain boundaries, etc.), dispersed particles are formed nitride alloying elements. Since elements such as Cr, Mo, V and others, dissolved in the matrix, increase the solubility of nitrogen in the α-phase and form special nitrides MN and M_2N. And after reaching the limit of nitrogen solubility in iron, the γ'-phase (Fe_4N) and a high-nitrogen ε-phase ($Fe_{2-3}N$) are formed on the surface. However, in the selected and considered modes of nitriding, a nitride layer consisting of these phases is not detected on the surface. In this case, the formation of lamellar particles from the excess γ'-phase (Fe_4N) is observed in the diffusion layer during cooling after nitriding. The formation of a continuous nitride layer consisting of the γ'-phase and the ε-phase is observed only at long durations of the nitriding process in the electrolyte under consideration.

Thus, the formation of finely dispersed nitrides of alloying elements after nitriding, as well as lamellar particles from the excess γ′-phase (Fe$_4$N) in the near-surface layer of steel is quite natural. Since, previously carried out by the schools of Lakhtin [17, 21], a systematic study of the kinetics and phase composition of the nitrided layer in alloyed steels showed differences in the specificity of the layer growth on alloyed ferrite and pure iron. The main difference is that nitrogen can interact with some alloying elements by forming special nitrides in addition to iron nitrides. At the same time, it was found that it is these nitrides of alloying elements and their degree of dispersion that ultimately determine the hardness of nitrided steel [22, 23].

Also, the formation of a γ′-nitride particle in the diffusion layer during cooling can be explained as follows. During cooling to room temperature, a strongly supersaturated solid solution appears due to the poor solubility of nitrogen in the α-phase at low temperatures. And this leads to the precipitation, preferably on dislocations, of α″-nitride particles of plate form with a certain orientation, which are further transformed into γ′-nitrides [15, 24]. The mechanism corresponds to the release of carbon and the formation of carbides during tempering of the hardened steel.

The experimental researches carried out in this work confirm the veracity of this model. So, the nitrided layer consists only of a diffusion solid solution (nitrogenous martensite), and an increase in the nitriding temperature to 500–550 ºC leads to the formation of nitrides in the solid solution γ′-phase (Fe$_4$N) after electrolyte-plasma nitriding of high-speed steels at a temperature of 450 °C during 7 minutes. The nitrided layer consists of a diffusion layer — α + γ′ + MN phase during the electrolyte-plasma nitriding of high-speed steels at a temperature of 550 ºC during 7 min. The formation of a nitrided layer consisting only of a diffusion layer without a nitride layer in the selected modes is associated with a low nitrogen concentration in a low-temperature plasma (vapor-gas envelope), as well as with a shorter nitriding duration. This is because much less nitrogen is usually required to form a diffusion layer on the surface of alloy steels than to form a compound layer (nitride layer) [25, 26]. In addition, metallographic analysis of the modified layer, carried out in [3], showed that after electrolyte-plasma nitriding during 7 min in an electrolyte based on carbamide, a continuous nitride layer (iron nitride layer) was observed on the surface. Similar results were obtained in [27] during the electrolyte-plasma nitriding of structural steels in more active electrolytes based on ammonia.

The possibility of obtaining a modified layer consisting only of a diffusion layer (α + γ′ + MN phases) on the surface of steels is the main advantage of electrolyte-plasma nitriding, in contrast to classical gas nitriding in ammonia, where a nitride layer is formed, consisting of two phases — γ′+ε, which is a source of internal stresses at the interface and causes brittleness and flaking of the hardened layer during operation.

Conclusions

A qualitative model has been developed for the interaction of low-temperature plasma with a steel surface during electrolyte-plasma nitriding. In accordance with this model, in the first moments of the interaction of low-temperature plasma with the steel surface in the near-surface layer, an accelerated formation of the Fe$_{α(N)}$ solid solution occurs due to the action of directed bombardment of charged particles, which enhances the adsorption and diffusion of nitrogen into the interior of the material, then, as further saturation in In places with an increased level of free energy (at lattice defects, at grain boundaries, etc.), dispersed particles of nitride of alloying elements are formed. Subsequently, transformations occur in the surface zone of the layer, leading to the formation of nitrides of the γ′-phase (Fe$_4$N) and ε-phase (Fe$_{2–3}$N) in it when the limiting solubility of nitrogen in iron is exceeded.

Thus, electrolyte-plasma nitriding opens up many new possibilities, in particular: varying the nitriding temperature over a wide range (400–700 ºC), the targeted production of a nitrided layer consisting only of a diffusion layer without a layer of compounds, while obtaining a diffusion layer with particles γ′-phase (Fe$_4$N) of plate form and with finely dispersed nitrides MN (CrN).

References

1   Rakhadilov B.K. The cathodic electrolytic plasma hardening of the 20Cr2Ni4A chromium-nickel steel / B.K. Rakhadilov, V.V. Buranich, Z.A. Satbayeva, Zh.B. Sagdoldina, R.S. Kozhanova, A.D. Pogrebnjak // Journal of Materials Research and Technology. — 2020. — Vol. 9(4). — P. 6969–6976.

2 Rakhadilov V.K. Influence of Electrolyte-Plasma Surface Hardening on the Structure And Properties of Steel 40HN / B.K. Rakhadilov, Z.A. Satbaeva, L.B. Bayatanova, M.K. Kilyshkanov, K.A. Kalibayev, A.K. Kochneva // Journal of Physics: Conference Series. — 2019. doi:10.1088/1742–6596/1393/1/012119. — URL: https://iopscience.iop.org/article/10.1088/1742-6596/1393/1/012119

3 Skakov M. Influence of electrolyte plasma treatment on structure, phase composition and microhardness of steel P6M5 / M. Skakov, B. Rakhadilov, M. Sheffler // Key Engineering Materials. — 2013. — Vol. 531–532. — P. 627–631.

4 Zhurerova L.G. Effect of the PEN/C surface layer modification on the microstructure, mechanical and tribological properties of the 30CrMnSiA mild-carbon steel / L.G. Zhurerova, B.K. Rakhadilov, N.A. Popova, M.K. Kylyshkanov, V.V. Buraniche, A.D. Pogrebnjak // Journal of Materials Research and Technology. — 2020. — Vol. 9(1). — P. 291–300.

5 Rakhadilov B.K. Microstructure and Tribological Properties of Electrolyte Plasma Nitrided High Speed Steel / B.K. Rakhadilov, M.K. Skakov, M. Scheffler // Materials testing. — 2015. — No. 4(57). — P. 360–365.

6 Белкин П.Н. Термическая и химико-термическая обработка сталей при нагреве в растворах электролитов / П.Н. Белкин, Е.А. Пасинковский // Металловедение и термическая обработка металлов. — 1989. — № 5. — С. 12–17.

7 Суминов И.В. Плазменно-электролитическое модифицирование поверхности металлов и сплавов: [В 2 т.] / И.В. Суминов, П.Н. Белкин, А.В. Эпельфельд, В.Б. Людин, Б.Л. Крит, А.М. Борисов; под ред. И.В. Суминова. — М.: Техносфера, 2011. — Т. 1. — 464 с.

8 Кидин И.Н. Электрохимико-термическая обработка металлов и сплавов / И.Н. Кидин, В.И. Андрюшечкин, В.А. Волков, А.С. Холин. — М.: Металлургия, 1978. — 320 с.

9 Самсонов Г.В. Некоторые особенности формирования покрытий в процессе реакционной диффузии / Г.В. Самсонов, Г.Л. Жуковский // Защитные покрытия на металлах. — 1974. — № 7. — С. 3–11.

10 Дураджи В.Н. Нагрев металлов в электролитной плазме / В.Н. Дураджи, А.С. Парсаданян. — Кишинев: Штиинца, 1988. — 216 с.

11 Словецкий Д.И. Механизмы неравновесных плазмохимических реакций / Д.И. Словецкий // Химия плазмы. — 1991. — Т.3. — С. 94–100.

12 Белкин П.Н. Электрохимико-термическая обработка металлов и сплавов / П.Н. Белкин. — М.: Мир, 2005. — 336 с.

13 Федоренкова Л.И. Особенности диффузии при обработке металлов в электролитной плазме / Л.И. Федоренкова // Вестн. Днепропетр. ун-та. Сер. Физика. Радиоэлектроника. — 2007. — № 12/1(14). — С. 104–106.

14 Оулет Р. Технологическое применение низкотемпературной плазмы / Р. Оулет, М. Барбье. — М.: Энергоатомиздат, 1983. — 144 с.

15 Пастух И.М. Теория и практика безводородного азотирования в тлеющем разряде / И.М. Пастух. — Харьков: ННЦ ХФТИ, 2006. — 364 с.

16 Edenhofer B. Physikalishe und metallkundliche Vorgange beim Nitriren in Plasma einer Glimmentladung / B. Edenhofer // Harterei-Technishe Mitteilungen. — 1974. — Vol. 29(2). — P. 105–112.

17 Лахтин Ю.М. Теория и технология азотирования / Ю.М. Лахтин, Я.Д. Коган, Г.Й. Шпис, З. Бемер. — М.: Металлургия, 1991. — 320 с.

18 Панайоти Т.А. Азотирование высокопрочных сталей и сплавов в тлеющем разряде / Т.А. Панайоти. — М.: Машиностроение, 1989. — 40 с.

19 Арзамасов Б.Н. Ионная химико-термическая обработка сплавов / А.Г. Братухин, Ю.С. Елисеев, Т.А. Панайоти. — М.: Изд-во МВТУ им. Н.Э. Баумана, 1999. — 400 с.

20 Сыропятов В.Я. Современная концепция азотного потенциала / В.Я. Сыропятов, В.М. Зинченко, Ю.А. Перекатов // Металловедение и термическая обработка металлов. — 2004. — № 1. — С. 7–12.

21 Лахтин Ю.М. Химико-термическая обработка металлов / Ю.М. Лахтин, Б.Н. Арзамасов. — М.: Металлургия, 1985. — 256 с.

22 Guo-meng Li. Study of M50NiL steel under carburizing and nitriding duplex treatment / Li Guo-meng, Liang Yi-long, Yin Cun-hong, Sun Hao, Zhu Zhen-long // Surface and Coatings Technology. — 2019. — Vol. 375. — P. 132–142.

23 Xiangfeng Zhang. Pan Erosion–corrosion resistance properties of 316L austenitic stainless steels after low-temperature liquid nitriding / Xiangfeng Zhang, JunWang, Hongyuan Fan, Dong Pan // Applied Surface Science. — 2018. — Vol. 440. — P. 755–762.

24 Герасимов С.А. Структура и износостойкость азотированных сталей и сплавов / С.А. Герасимов, Л.И. Куксенова, В.Г. Лаптева. — М.: Изд-во МГТУ им. Н.Э. Баумана, 2012. — 518 с.

25 Петрова Л.Г. Комбинированная технология диффузионного насыщения металлами углеродистых сталей, совмещённая с гидроплазменным азотированием / В.А. Александров, П.Е. Демин // Вестн. ХНАДУ. — 2011. — № 54. — С. 52–58.

26 Belkin P. Anodic Plasma Electrolytic Saturation of Steels by Carbon and Nitrogen / A. Naumov, S. Shadrin, I. Dyakov, A. Zhirov, S. Kusmanov, T. Mukhacheva // Advanced Materials Research. — 2013. — Vol. 704. — P. 37–42.

27 Белкин П.Н. Химико-термическое упрочнение стальных деталей при анодном процессе / П.Н. Белкин, Е.А. Пасинковский, А.К. Товарков // Надежность и долговечность машин и сооружений. — 1990. — № 18. — С. 80–86.

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Карбамид негізіндегі электролитте электролитті-плазмалық азоттау кезінде төментемпературалы плазманың болат бетімен өзара әрекеттесу моделі

Мақалада төментемпературалы плазманың пайда болу ерекшеліктері және оның металл бетімен өзара әрекеттесуі зерттелді. Зерттеу нәтижелерін қорытындылай келе және электролит-плазмалық процестің өзіндік ерекшеліктерін ескере отырып, электролит-плазмалық азоттау кезінде төментемпературалы плазманың болат бетімен өзара әрекеттесуінің сапалы моделі жасалды. Осы модельге сәйкес, төментемпературалы плазманың болаттың бетімен әрекеттесуінің алғашқы сәттерінде беткі қабаттағы қатты ерітіндінің тез түзілуі жүреді, $Fe_{\alpha(N)}$ зарядталған бөлшектерді бағытталған бомбалаудың әсерінен, материалдың тереңдігіне азоттың адсорбциясы мен диффузиясын күшейтеді, содан кейін еркін энергия деңгейі жоғары жерлерде одан әрі қанығады (тордың ақауларында, астық шекараларында және т.б.). Легірлеуші элементтердің нитридінің дисперсті бөлшектері пайда болады. Одан әрі қабаттың беткі аймағында азоттың шекті ерігіштігі асып кетсе, онда γ'-фаза (Fe_4N) және ε-фаза $(Fe_{2-3}N)$ нитридтерінің пайда болуына әкелетін өзгерістер болады. Осылайша, электролитті-плазмалық азоттандыру көптеген жаңа мүмкіндіктерді ашады, атап айтқанда: азоттандыру температурасының кең ауқымдағы өзгеруі (400–700 ºC), азотталған қабатты мақсатты түрде алу, тек диффузиялық қабаттан тұратын қосылыстар қабаты жоқ, ал диффузиялық қабатты α'-фазалы бөлшектермен (Fe_4N) пластиналық пішінді және MN (CrN) ұсақ дисперсті нитридтерімен алу. Электролитте (төментемпературалы плазма) электр разрядын қолдану материалдар бетінің қыздыру және диффузиялық қанықтыру жылдамдығын арттыруға мүмкіндік береді. Бұл жұмыстың практикалық маңызы зор, өйткені электролитті плазмалық азоттаудың зерттелген әдісі жоғары физика-механикалық қасиеттері бар болаттарға модификацияланған беткі қабатты алуға мүмкіндік береді.

Кілт сөздер: плазма, электролит-плазмалық өңдеу, азоттандыру, қанықтыру, электролит, болат, модель, модификацияланған қабат, фаза.

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Модель взаимодействия низкотемпературной плазмы с поверхностью стали при электролитно-плазменном азотировании в электролите на основе карбамида

В статье изучены особенности образования низкотемпературной плазмы и ее взаимодействия с металлической поверхностью. Обобщая имеющиеся результаты исследований и учитывая специфические особенности электролитно-плазменного процесса, разработана качественная модель взаимодействия низкотемпературной плазмы с поверхностью стали при электролитно-плазменном азотировании. В соответствии с этой моделью, в первые моменты взаимодействия низкотемпературной плазмы с поверхностью стали в приповерхностном слое происходит ускоренное образование твердого раствора $Fe_{\alpha(N)}$ за счет воздействия направленной бомбардировки заряженных частиц, усиливающего адсорбцию и диффузию азота в глубь материала, затем, по мере дальнейшего насыщения, в местах с повышенным уровнем свободной энергии (на дефектах решетки, на границах зерен и т.п.) образуются дисперсные частицы нитрида легирующих элементов. В дальнейшем при превышении предельной растворимости азота в железе в поверхностной зоне слоя происходят превращения, приводящие к образованию в ней нитридов γ'-фазы (Fe_4N) и ε-фазы $(Fe_{2-3}N)$. Таким образом, электролитно-плазменное азотирование открывает множество новых возможностей, в частности, варьирование температурой азотирования в широких пределах (400–700 ºC); целенаправленное получение азотированного слоя, состоящего только из диффузионного слоя без слоя соединений, при этом получение диффузионного слоя с частицами α'-фазы (Fe_4N) пластинчатой формы и с мелкодисперсными нитридами MN (CrN). Применение электрического разряда в электролите (низкотемпературной плазмы) позволяет увеличить скорость нагрева и диффузионного насыщения поверхности материалов. Данная работа имеет важное практическое значение, так как изучаемый способ электролитно-плазменного азотирования позволяет получить модифицированный поверхностный слой на сталях с высокими физико-механическими свойствами.

Ключевые слова: плазма, электролитно-плазменная обработка, азотирование, насыщение, электролит, сталь, модель, модифицированный слой, фаза.

References

1 Rakhadilov, B.K., Buranich, V.V., Satbayeva, Z.A., Sagdoldina, Zh.B., Kozhanova, R.S., & Pogrebnjak, A.D. (2020). The cathodic electrolytic plasma hardening of the 20Cr2Ni4A chromium-nickel steel. *Journal of Materials Research and Technology*, *9(4)*, 6969–6976.

2 Rakhadilov, B.K., Satbaeva, Z.A., Bayatanova, L.B., Kilyshkanov, M.K., Kalibayev, K.A., & Kochneva, A.K. (2019). Influence of Electrolyte-Plasma Surface Hardening on the Structure And Properties of Steel 40HN. *Journal of Physics: Conference Series*, doi:10.1088/1742–6596/1393/1/012119. Retrieved from: https://iopscience.iop.org/article/10.1088/1742–6596/1393/1/012119

3 Skakov, M., Rakhadilov, B. & Sheffler, M. (2013). Influence of electrolyte plasma treatment on structure, phase composition and microhardness of steel P6M5. K*ey Engineering Materials, 531–532*, 627–631.

4 Zhurerova, L.G., Rakhadilov, B.K., Popova, N.A., Kylyshkanov, M.K., Buraniche, V.V., & Pogrebnjak, A.D. (2020). Effect of the PEN/C surface layer modification on the microstructure, mechanical and tribological properties of the 30CrMnSiA mildcarbon steel. *Journal of Materials Research and Technology, 9(1)*, 291–300.

5 Rakhadilov, B.K., Skakov, M.K., & Scheffler, M. (2015). Microstructure and Tribological Properties of Electrolyte Plasma Nitrided High Speed Steel. *Materials testing*, 4(57), 360–365.

6 Belkin, P.N. & Pasinkovskiy, E.A. (1989). Termicheskaia i khimiko-termicheskaia obrabotka stalei pri nahreve v rastvorakh elektrolitov [Thermal and chemical-thermal treatment of steels when heated in electrolyte solutions]. *Metallovedenie i termicheskaia obrabotka metallov — Metal science and heat treatment,* 5, 12–17 [in Russian].

7 Suminov, I.V., Belkin, P.N., Epelfeld, A.V., Lyudin, V.B., Krit, B.L., Borisov, A.M. (Ed. by I.V. Suminova), (2011). *Plazmenno-elektroliticheskoe modifitsirovanie poverkhnosti metallov i splavov [Plasma-electrolytic modification of the surface of metals and alloys]*. Moscow: Tekhnosfera [in Russian].

8 Kidin, I.N., Andryushechkin, V.I., Volkov, V.A., & Kholin, A.S. (1978). *Elektrokhimiko-termicheskaia obrabotka metallov i splavov [Electrochemical and heat treatment of metals and alloys]*. Moscow: Metallurhiia [in Russian].

9 Samsonov, G.V., & Zhunkovskiy, G.L. (1974). Nekotorye osobennosti formirovaniia pokrytii v protsesse reaktsionnoi diffuzii [Some features of coating formation in the process of reaction diffusion]. *Zashchitnye pokrytiia na metallakh — Protective coatings on metals,* 7, 3–11 [in Russian].

10 Duradzhi, V.N., & Parsadanyan, A.S. (1988). *Nahrev metallov v elektrolitnoi plazme [Heating of metals in an electrolyte plazma]*. Kishinev: Shtiintsa [in Russian].

11 Slovetskiy, D.I. (1991). Mekhanizmy neravnovesnykh plazmokhimicheskikh reaktsii [Mechanisms of non-equilibrium plasma-chemical reactions]. *Khimiia plazmy — Plasma chemistry, 3*, 94–100 [in Russian].

12 Belkin, P.N. (2005). *Elektrokhimiko-termicheskaia obrabotka metallov i splavov [Electrochemical and heat treatment of metals and alloys]*. Moscow: Mir [in Russian].

13 Fedorenkova, L.I. (2007). Osobennosti diffuzii pri obrabotke metallov v elektrolitnoi plazme [Features of diffusion in the treatment of metals in an electrolyte plasma]. *Vestnik Dnepropetrovskoho universiteta. Seriia Fizika. Radioelektronika — Bulletin of the Dnepropetrovsk University. Series Physics. Radionics,* 12/1(14), 104–106 [in Russian].

14 Oulet, R., & Barbye, M. (1983). *Tekhnolohicheskoe primenenie nizkotemperaturnoi plazmy [Technological application of low-temperature plasma]*. Moscow: Enerhoatomizdat [in Russian].

15 Pastukh, I.M. (2006). *Teoriia i praktika bezvodorodnoho azotirovaniia v tleiushchem razriade [Theory and practice of hydrogen-nitriding in a glow discharge]*. Kharkov: NNTs KhFTI [in Russian].

16 Edenhofer, B. (1974). Physikalishe und metallkundliche Vorgange beim Nitriren in Plasma einer Glimmentladung. *Harterei-Technishe Mitteilungen, 29(2)*, 105–112.

17 Lakhtin, Yu.M., Kogan, Ya.D., Shpis, G.Y., & Bemer, Z. (1991). *Teoriia i tekhnolohiia azotirovaniia [Theory and technology of nitriding]*. Moscow: Metallurhiia [in Russian].

18 Panayoti, T.A. (1989). *Azotirovanie vysokoprochnykh stalei i splavov v tleiushchem razriade [Nitriding of high-strength steels and alloys in a glow discharge]*. Moscow: Mashinostroenie [in Russian].

19 Arzamasov, B.N., Eliseyev, Yu.S., & Panayoti, T.A. (1999). *Ionnaia khimiko-termicheskaia obrabotka splavov [Ionic chemical-heat treatment of alloys]*. Moscow: N.E. Bauman MHTU Publ. [in Russian].

20 Syropyatov, V. Ya., Zinchenko, V.M., & Perekatov, Yu.A. (2004). Sovremennaia kontseptsiia azotnoho potentsiala [The modern concept of the nitrogen pote]. *Metallovedenie i termicheskaia obrabotka metallov — Metal science and heat treatment,* 1, 7–12 [in Russian].

21 Lakhtin, Yu.M., & Arzamasov, B.N. (1985). *Khimiko-termicheskaia obrabotka metallov [Chemical and heat treatment of metals]*. Moscow: Metallurhiia [in Russian].

22 Guo-meng Li, Yi-long Liang, Cun-hong Yin, Hao Sun, & Zhen-long Zhu (2019). Study of M50NiL steel under carburizing and nitriding duplex treatment. *Surface and Coatings Technology*, *375*, 132–142.

23 Xiangfeng Zhang, JunWang, Hongyuan Fan, Dong Pan (2018). Erosion–corrosion resistance properties of 316L austenitic stainless steels after low-temperature liquid nitriding. *Applied Surface Science*, *440*, 755–762.

24 Gerasimov, S.A., Kuksenova, L.I., & Lapteva, V.G. (2012). *Struktura i iznosostoikost azotirovannykh stalei i splavov [Structure and wear resistance of nitrided steels and alloys]*. Moscow: N.E. Bauman MSTU Publ. [in Russian].

25 Petrova, L.G., Aleksandrov, V.A., & Demin, P.Ye. (2011). Kombinirovannaia tekhnolohiia diffuzionnoho nasyshcheniia metallami uhlerodistykh stalei, sovmeshchonnaia s hidroplazmennym azotirovaniem [Combined technology of diffusion saturation of carbon steel metals combined with hydroplasma nitriding]. *Vestnik Kharkovskoho natsionalnoho avtomobilno-dorozhnoho universiteta — Bulletin of the Kharkiv National Automobile and Highway University,* 54, 52–58 [in Russian].

26 Belkin, P., Naumov, A., Shadrin, S., Dyakov, I., Zhirov, A., Kusmanov, S., & Mukhacheva, T. (2013). Anodic Plasma Electrolytic Saturation of Steels by Carbon and Nitrogen. *Advanced Materials Research, 704*, 37–42.

27 Belkin, P.N., Pasinkovskiy, E.A., & Tovarkov, A.K. (1990). Khimiko-termicheskoe uprochnenie stalnykh detalei pri anodnom protsesse [Chemical-thermal hardening of steel parts during the anodic process]. *Nadezhnost i dolhovechnost mashin i sooruzhenii — Reliability and durability of machines and structures*, 18, 80–86 [in Russian].

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Modeling of magnetic fields and signals of a ferromagnetic pipe flaw detector induced by a through hole defect

A numerical model has been developed for interaction of the magnetizing field of a short solenoid with a ferromagnetic pipe exhibiting a through hole in the wall, which takes into account nonlinear magnetic properties of the test object. This model was used to calculate spatial distribution of magnetic induction in the pipe wall and spatial distribution of the components of the magnetic induction vector near the pipe surface with a through hole. The validity of the numerical model was confirmed by physical modeling results. The results of theoretical and experimental studies were used to develop a simplified analytical model that describes behavior of the magnetic field of the defect and the electrical signal of the induction transducer of a magnetic flaw detector that implements the method of magnetic flux leakage. It is shown that the dependence of the signal of the induction transducer induced by the through hole on the gap is close to a linear one, and its dependence on the hole diameter is close to a quadratic one. The results obtained in the study can be used for creation, numerical modeling and measurement of magnetic fields.

Keywords: magnetic flux leakage method, induction transducer, finite element method, analytical model.

Introduction

Some of the most important traditional objects of non-destructive testing are metal pipes: heat-exchangers, drill pipes and tubing pipes used to transport various liquids and gases, including water and gas pipes, and others. Types of inspection to detect continuity defects include acoustic, capillary, radiation and eddy current techniques. For ferromagnetic pipes, widely spread techniques are magnetic non-destructive testing, primarily magnetic flux leakage testing (MFL).

MFL implies magnetization of the test object in a constant or low-frequency alternating magnetic field and distortions of the magnetic field lines of force near continuity defects [1–3]. As a result, part of the magnetic flux is displaced by the defect towards the surface to form local leakage flux. Disturbance of the magnetic flux depends on size and shape of the defect, and its depth and orientation both in the test object and relative to the direction of the magnetizing field.

Magnetic leakage fields are recorded using magnetic powder (magnetic particle inspection), magnetic tape (magnetic-tape inspection), induction transducers (induction method), flux gates (flux gate inspection), Hall sensors (Hall effect method), and magnetoresistors (magnetoresistance testing) [4].

Research objective

The induction method has proven high efficiency for in-service inspection of drill, tubing and coiled tubing (CT). Classical implementation of the method for flaw detection in these types of pipes implies magnetization of the test object by a constant longitudinal magnetic field created by a short solenoid [5, 6]. In-

duction coils are placed in the central part of the solenoid with central turns located on a cylindrical surface, which is coaxial to the pipe surface. The number of induction coils is determined to minimize the effect of the test object heterogeneity and to overlap the sensitivity zones of adjacent coils (eight coils are most often used). This ensures the smallest gap between the induction transducer and the pipe surface (of the order of several mm).

1 — pipe; *2* — hole; *3* — solenoid; *4* — induction coil
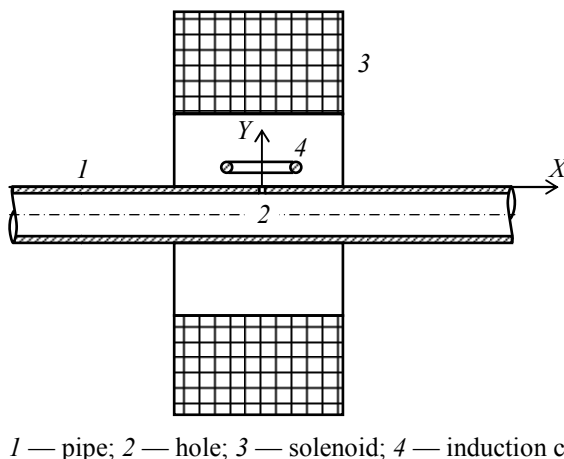
Figure 1. Ferromagnetic pipe with a through hole in the magnetic field of the solenoid

The aim of the study is to develop a mathematical model of the interaction of the magnetizing field with a ferromagnetic pipe exhibiting a through hole in the wall. The tasks to be solved are as follows:
− development of a numerical model of the interaction of the constant magnetic field of a short solenoid with a pipe having a through hole in the wall using the finite element method;
− experimental verification of the developed numerical model;
− finding simplified analytic expressions describing the magnetic field of the defect and the electrical signal of the induction transducer.

Figure 1 schematically shows the geometry of the problem being solved. A test object was a pipe section made of St3 steel of water and gas pipeline assortment: 33.5 mm outer diameter; 3.2 mm wall thickness; 500 mm length; 1.5–3 mm hole diameter. It was assumed that the pipe was magnetized by the solenoid with a length of 100 mm, an outer diameter of 240 mm, an inner diameter of 120 mm and maximum magnetomotive of $I\,w_1 = 6$ kA-turns, where I is the current of the solenoid; w_1 is the number of turns of the solenoid. The arrangement of the pipe and the solenoid was assumed to be coaxial.

Numerical Modeling Results

The finite element method (FEM) was used to develop the model. The advantages of FEM in solving real problems are versatility, an arbitrary shape of the inspected area, no need of object approximation with standard geometric figures, and solution of asymmetric problems with allowance for heterogeneity of the parameters of materials and media [7–10].

The outer boundary of the study area in modeling was assumed to be a cylindrical surface. A mesh compaction mechanism was applied to increase the accuracy of calculations (Fig. 2). The magnetic properties of steel were set by the main magnetization curve St3 [11].
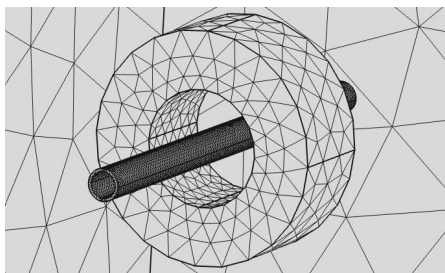
Figure 2. Numerical model after meshing

Equipotential lines and color spectrum in Figure 3*a* show the distribution of magnetic induction *B* in the pipe wall during its interaction with the solenoid magnetic field at $I w_1$ = 6 kA-turns and the hole diameter of 3 mm obtained in numerical modeling. Figure 3*b* presents enlarged distribution of magnetic induction in the pipe wall near the hole with its center located in the transverse plane of the axially-symmetric solenoid.

a   *b*
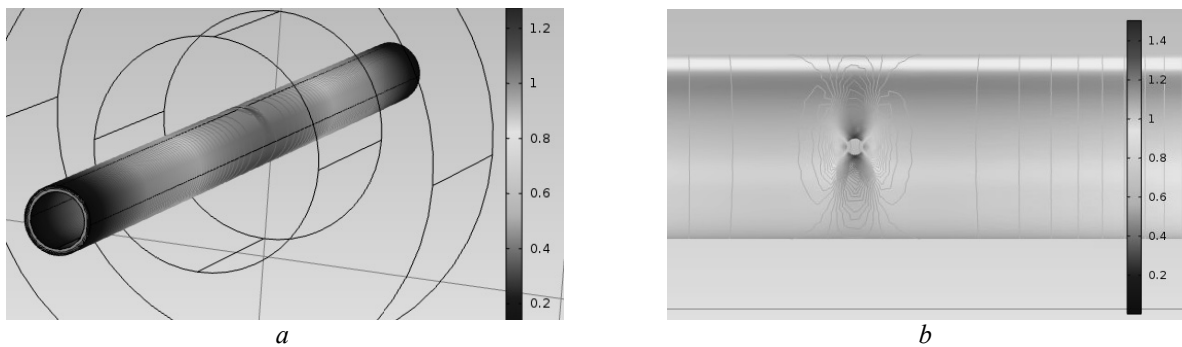
Figure 3. Distribution of magnetic induction in the pipe wall along the pipe length (*a*) and near the hole (*b*)

Figure 4*a* shows spatial distribution of magnetic induction near the hole at a distance of 3 mm from the pipe surface. Figure 4*b* presents spatial distribution of magnetic induction for the normal component of the magnetic field induction.

a   *b*
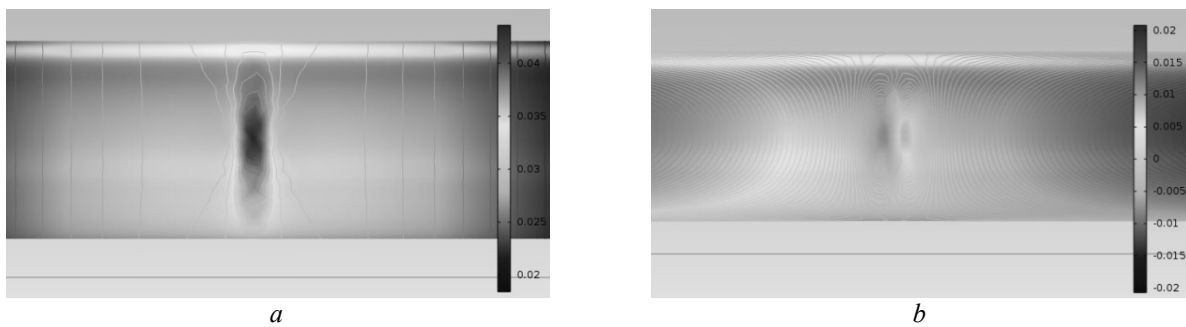
Figure 4. Distribution of the module of the magnetic induction vector (a) and its normal component (b)
near the hole at a distance of 3 mm from the pipe surface
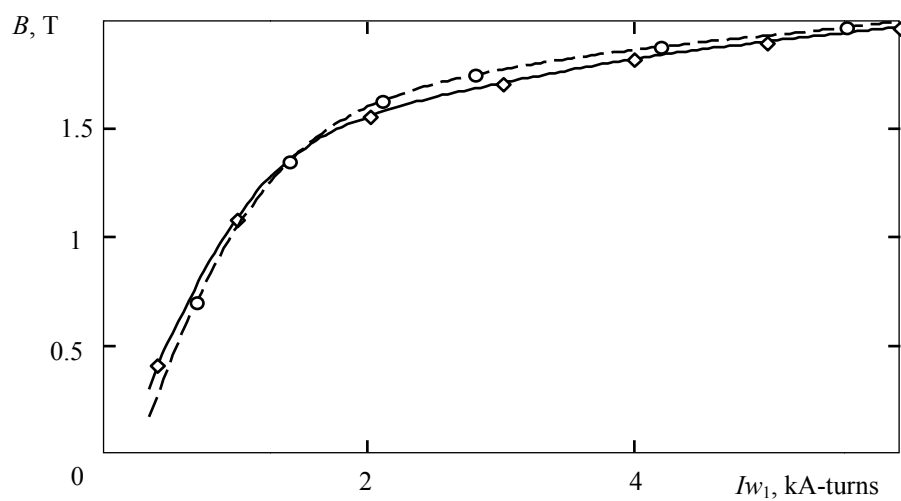
Figure 5. Dependence of the magnetic induction in the pipe wall
in the transverse plane of the axially-symmetric solenoid on the $I w_1$ value

The developed numerical model takes into account nonlinear properties of the ferromagnetic material of the test object. Figure 5 shows the dependence of the magnetic field induction in the pipe wall of the axially-symmetric solenoid on the value of Iw_1 obtained by numerical modeling (dashed line). The analysis of these results shows compliance with experimental data that is applicable for most of practical tasks (solid line). Induction was measured using a standard method based on the EMF integration of the external feed-through transducer that occurs when the solenoid current changes abruptly.

Figure 6 shows spatial distribution of tangential B_x and normal B_y components of the magnetic field induction vector at a distance of 3 mm from the pipe surface along the longitudinal axis X. Modeling assumed that the center of the hole is located in the axially-symmetric solenoid (Fig. 1). Discrepancy between the obtained results and the results of measuring the B_y component using the Hall sensor did not exceed 20 %.

Figure 6. Dependences of the tangential (*a*) and normal (*b*) components of the magnetic induction
on the X coordinate at different distances from the pipe surface

Analytical Modeling Results

The results of numerical and physical modeling were used to develop a fairly simple approximate analytical model to describe the magnetic field of the hole in the wall of a magnetized pipe. Analysis of various versions of the model [12, 13] showed that the basic version to use can be a hole replaced with two conductors with current I_c oriented perpendicular to the cross section of the test object and with the coordinates of the axes $X_1 = 0$; $Y_1 = 0$ and $X_2 = 0$; $Y_2 = -T$. In this case, according to [12; 42], the components of the magnetic field strength can be calculated by the equations:

$$H_x = \frac{I_\text{п}}{2\pi}\left(\frac{Y}{X^2 + Y^2} - \frac{Y+T}{X^2 + (Y+T)^2}\right); \quad H_y = \frac{I_\text{п}}{2\pi}\left(\frac{X}{X^2 + Y^2} - \frac{X}{X^2 + (Y+T)^2}\right). \quad (1)$$

For pipes with an outer diameter of 20 to 45 mm, compliance between the calculation results obtained by equation (1) and those obtained in physical modeling that is applicable for practical tasks can be achieved at $T \approx \dfrac{R}{2}$, where R is the pipe radius.

It should be noted that not the absolute values of the components of the magnetic leakage field strength proportional to the magnetic field induction in the pipe wall are of interest, but their spatial distribution over the pipe surface. Thus, in order to eliminate the effect of I_c on the calculation results, we will use not absolute but relative values of the components of the scattering magnetic field strength h_x and h_y normalized by the value of the field strength H_0 at the point with coordinates $(0, T)$:

$$h_x = \frac{H_x}{H_0} = \frac{y}{x^2 + y^2} - \frac{y+0{,}5}{x^2 + (y+0{,}5)^2}; \quad h_y = \frac{H_x}{H_0} = \frac{x}{x^2 + y^2} - \frac{x}{x^2 + (y+0{,}5)^2}, \quad (2)$$

where $x = \dfrac{X}{R}$ and $y = \dfrac{Y}{R}$ are relative values of the coordinates normalized by the value of the pipe radius.

Figure 7 shows the dependences of the components of the magnetic leakage field calculated using equation (2) on the x coordinate for different values of y.
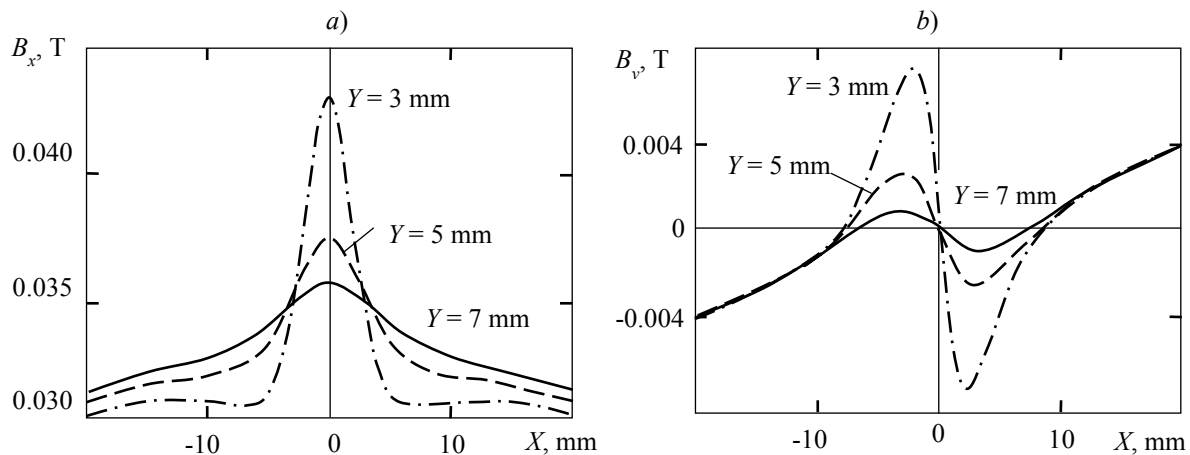

a)   *b)*
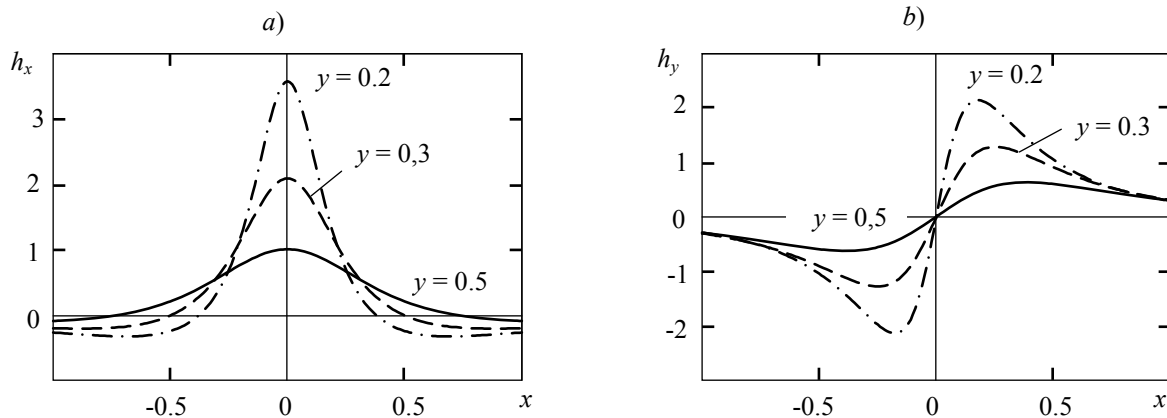
Figure 7. Dependences of the tangential (*a*) and normal (*b*) components of the magnetic leakage field
on the x coordinate at different distances from the pipe surface y

The h_y component is used for practical implementation of the method of induction flaw detection. Assume that this component of the scattering magnetic field is measured by a rectangular induction winding with the central turn of $2A \times 2A$ located on the cylindrical surface coaxial to the pipe surface in the central part of the solenoid (Fig. 1).

According to the law of electromagnetic induction, the EMF induced in the coil at a constant pipe velocity V is calculated as follows:

$$e = -w_2 \frac{d\Phi}{dt} = -w_2 V \frac{d\Phi}{dX} \,, \tag{3}$$

where w_2 is the number of turns in the coil, Φ is magnetic flux passing through the central turn of the coil, which is determined through integration of the induction of the magnetic leakage field over the surface of the turn:

$$\Phi = \mu_0 2A \int\limits_{X-A}^{X+A} H_y(X, Y) \, dX \,, \tag{4}$$

where μ_0 is permeability of vacuum.

Equation (4) assumes that the magnetic leakage field is homogeneous in the transverse direction within the coil.

As already mentioned, the behavior of the leakage field above the pipe surface and of the coil signal induced by the field is of great interest. By analogy with the previous equations, we will find not the absolute EMF value, but its relative value:

$$e^* = \frac{e}{E_0} = \frac{d}{dx} \int\limits_{x-a}^{x+a} h_y(x, y) \, dx; \quad E_0 = -w_2 \mu_0 2AVH_0 \,, \tag{5}$$

where $a = \dfrac{A}{R}$ is a relative value of the coil size normalized by the value of the pipe radius.

The normalized value of E_0 is numerically equal to the EMF arising in the induction coil at the velocity of mutual displacement of the field source and the coil V and an abrupt change in the normal component of the magnetic field strength from zero to H_0.

Figure 8 shows the dependence of the EMF of the induction transducer with dimensions of the central turn of $0.8R \times 0.8R$ on the displacement of the pipe section with the hole relative to the transducer with various gaps. The dependence of the signal of the induction transducer on time $e^*(t)$ exhibits similar behavior.

The numerical results obtained using equation (5) and in physical modeling are similar for the proposed model that is applicable for most of practical tasks.
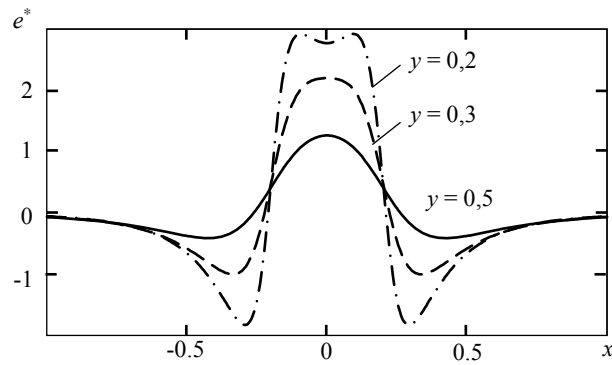
Figure 8. Dependence of the EMF of the induction transducer on the x coordinate
at different distances from the pipe surface y

Figure 9 shows a comparison of the calculated $e^*(X)$ and experimental $e_э^*(X)$ dependences of the EMF of the induction transducer with the central turn of 13×13 mm² and a gap of $Y = 5$ mm. Experimental data were obtained for the hole 3 mm in diameter, $I\,w_1 = 6$ kA-turns and the pipe velocity of 0.285 m/s. For clarity, the maximum value of the function $e_э^*(X)$ was equalized with the maximum value of $e^*(X)$.
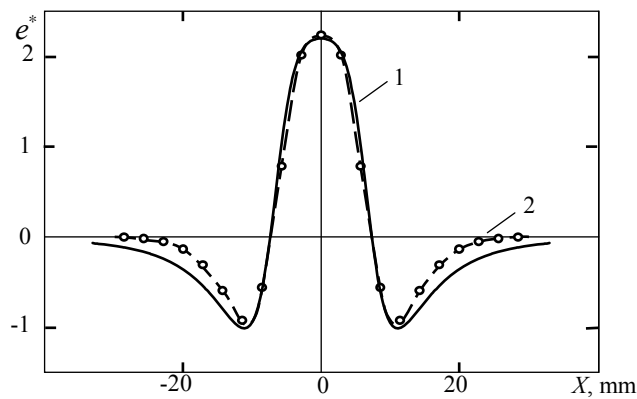
Figure 9. The calculated (1) and experimental (2) dependences of the signal
of the induction transducer on the shift of the hole along the X axis

Figure 10 shows the calculated and experimental dependences of the maximum value of the induction transducer signal induced by the hole on the gap y. For the gap range from 0 to 0.5 R, this dependence is close to linear.
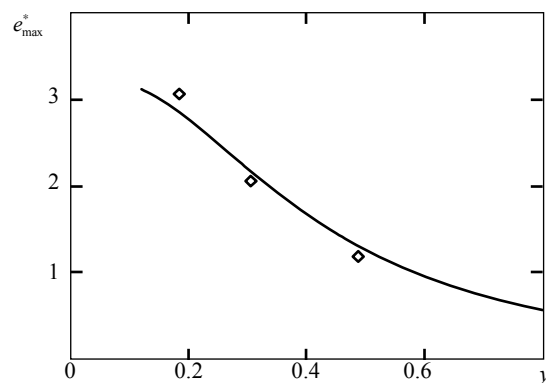
Figure 10. The calculated (solid line) and experimental (rhomboid marks) dependences
of the signal of the induction transducer on the gap

In addition, the dependence of the maximum value of the induction transducer signal on the diameter of the hole was determined experimentally. This dependence is quadratic, which is due to the almost linear dependence of the induction (strength) of the magnetic leakage field on the volume of a through defect detected in the continuity of the cylindrical surface.

Conclusion

The numerical model of interaction between the magnetizing field of a short solenoid and a ferromagnetic pipe with a through hole in the wall has been developed with regard to the nonlinear magnetic properties of the test object. The validity of the numerical model was confirmed by the results of physical modeling. Based on the obtained theoretical and experimental results, a simplified analytical model was developed to describe the behavior of the magnetic field of the defect and of the electrical signal of the induction transducer with an accuracy applicable for most of practical tasks. It is shown that the dependence of the signal of the induction transducer induced by the through hole on the gap is close to a linear one, and its dependence on the hole diameter is close to a quadratic one.

References

1 Christie R. Monitoring and managing coiled tubing integrity / R. Christie, Ch. Liu, R. Stanley, M. Torregrossa, E. Zheng, L. Zsolt // Oilfield Review. — 2015. — Vol. 27, No. 1. — P. 48–56.

2 Потапов А.И. Электромагнитные и магнитные методы неразрушающего контроля материалов и изделий: [В 2 т.]. — Т. 2: Электромагнитные и магнитные методы дефектоскопии и контроля свойств материалов / А.И. Потапов, В.А. Сясько, П.В. Соломенчук. — СПб.: Нестор-История, 2015. – 440 с.

3 Slesarev D.A. Data processing and representation in the MFL method for nondestructive testing / D.A. Slesarev, A.A. Abakumov // Russian Journal of Nondestructive Testing. — 2013. — Vol. 49, No. 9. — P. 3–9.

4 ГОСТ Р 55612–2013. Контроль неразрушающий магнитный. Термины и определения. — М.: Стандартинформ, 2018. — 14 с.

5 Установка неразрушающего контроля бурильных труб магнитным методом в мобильном исполнении «Магпорта-бур 1.2». Руководство по эксплуатации. — СПб., 2016. — 20 с.

6 The ARTIS-3 Portable Inspection System. — URL: http://www.oem-usa.com/products/EMIportable4500.html.

7 Шубочкин А.Е. Развитие и современное состояние вихретокового метода неразрушающего контроля: моногр. / А.Е. Шубочкин. — М.: Изд. дом «Спектр», 2014. — 288 с.

8 Potapov A.I. Optimization of the parameters of primary measuring transducers that use the MFL technology / A.I. Potapov, V.A. Syas'ko, O.P. Pudovkin // Russian Journal of Nondestructive Testing. — 2013. — Vol. 51, No. 8. — P. 64–71.

9 Aikeyeva A.A. Modeling electromagnetic systems / A.A. Aikeyeva, B.A. Zhautikov, A.M. Aidarkhanov, A.S. Zhanasbayeva, F.B. Zhautikov, A.S. Belgibayev // Bulletin of the university of Karaganda – Physics. — 2014. — No. 3(75). — P. 28–34.

10 Aikeyeva A.A. Development of imitating model of skip motion in the program environment ANSYS Maxwell / A.A. Aikeyeva, X.S. Rogovaya, A.R. Tanskozhanova, A.E. Ayubekova, P.A. Mukhtarova, A.E. Ospanov // Bulletin of the university of Karaganda – Physics. — 2017. — No. 1(85). — P. 82–88.

11 Шелихов Г.С. Магнитопорошковая дефектоскопия / Г.С. Шелихов, В.В. Клюев. — М.: Изд. дом «Спектр», 2010. — 336 с.

12 Неразрушающий контроль: справ.: [В 8 т.] / под ред. В.В. Клюева. — Т. 6: [В 3 кн.] — Кн. 1: Магнитные методы контроля; Кн. 2: Оптический контроль; Кн. 3: Радиоволновой контроль. — М.: Машиностроение, 2006. — 848 с.

13 Кушнер А.В. Анализ моделей дефектов в теоретических исследованиях магнитных полей рассеяния, возникающих при намагничивании ферромагнитных объектов / А.В. Кушнер, В.А. Новиков // Вестн. Белорус.-Рос. ун-та. — 2014. — № 1(42). — С. 95–105.

А.Е. Гольдштейн, В.Ю. Белянков

Ферромагниттік құбырлардың индукциялық дефектоскоптың магниттік өрістері мен сигналдарын өтпелі тесік түріндегі ақаудан модельдеу

Бақылау объектісінің сызықты емес магниттік қасиеттерін ескере отырып, қысқа соленоидтың магниттелетін өрісінің ферромагниттік түтікпен қабырға саңылауы арқылы әрекеттесуінің сандық моделі жасалды. Осы модельді қолдана отырып, құбыр қабырғасында магниттік индукцияның кеңістіктік таралуы және саңылау болған кезде құбырдың бетіне жақын магниттік индукция векторының компоненттерінің кеңістіктік таралуы есептеледі. Сандық модельдің дұрыстығы физикалық модельдеу нәтижелерімен расталады. Теориялық және эксперименттік зерттеулердің нәтижелеріне сүйене отырып, магнит ағынының шашырау әдісін жүзеге асыратын магниттік дефектоскоптың индукциялық түрлендіргішінің магниттік өрісі мен электрлік дабылының өзгеру

сипатын сипаттайтын жеңілдетілген аналитикалық модель ұсынылды. Индукциялық түрлендіргіштің саңылаудан шығатын дабылы сызыққа жақын саңылауға және саңылау диаметріне квадратқа жақын тәуелділікке ие екендігі көрсетілген. Мақалада келтірілген нәтижелерді магниттік өрістерді математикалық модельдеу және өлшеу мәселелерін шешуде қолдануға болады.

Кілт сөздер: магнит ағынының шашырау әдісі, индукциялық түрлендіргіш, соңғы элемент әдісі, аналитикалық модель.

А.Е. Гольдштейн, В.Ю. Белянков

Моделирование магнитных полей и сигналов индукционного дефектоскопа ферромагнитных труб от дефекта типа сквозное отверстие

Разработана численная модель взаимодействия намагничивающего поля короткого соленоида с ферромагнитной трубой со сквозным отверстием стенки, учитывающая нелинейные магнитные свойства объекта контроля. С использованием данной модели рассчитано пространственное распределение магнитной индукции в стенке трубы и пространственное распределение составляющих вектора магнитной индукции вблизи поверхности трубы при наличии отверстия. Корректность численной модели подтверждена результатами физического моделирования. На основе результатов теоретических и экспериментальных исследований предложена упрощенная аналитическая модель, описывающая характер изменения магнитного поля дефекта и электрического сигнала индукционного преобразователя магнитного дефектоскопа, реализующего метод рассеяния магнитного потока. Показано, что сигнал индукционного преобразователя от сквозного отверстия имеет зависимость от зазора, близкую к линейной, и зависимость от диаметра отверстия, близкую к квадратичной. Результаты, представленные в статье, могут быть использованы при решении задач создания, математического моделирования и измерения магнитных полей.

Ключевые слова: метод рассеяния магнитного потока, индукционный преобразователь, метод конечных элементов, аналитическая модель.

References

1   Christie, R., Liu, Ch., Stanley, R., Torregrossa, M., Zheng, E., & Zsolt, L. (2015). Monitoring and Managing Coiled Tubing Integrity. *Oilfield Review, 27,* 1, 48–56.

2   Potapov, A.I., Syasko, V.A., & Solomenchuk, P.V. (2015). *Elektromahnitnye i mahnitnye metody nerazrushaiushcheho kontrolia materialov i izdelii. Elektromahnitnye i mahnitnye metody defektoskopii i kontrolia svoistv materialov [Electromagnetic and magnetic methods of non-destructive testing of materials and products. Electromagnetic and magnetic methods of defectoscopy and control of material properties]* (Vols 1–2; vol. 1). Saint Petersburg: Nestor-Istoriia [in Russian].

3   Slesarev, D.A., & Abakumov, A.A. (2013). Data processing and representation in the MFL method for nondestructive testing. *Russian Journal of Nondestructive Testing, 49,* 9, 3–9.

4   *HOST R 55612–2013. Kontrol nerazrushaiushchii mahnitnyi. Terminy i opredeleniia [GOST R 55612–2013 Non-destructive magnetic control. Terms and Definitions]* (2018). Moscow: Standartinform [in Russian].

5   *Ustanovka nerazrushaiushcheho kontrolia burilnykh trub mahnitnym metodom v mobilnom ispolnenii «Magportabur 1.2». Rukovodstvo po ekspluatatsii [NDT installation for drill pipes by the magnetic method in the mobile version «Magportabur 1.2»: Manual]*. (2016). Saint Petersburg [in Russian].

6   *The ARTIS-3 Portable Inspection System*. Retrieved from: http://www.oem-usa.com/products/EMIportable4500.html.

7   Shubochkin, A.E. (2014). *Razvitie i sovremennoe sostoianie vikhretokovoho metoda nerazrushaiushcheho kontrolia [Development and current state of the eddy current method of non-destructive testing]*. Moscow: Spektrum [in Russian].

8   Potapov, A.I., Syasko, V.A., & Pudovkin, O.P. (2013). Optimization of the parameters of primary measuring transducers that use the MFL technology. *Russian Journal of Nondestructive Testing, 51,* 8, 64–71.

9   Aikeyeva, A.A., Zhautikov, B.A., Aidarkhanov, A.M., Zhanasbayeva, A.S., Zhautikov, F.B., & Belgibayev, A.S. (2014). Modeling electromagnetic systems. *Bulletin of the university of Karaganda – Physics, 3, 75,* 28–34.

10   Aikeyeva, A.A., Rogovaya, X.S., Tanskozhanova, A.R., Ayubekova, A.E., Mukhtarova, P.A., & Ospanov, A.E. (2017). Development of imitating model of skip motion in the program environment ANSYS Maxwell. *Bulletin of the university of Karaganda — Physics, 1, 85,* 82–88.

11   Shelikhov, G.S., & Klyuev, V.V. (2010). *Mahnitoporoshkovaia defektoskopiia [Magnetic particle inspection]*. Moscow: Spektrum [in Russian].

12   Klyuev, V.V. (Ed.). (2006). *Nerazrushaiushchii kontrol: spravochnik v 3 knihakh. Kniha 1: Mahnitnye metody kontrolia. Kniha 2: Opticheskii kontrol. Kniha 3: Radiovolnovoi kontrol [Nondestructive Testing. Handbook. 1. Magnetic control methods, 2. Optical control, 3. Radio wave control* (Vols. 1–8; vol. 6). Moscow: Mashinostroenie [in Russian].

13   Kushner, A.V., & Novikov, V.A. (2014). Analiz modelei defektov v teoreticheskikh issledovaniiakh mahnitnykh polei rasseianiia, voznikaiushchikh pri namahnichivanii ferromahnitnykh obektov [Analysis of model defects in theoretical studies of scattering magnetic fields arising from magnetization of ferromagnetic objects]. *Vestnik Belorussko-Rossiiskoho universiteta — Bulletin of the Belarusian-Russian University,* 1, 42, 95–105 [in Russian].

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Identification of distortion of the navigator's time in model experiment

This article discusses a formal analysis of time perception made by sea transport navigators being in critical situations while performing vessel navigation. The carried out analysis of experimental data and investigations of marine accidents provided us with valuable insights of having wide range of cases in which navigators, while performing complex maneuvers (i.e. mooring operation), are highly likely to be involved into facing challenges of getting poor time comprehension during template implementation process. It is worth mentioning that while having it this very issue is being influenced on by external and internal factors. It, for its part, is noticed to considerably contribute into the increased likelihood of accidents. The main goal of this study is reported to be the development of a concept of having formal and automated means and methods for the identification distortion of the navigator's time (DNT) as being an indicator of negative manifestation of human factor in critical situations. For the sake of having been able to accomplish this goal a generalized model for the formation of t DNT was proposed as well as mathematical models and automated tools were introduced to be used for DNT intervals identification when analyzing the physical trajectory of the vessel's movement. Besides, the generating individual time codes in emergency situations system is managed to be successfully revealed. Moreover, the carried out experiments using the certified navigation simulator Navi Trainer 5000 are said to have confirmed the convincing cogency and to have made clear evidences of providing practical value of the proposed approaches. It goes without saying that these issues are sure to significantly improve the safety-driven process of keeping a navigational watch while navigating a vessel.

Keywords: experimental data, navigator's time distortion, ergatic and automated systems.

Introduction

Contemporary being used tools for the analysis of experimental data of physical processes, getting impact on the trajectory of the ship are encountering the need of having certain amount of ambiguity with regard to the human- navigator fault [1]. This very circumstance is able to directly affect the accuracy of predicting the vessel movement [2]. As a result, it turns out not to provide any possibilities to determine the valid reasons for the deviation of the trajectories from the optimal ones calculated by the onboard information and intelligent systems (Fig. 1).

Figure 1. Deviation from the optimal trajectory due to the influence of uncertain factors

Consequently, the calculation of the full range of physical parameters does not authorise the on-board computer to be using the autopilot due to the peculiarities of the port waters locations and international legislation [3].

As it is vividly seen, the initial analysis of the trajectory of the maneuver on the right in Figure 1 is noticed to provide significant difference from the optimal one for no apparent reason. The analysis delivers us the opportunity to single out one of the key reasons for the following navigator's behavior happening to be due to the perception of the situation regarding the time range of the operation [4–7]. The parameter of time perception by the navigator is considered to be an uncertainty $a \in A$ in the situation $s \in S$ with having the situation identifier presented in the form $\pi(s) = \varphi(s, A) = \bigcup_{a \in A} \varphi(s, a)$, whereas the optimality ε is reported to take into account uncertainties in the following form:

$$\widetilde{\mathrm{Max}}(S, \varepsilon) = \left\{ s \in S \mid \pi(s) \subset \mathrm{Max}(\pi(s), \varepsilon) \right\} = \left\{ s \in S \forall x \in \pi(s), f(x) \right\} \geq \sup\left\{ f(y) \mid y \in \pi(S) \right\} - \varepsilon =$$
$$= \left\{ s \in S \mid \inf\left\{ f(x) \mid x \in \pi(s) \right\} + \varepsilon \geq \sup\left\{ f(y) \mid y \in \pi(S) \right\} \right\},$$

where: a — is a set of uncertainties in the form of metadata belonging to A; S — is a set of navigator strategies; s — is a strategy that determines the current situation; $\pi(s)$ — is a situation determined by the strategy; φ — is a mapping that determines the situation on the pair (s, a); ε — is a set of optimal situations for some admissible subset of situations X, $R(X, \varepsilon) \subset X$; f — is a vector performance criterion; x, y — is an element of an admissible subset of situations X defined by the dominance relation "$\succ$".

The research data and the indicated dependencies are empowered to determine the degree of influence on the situation of information signals from the physical environment with the data of navigation sensors and devices being used. However, the central tendency of having time recognised only as a discrete component in the proposed above models is highly likely not to present possibilities of finding out factors of its perception [8].

Other models are certain to submit the situation as a descriptive one basing on empirical experiments of getting clear and convincing evidences of the hypothesis of the change in the navigator's time perception in emergency situations. Nevertheless, these issues happen not to implement an understandable patterns of the dependences of time perception when performing tasks in a formal form. The only obvious item to be paid attention to is having the subjective up-to-individual time calculation being significantly different from the devices' readings [9, 10]. This process directly affects the navigator's behavior making an inevitable contribution to uncertainty in decision making [11]. Hence, in its turn, it can affect the physical trajectory of the vessel. It would be beneficially taken into account that the time factor a should be introduced as being the difference between the real perception according to the i-th parameter of the navigation system $a_r(t)_i$ and the distorted one $a_d(\Delta t)_i$ in the form: $D(i)_t = \left| a_d(\Delta t)_i - a_r(t)_i \right|$

These all mentioned above issues seem to cause contradictions between the need of getting explicit identification of the distortion or «distortion of the navigator's time» (DNT) when performing maneuvers and the capabilities of contemporary electronic and automated navigation systems.

Thus, the relevance of this study is said to be the necessity to determine the formal models of ship control performed by the navigator with due regard for DNT basing on experimental navigation data.

The aim of the study targeting to be fulfilled is having formal and automated means developed and methods for determining DNT as an indicator of the negative human factor manifestation of the navigator in emergency situations on sea transport identified.

Research objectives:

1. To develop a generalized model for the formation of DNT in order to determine the level of its individual distortion.

2. To build mathematical models and automated means for identifying the DNT intervals on the physical trajectory of the vessel.

3. To elaborate a formal system for the shaping of individual time codes and identify the conditions for their operation in critical emergency situations.

4. To carry out experiments evaluating the viability of the proposed means of experimental detection of DNT when navigating a vessel by having the navigation simulator Navi Trainer 5000 involved.

Problem statement

Research methods. To illustrate the ideas let us consider the trajectory of the navigators' decision-making by way of a Markov homogeneous chain of the form:

$$\sum_{j=1}^{n} p_{ij} = \sum_{j=1}^{n} p_{v} \zeta_{ij}^{1} + \sum_{j=1}^{n} q_{v} \zeta_{ij}^{0} = p_{v} + q_{v} = 1,$$

where p_{ij} — is a probability of transition from state a_i to state a_j; p_v — is a probability of DVN manifestation, at $q_v = 1 - p_v$; n — is a border of possible typical states; ζ_{ij}^{0}, ζ_{ij}^{1} — is an stochastic matrices, where indices 1 — penalty, and 0 — not penalty.

Then in this case the mathematical expectation of the occurrence of DNT on the trajectory will be presented in the form of the following equation:

$$M(A,C) = \sum_{j=1}^{n} Q_j p_{vj},$$

where M — is a mathematical expectation; Q_j — is a final probability of the state a_i; A — is a state automaton; C — is an environ.

Nonetheless, it must be emphasised that the actual observed occurrence of DNT can be treated as being extremely intricate to be uncovered in the form of the matrix of transition states. The reason for not being capable of dealing with it is considered to be randomness of DNT manifestation meeting the eye. Contemporary tendency of explaining it is based on the affairs of having this phenomenon dependable on the number of information factors perceived simultaneously by the navigator. It must be especially taken into account if he occurs to find them self in critical or emergency situations [13].

It must be added that the analysis of decision-making processes by navigators is possible to be described by the mathematical apparatus of fuzzy systems withal. So, the reference to source [14] is providing us with the definition of mutually mini-related quantities $\xi_1, \ldots, \xi_n$ as being introduced as follows:

$$\mu_{\xi_1, \ldots, \xi_n}(x_1, \ldots, x_n) = \varsigma\{\gamma \in \Gamma : \xi_1(\gamma) = x_1, \ldots, \xi_n(\gamma) = x_n\} = \varsigma\{\xi_1^{-1}(x_1) \cap \ldots \cap \xi_n^{-1}(x_n)\}, \forall (x_1, \ldots, x_n) \in R^n,$$

where $x_1, \ldots, x_n$ — is an observed sample values; ς — is the measure of the possibility; Γ — is set of the system elements; γ — is an atomic element of the system; R — is the modal value of the capability of the magnitude; $\xi_1, \ldots, \xi_n$ — is a fuzzy values.

Simultaneously, for the sake of rationing $\xi_1, \ldots, \xi_n$ a criterion α is welcomed as the level of risk of erroneous distributions of the estimate. In addition, the form of distribution of possible polar values H in terms of the coefficient ambiguity with regard to b' the investigated parameter ρ' (DTN) is described by the following dependencies [14]:

$$b' = \frac{\max\limits_{1 \le i \le n} x_i - \min\limits_{1 \le i \le n} x_i}{H_+^{-1}(\alpha) - H_-^{-1}(\alpha)}, \quad \rho' = \frac{1}{2}\left(\max\limits_{1 \le i \le n} x_i - \min\limits_{1 \le i \le n} x_i\right) + \frac{b'}{2}\left(H_+^{-1}(\alpha) - H_-^{-1}(\alpha)\right),$$

where b' — is a fuzzy factor; ρ' — is an the investigated parameter DVN; α' — is a standardization criterion of $\xi_1, \ldots, \xi_n$; H — is a distribution of possible polar values.

From these mentioned above descriptions it is vividly seen that the distribution of quantities may generally be having «normal» behaviour pattern in the form of an ellipsoid and within the framework of problem solving $\xi_\alpha^+ - \xi_\alpha^- \to \min$; $\mu_{\xi_1, \ldots, \xi_n}(x_1, \ldots, x_n, \rho', b') = \alpha$. However, the latter approach happens to be complicated enough to be appealed to in the aforementioned problem since having DNT factor poorly correlated with the concept of normal distribution. It is worth noticing that this issue mostly depends on inhomogeneous spectrum of parameters (Fig. 2).

So, for the aim of getting more accurate determination of the nature of this uncertainty experimental data of navigation devices and sensors during maneuver operations in the Bosphorus is said to have been performed. To meet this desired outcome the certified navigation simulator Navi Trainer 5000 located at the Kherson State Maritime Academy had been made use of.

The peculiarity of the location can have troublesome air due to the fact of maneuvering with multiple controlled targets [15, 16].
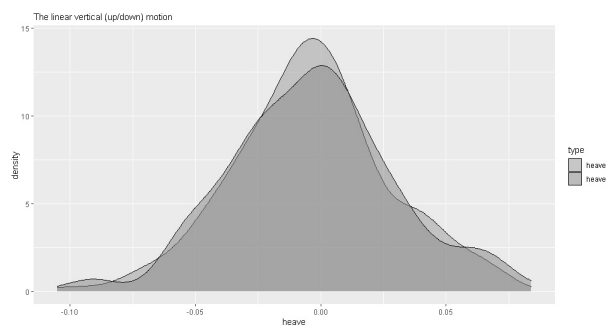
Figure 2. Ratios of natural factors of wind «wind 1,2» and waves «heave 1,2»

With regard to the spoken above circumstances the condition of the location as well as similar natural factors, time of day (season) and location of the port had been welcomed to pay attention to.

Despite observing similar initial conditions and high level of qualifications of navigators the graphic of the longitudinal movement of the **surge** vessel is noticed to be different significantly. Besides, it was uncovered that the navigator get used to choosing a maneuver being untypical for this location (Fig. 3).
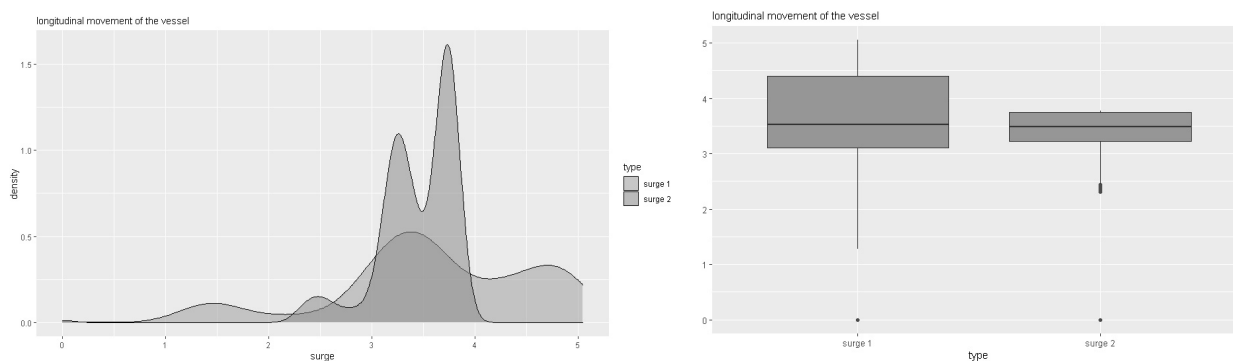

Figure 3. Graphs of density distribution and median of the vessel's longitudinal movement «surge». Surge 1 with autopilot and Surge 2 with manual captain control

Thus, this situation was successfully dealt with having the accident avoided. Nevertheless, the navigator was highly likely not to consider his actions to be erroneous ones. Therefore, a precedent associated with the expectations of the navigator personality in emergency situations is on the point of resurfacing. It goes without saying that this manner could directly be delivering huge impact on his behavior pattern when navigating the ship [17]. So, the certain complexity of the indicated experiments and a number of having happened typical situations found out during the investigation of accidents at marine transport are leading to a real challenge and necessity in having a detailed analysis and mathematical description of these processes and phenomena.

Material and method

For the sake of getting a visual determination of the individual distortion level of DNT the generalized model is proposed to be introduced being built on the basis of a Cartesian coordinate system. Its axes are about to be factors possible to be divided into three groups with polar coordinates (Fig. 4).

The generalized model of the formation of DNT in three-dimensional space is reported to be represented by the following coordinates: $(x; -x)$ — environment: day/night; $(y; -y)$ — navigation systems and sensors: full/partial watch; $(z; -z)$ — voice commands: native language / foreign.

It is clearly seen that points *A*, *B*, *C* are displayed along each axis at nominal distance in the form of certain informational factors being able to be covered simultaneously by the navigator [18]. Meanwhile, it must be brought up that the maximum of factors with zero DTN, t_{ij} is specified according to navigator's experience: 7 — inexperienced operator (1 time in the current position); 8 — average operator in experience (2–3 times in the current position); 9 — experienced operator (4 or more times in the current position).
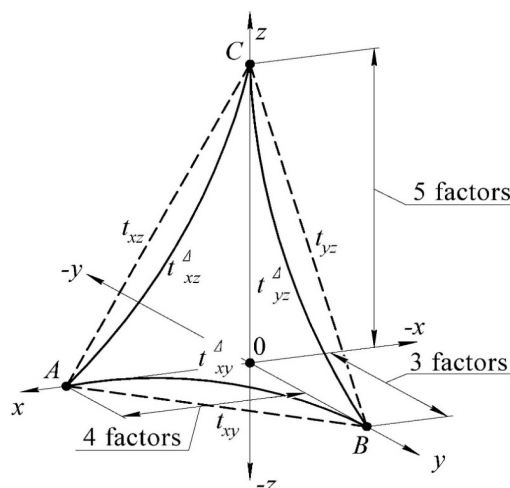
Figure 4. Model with 12 factors determining DTN, t_{ij}^{Δ} — being depicted

The critical sum of the parameters are noticed to simultaneously affect each segment of the ABC triangle and, as a consequence, the level of DNT is being increased. This interpretation of the model of the formation of DNT seems close to the terms of the geometric group theory [19, 20]. Proceeding from similarities metric and space for more specified description of the model for the formation of DNT seems highly likely to be constructed not speaking about further provided research tasks.

Nevertheless, according to the geometric theory of groups the definition of the metric, space and generator system should be stated as being an important step. Thus, the specifics of the subject field as well as the research tasks are making us give objectives that include engaging with determining the conditions of the formal system process.

Appropriately, at each certain moment of watchkeeping the navigator objectively carries out only one set of forming axes of the geometric system: $(x, -x; y, -y; z, -z)$. It is sure to be meant that all possible actions of the navigator are about to be performed within one of the eight quadrants of the Cartesian coordinate system. Therefore, the formal system of navigator actions of the navigator in the form of the Cayley graph seems possible to be represented as following (Fig. 5).
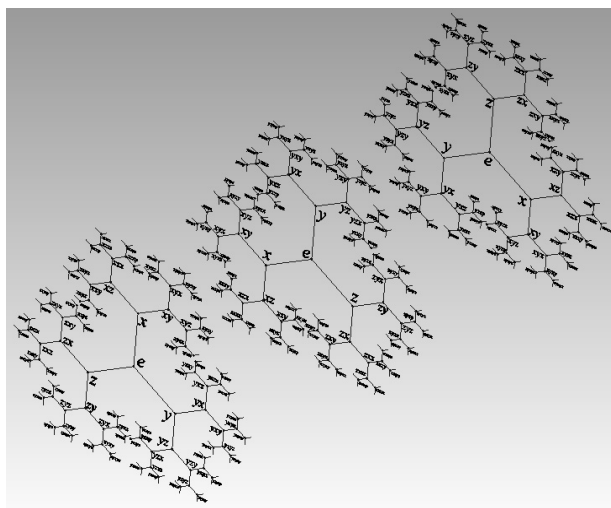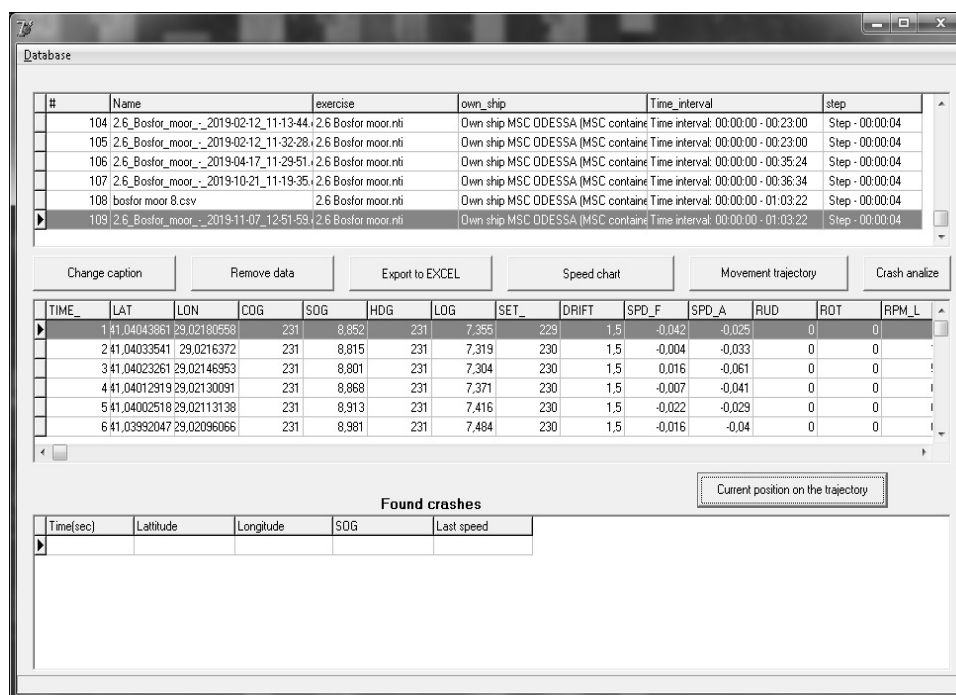

Figure 5. Formations of the Cayley graph

Basing on the evidence of having this graph $Cay\langle x, y, z \mid x^2 = y^2 = z^2 = e \rangle$, built in the system of generators x, y, z there are substantial grounds for believing in its being a subject to affine transformations on the flat, in particular, relatively to the centre e.

Therefore, the possible rotations (displacements) of the graph are supposed to be multiples of 120º shaping three varieties of the graph G_1, G_2 and G_3 in the way that: $G_2 = f(G_1)$, $G_3 = g(G_2) = g(f(G_1))$. This means that the graphs are obviously congruent with each other $G_1 \cong G_2 \Rightarrow G_2 \cong G_3$.

Imagine a situation when a navigator is involved into performing actions along a pre-planned trajectory of events [21]. Primarily, the navigator miscounts his actions having in mind his own experience. At the same time, on the basis of already acquired skills an individual time frame is formed delivering the possibility to judge if it is the acceptable course of events or unable to be endured one.

Having been obtained in 2 years period data of the navigation tasks and vessel control maneuver carryings out using ECDIS, ARPA and other devices let the database with an accuracy from 1 to 4 seconds track the navigator's actions (Fig. 6).

Figure 6. Database of navigation events

The analysis of the data provided the opportunity to determine the temporal environs for a wide class of actions being carried out during a navigational watch with regard to to each navigator. It is said to have been succeeded by means of the Navi Trainer 5000 navigation simulator. In addition, the developed classification scheme enhances having unacceptable increases or decreases in time frames. Further psychological research has revealed that an increase in time frames can be treated as key indicator of the restructuring of strategy. In contrast to aforementioned one, decrease indicates an increase in functional entropy, loss of control over the situation [18].

Thus, the shaping of mathematical models, software and hardware for identifying the DNT intervals on the physical trajectory of the ship's movement within the framework of the proposed approaches has been highly likely to happen.

Suppose a situation when the navigator has already defined the trajectory of actions in the form of yxyzyx. Then each point-node of the trajectory is sure to be involved into work and interaction with a finite number of devices and objects of perception (i.e. RADAR, ARPA, AIS, ECDIS, GPS and whatever).

As previously indicated, the excess amount of perception objects on the captain's bridge would definitely be leading to a loss of control, uncertainty and, as a consequence, would cause to an excess of time for the navigation task carrying out. Thus, let the trajectory in each of its nodes have the possibility of triggering DNT constituting to be a movable structure on flat (Fig. 7).
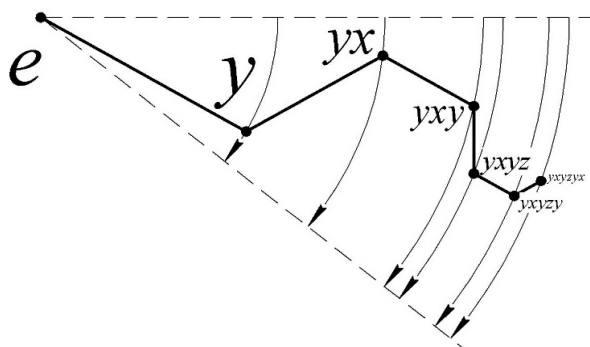
Figure 7. The process of displacement of nod-points

Furthermore, initially the graph is about to correspond to the *xyz* scheme, an offset by an angle $\frac{2\pi}{3}$ would provide the *zxy* scheme, and $\frac{4\pi}{3}$ the *yzx* one. The zero displacement or 2π would be denoted as a_0, respectively $\frac{2\pi}{3}$ as a_1 and $\frac{4\pi}{3}$ as a_2:

$$a_0 \cdot a_0 = a_0, \ a_0 \cdot a_1 = a_1 \cdot a_0 = a_1,$$
$$a_0 \cdot a_2 = a_2 \cdot a_0 = a_2, \ a_1 \cdot a_1 = a_2,$$
$$a_1 \cdot a_2 = a_2 \cdot a_1 = a_0, \ a_2 \cdot a_2 = a_1.$$

For instance, let us example a typical case from the analyzed data, to be exactly shift of a_1 along the trajectory yxyz**y**x with regard to the scheme *xyz*. The transition along the fifth point of the trajectory in the form of: yxyzyx → zyzxzx turns out to be observed. So, according to having been provided trajectory additional time had been spent by the navigator for the aim of having visual analysis of the environment beyond the time frame. In this case the identification of DNT is said to be obvious: yxy**zz**x.

The proposed model for DNT identification lets you process any possible trajectory of the navigator's behavior within the framework of the selected system of generators of the group *G*.

Besides, an opportunity of getting the auto DNT identification is said to be launched. The only question to be paid attention to is availability of experimental database of tasks performed by navigators in more than three years period. Hence, as a result of the analysis, the individual peculiarity of the navigators' graph shift was said to be successfully noted. Conversely, the probabilistic options of the transition from a trajectory node a_i to the node a_j in typical situations [22] were certain to be detected. It must be emphasised that the navigator's connections having been built on the basis of prior experience are sure to contribute to the probability of such a transition ζ_{ij}^l. One more essential element is the consolidation of the input parameters of the situation taking place with probability of positive outcome highly likely to be practically guaranteed. Thus, the navigator at each nodal point with an input probability $\left(\zeta_{ij}^l; 1 - \zeta_{ij}^l \right)$ is sure to carry out whatever is necessary for him to be done: do not change the planned trajectory a_1 or perform a shift within the graph a_2 with the corresponding probabilities $Q_1(t)$ and $Q_2(t)$ at time t.

Positive consequences tend to be forming a row of the matrix of transition probabilities in the form $\left((1-a) + a\zeta_{ij}^l; a(1 - \zeta_{ij}^l) \right)$, negative consequences succeed in having a probability row $\left(a\zeta_{ij}^l; 1 - a\zeta_{ij}^l \right)$, then in this case (1):

$$\overline{\zeta_{11}^0(t+1)} = \zeta_{11}^0(t) - Q_1(t)(1-p_1)(1-a)\left[\zeta_{11}^0(t)(p_1+p_2) - p_2 \right],$$
$$\overline{\zeta_{11}^1(t+1)} = \zeta_{11}^1(t) - Q_1(t)(1-a)p_1\left[\zeta_{11}^1(t)(p_1+p_2) - p_2 \right],$$
$$\overline{\zeta_{22}^0(t+1)} = \zeta_{22}^0(t) - Q_2(t)(1-p_2)(1-a)\left[\zeta_{22}^0(t)(p_1+p_2) - p_1 \right],$$
$$\overline{\zeta_{22}^1(t+1)} = \zeta_{22}^1(t) - Q_2(t)p_2(1-a)\left[\zeta_{22}^1(t)(p_1+p_2) - p_1 \right],$$

for $A(t+1) = \begin{Vmatrix} \overline{\zeta_{11}^0(t+1)} & \overline{\zeta_{11}^1(t+1)} \\ \overline{\zeta_{22}^0(t+1)} & \overline{\zeta_{22}^1(t+1)} \end{Vmatrix}$, (1)

where p_{ij} — is a transition state probability.

It must be underlined that the matrix of navigator transition probabilities is being normalized and refined with each location being passed through while tasks and maneuvers performing. Furthermore, the experimental data provided in the course «The Ship's Captain and the Pilot» [23] clearly illustrate the idea that navigators beyond the age of 45 have already had a formed matrix of transition probabilities for the most amount of typical situations making entanglement possibly influence to introduce changes in their behavior. For example, one of the significant factors influencing the transitions described above can be brought out by Professor V.A. Kasyanov. [24], «subjective entropy» which represents the mental state of the navigator being in a problem situation. Indirectly, the manifestation of subjective entropy can be judged basing on the analysis of the curves of the speed and course of the vessel (Fig. 8). Its symbolizing the scale of navigator's having confidence in the actions performed.

Figure 8. Model for the identification of DNT intervals on the physical trajectory of the vessel movement

Experimental data have highlighted that the navigator is used to control the machine telegraph and the rudder of the vessel confusedly even in straight areas of the Bosphorus. It is noticed to be a clear evidence issued from fluctuations in the curves. Hence, it allows to have the formal perception defined as well as software and hardware for the DNT intervals identification on the physical trajectory of the vessel's movement drawn up.

The research problem being deemed to be the most appropriate for our purposes to be reached is the distribution entropy $\pi(\sigma_i)$ in the Shannon form. Suppose, that at the very beginning of the trajectory the navigator is facing the difficulty of choosing a class from k ones for the aim of the problem being solved that is included in the set $S_a\big|_{\sigma_0}$. There is a finite number of alternatives L_s and, accordingly, the value of the function of their preferences π_{L_s} being in each s-class. So, taking into consideration that $\pi_s = L_s \pi_{L_s}$ the navigator's entropy would be represented in the form:

$$H_\pi^k = -\sum_{s=1}^{k} \pi_s \ln \pi_s + \sum_{s=1}^{k} \pi_s \ln L_s; \left(k \in \overline{1,N}\right). \tag{2}$$

In this case, entropy seems to reach a maximum at: $\pi_s = \dfrac{1}{k}$, $\sum_{i=1}^{N} \pi(\sigma_i) = \sum_{s=1}^{k} \pi_{L_s} L_s = 1 \Rightarrow \sum_{s=1}^{k} \pi_s = 1$.

$$H_\pi^k = \ln k + \ln \sqrt[k]{L_1 L_2 \cdot ... \cdot L_k} \tag{3}$$

Having been delivered formulas successfully demonstrate that experimental connections are sure to occur for only one class of problems causing significant entropy reduction. Thereby this process is involved into defining a model of behavior in the form of the graph displacement. To a certain point, the correlation to be mentioned is less amount of the experiential connections are bigger t_{ij}^Δ and more critical the manifestation of DNT is. Having this issue in mind we are sure to emphasise the growing focus on delivering high-quality trainings to navigators in the educational process course being aware and using modern innovative technologies and methods [25].

For the sake of revealing the principles of individual time codes formation as well as of identifying the trigger conditions for their functioning in critical situations the concept of «subjective time» is said to be considered. As a component of the systemopaterna f, this concept is noticed to possess a fractal structure being able to be directly represented by information and by the energy spent on achieving the certain goal $\underline{e}_f$ or actions $F = \{f/\mu\}_t$ [26, 27]. This item is completely justified in our study. Furthermore, the analysis of experimental data is helpful enough with illustrating that more than 47 % of navigators get used to having the same sequence of actions/operations when performing typical maneuvers (i.e. mooring, diverging from the vessel and whatever) [28, 29]. Although, despite mentioned above, the time intervals between the stages
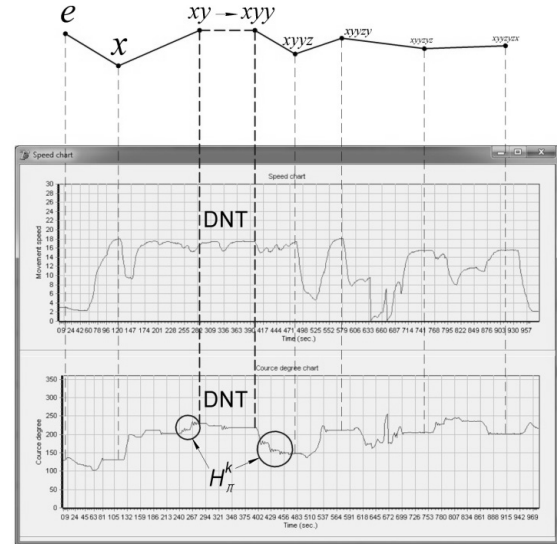
of actions (nodes of trajectories) as well as the total available energy $E(t)$ are expressed in an individual capacity. For example, the energetic concept of carrying out the trajectory of actions of a fractal graph by a navigator with an aim to achieve the intended target is possible to be represented in the following way (4):

$$\forall t \ \sum_{f\in\{f\}} e_f(t) \le E(t), \ \forall f \in \{f\} \int e_f(t)\,\mathrm{d}t \le \underline{e}_f \qquad (4)$$

Experienced connections of the navigator and the individual manner of the carryings out of trajectories of actions are able to be managed by the developed system of stimuli $x(t)$ and reactions $r(t)$. The precise information about them can be expressed statistically and, therefore, their probabilistic nature is to be spoken about in the way that (5):

$$\forall t, \ \forall x(t) \in X, \ \Sigma_r p(r/x)\cdot\log\left[\,p(r/x)/p(r)\,\right] \to \max, \ \Sigma_r p(r/x)\cdot e(x,r) = \Sigma_{f/\mu\in F} e_{f/\mu}(t) \le E(t) \quad (5)$$

Thus, while having planning and anticipation the navigator is engaged into impact assessment of internal factors as well as external ones defining the trajectory to be an implementation mechanism $\mu(\{d/D\})$

regarding the criteria K in the form: $\forall f/\mu \ opt\mu : \{\underline{d}/D\}_f^* = \arg opt_{\{d/D\}} K\left(\mu(\{d/D\})\right).$

Consequently, the Cayley graph for identifying DNT enables to be represented as a set of system patterns (operations) k in the form of points or nodes of the trajectory whereabouts the estimation of the situation J is performed, identification of enough energy e/E for the implementation purposes of the plan is discharged and the formation of the image (sketch) Gs α of the situation is fulfilled. Therewith, the evaluation of the set of associations a/A and situational identifiers c/C for having events achieved can be expressed in the way b/B (6):

$$k = \left\{ f/\mu\{J_c\ c/C\} : \{J_a\ a/A\}, J_e\ e/E \to \{J_b\ b/B\}, \mu\in\{\mu\}_f \right\} \cup P_k, \{Gs(f/\mu)\} \subset k. \qquad (6)$$

Thus, at each point of the graph trajectory a situation seems to appear α and its conditions revaluation $U(\{\underline{c}/C\})$ is turning out to be done having dependable position of subjective entropy of the navigator on satisfaction issues $\alpha\triangledown$. In this case anticipation $\phi^{t/\Lambda}$ is possible to be presented in the form (7):

$$\phi^{t/\Lambda}\left(\{a/A\}\,|\,U(\{\underline{c}/C\})\right) = \cup_{\alpha\in\Omega}\left\{ f/\mu : \underline{t}/\Lambda, \left\{\langle J_\tau\underline{\tau}/T, J_t\,\underline{t}'/\Lambda\rangle\right\} \xrightarrow{\alpha,\,k} \{J_a\underline{a}/A\}_\alpha \,|\, \alpha\triangledown U(\{\underline{c}/C\})\right\}\right). \quad (7)$$

The precedents mentioned above are involved into the shaping of the manifestation of DNT by the critical impulse building Imp_{kr} being a result of revealing inconsistencies between the set of associations $\{J_a\ a/A\}$ of an event α and energy consumption $\underline{e}/E$ due to hard boosting process of information factors which could be represented in the form: $\left\{ Imp_{kr} : \{J_a\ a/A\}, \underline{e}/E \to \{b/B\}\right\}_t, \ \Sigma_{\{Imp\}}\underline{e}/E > E.$

Thereby, the having been introduced of this formal system is catering for setting the mechanism for the formation of individual time codes goals and for establishment of trigger conditions for their operation in critical situations.

Experiments

Within the framework of the provided research an experiment managed to be carried out for the sake of evaluating effectiveness of the proposed means of experimental diagnostics of the DNT when navigating a vessel. It was successfully performed using the navigation simulator Navi Trainer 5000.

In order to ensure assessment of the influence of the human factor in the form of DNT an analysis of the trajectories of the vessel was conducted at the Bosphorus location. Taking mooring operation as a typical one 11 different watches and one type of the vessel to be used the experiment was performed. Besides, while having each experiment samples of readings are reported to have been obtained from the devices.

First of all, let us consider the influence of the autopilot (autopilot) mode on the following samples being built on numerous vessel readings: rpm_port (main rotor speed), distance (distance travelled by the vessel from the very beginning of the training according to the LAS data), surge (longitudinal movement of the vessel, sway (lateral movement of the vessel), pitch (up / down rotation of the vessel around its transverse axis), yaw (change in course in degrees), roll (roll, inclined rotation of the vessel along its longitudinal axis), heave (linear vertical up / down movement). Let's construct diagrams of averages for all parameters bearing in mind the autopilot factor (Fig. 9, 10).
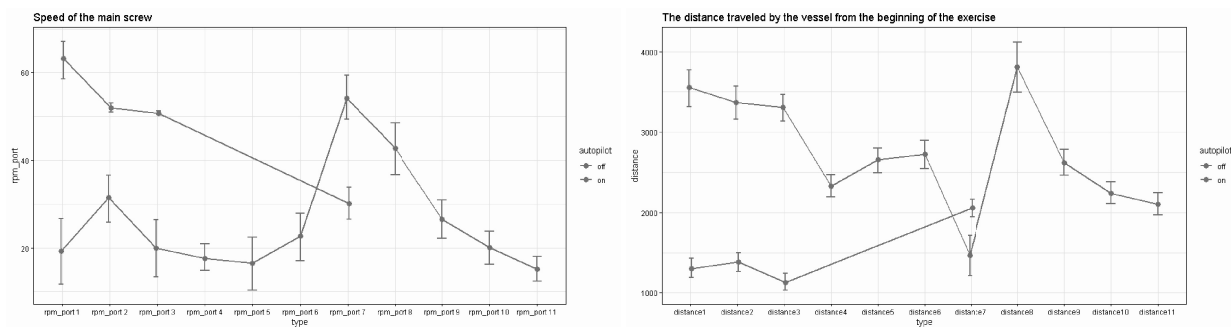
Figure 9. Diagram of confidence intervals for the rpm_port, distance parameter
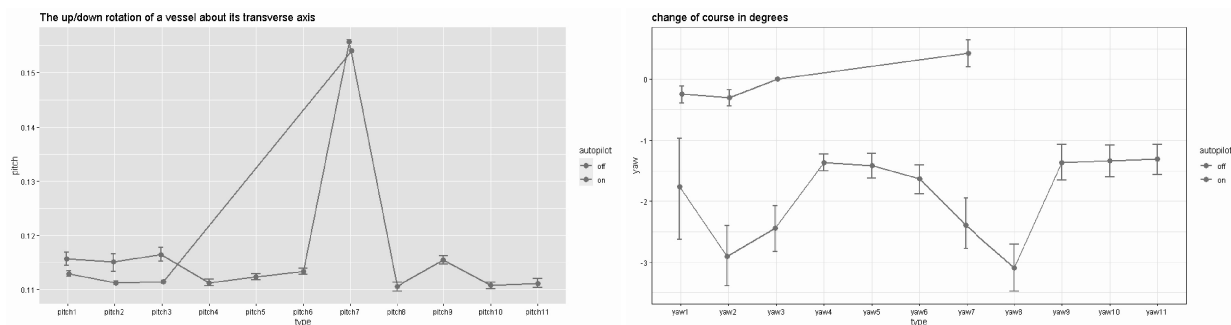
Figure 10. Diagram of confidence intervals for the parameter pitch, yaw
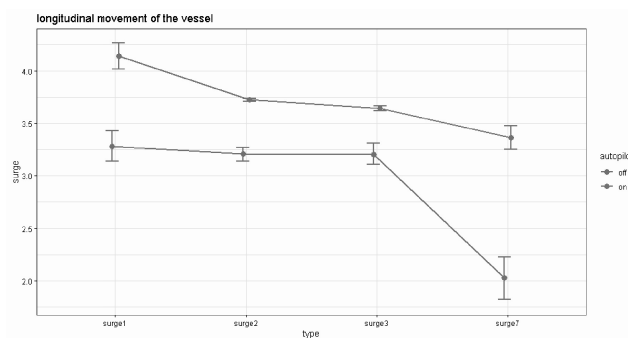
Figure 11. Plot of confidence intervals for the surge parameter for samples 1, 2, 3, 7

As it clearly seen from Figures 9–11 factor "autopilot" is considered to be important only for the first, second and seventh samples. So, for these issues we want separate diagrams to be built. Analysis of other parameters (i.e. surge, sway, roll, heave) are unable to make a difference as well. Necessary to check for homogeneity of variances using "Levene's test for homogeneity of variance across groups", also necessary to omit the check for normality as the sample sizes are noticed to be large enough. Lt's analyze on the surge parameter.

To analyze the experimental data, Levene's Test for Homo-geneity of Variance (center = median) was applied using RStudio.

Since F value = 47.758, $p < 0.05$, we are most likely to reject the null hypothesis of equality of variances. Consequently, in this case, the hypothesis of equality for ANOVA at $p < 0.01$ is to be denied.

Let's build a two-factor model with the interaction of factors based on ANOVA. Before coming to conclusions let's calculate the average table for this model and the summary results.

Since F value = 18.73, $p < 0.01$ the impact of collaboration between the factors is turning out to be statistically significant. Let's have Tukey's 'Honest Significant Difference' method carried out for delivering evidences which pairs are statistically significant difference.

Basing on the results of R-Project program's carrying out a statistically significant difference was noticed to have been found out between 1 and 7, 2 and 7, as well as 3 and 7 samples with the autopilot off. Besides, it occured likewise between 1 and 2, 1 and 3, 1 and 7, 2 and 7 samples when autopilot was on. Hence,

this issue is certain to be observed wherever in Figure 11 and in the table of averages. It must be made out that for the seventh sample averages for the «off» mode of the «autopilot» factor differ noteworthy from averages of all other samples as well as for the first sample averages for the «on» mode of the «autopilot» factor vary from all other samples). Thus, in experiment No. 7, DNT happened to be fixed twice. In addition, the automation process of the shaping of the trajectory of the vessel's route is shown in Figure 12.

Figure 12. Trajectory of movement of the vessel with the identification of DVN

Therefore, the effectiveness assessment of the proposed experimental diagnostics of DNT succeeded in having been delivered providing experimental confirmation when navigating a vessel. The Navi Trainer 5000 navigation simulator contributed into validation process. The developed automated tools enabled to identify at the initial steps the manifestation of DNT as well as to enhance the efficiency of cadets' trainings of the specialty "Sea and river transport. Navigation" while conducting such academic disciplines as: "Navigational Information Systems", "Ship Management" and whatever.

Result and Discussion

The proposed formal and algorithmic approaches as well as the developed automated tools for the sake of getting analysis of experimental data for DNT identification are sure to encourage and help along to bring the goal of reducing detrimental impact of the human factor in ship management field being persistent cause for concern in the contemporary world. Besides, in the course of the study a formal model of shaping and, as a consequence, DNT identification in the form of a model within the framework of the geometric theory of groups are reported to have been dealt with. This issue has turned out to open the door to visual representation of the phenomenon essence and to highlight the affecting factors of distortion level of the subjective time of the navigator. Being highly appreciated to be used in order to avoid this factor manifestation a formal-algorithmic system is reported to have been developed allowing to identify the intervals of the trajectory of the navigator's actions in the form of a fractal structure. The spoken above item concerned the possible ways of description the full set of options for the development of a critical situation in a formal form under the conditions of the entropy approach. Further establishment of the study is reported to be aimed at describing the principle of individual time codes shaping when performing tasks while maintaining a navigational watch.

Furthermore, the carried out experiments when performing the high complexity task — mooring operation in the Bosphorus Strait — enable to identify the fact of DNT manifestation by means of developed automated tools. As a result of the experiment, the effectiveness assessment of the proposed equipment of experimental diagnostics of DNT during ship control management using the navigation simulator Navi Trainer 5000 was contentedly performed. Beyond any doubt, the proposed approaches also are supposed to have been contributing to having process of navigators' training and retraining at much higher quality level during the course training and laboratory-practical course of disciplines "Navigation information systems" and "Ship management".

References

1   Hancock P. On time distortions under stress / P. Hancock, J. Weaver // Theoretical Issues in Ergonomics Science. — 2005. — Vol. 6, No. 2. — P. 193–211. DOI: 10.1080/14639220512331325747.

2   Nosov P.S. Automated identification of an operator anticipation on marine transport / P.S. Nosov, I.S. Popovych, V.V. Cherniavskyi, S.M. Zinchenko, Y.A. Prokopchuk, D.V. Makarchuk // Radio Electronics, Computer Science, Control. — 2020. — Vol. 3. — P. 158–172. DOI: 10.15588/1607–3274–2020-3-15.

3   COLREGS — International regulations for preventing collisions at sea [Electronic resource]. Retrieved from: http://www.jag.navy.mil/distrib/instructions/COLREG-1972.pdf.

4   Scheele F. Cognitive time distortion as a hidden condition of worker productivity / F. Scheele, D. Haftor, N. Pashkevich // Journal of Business Research. — 2019. — P. 591–596. DOI:10.1016/j.jbusres.2018.11.002.

5   Ogden R. Time distortion under threat: Sympathetic arousal predicts time distortion only in the context of negative, highly arousing stimuli / R. Ogden, J. Henderson, F. Mcglone, M. Richter // Plos one. — 2019. — P. 14. DOI: 10.1371/journal.pone.0216704.

6   El-Azhari A. Similar time distortions under the effect of emotion for durations of several minutes and a few seconds / A. El-Azhari, S. Haddar, R. Drago, S. Gil // Acta Psychologica. — 2020. — P. 210. DOI: 10.1016/j.actpsy.2020.103170.

7   Ono F. Individual differences in vulnerability to subjective time distortion / F. Ono, S. Horii, K. Watanabe // Japanese Psychological Research. — 2012. — P. 54. DOI: 10.1111/j.1468–5884.2011.00497.x.

8   Молодцов Д.А. Принципы оптимальности как математическая модель поведения человека / Д.А. Молодцов // Математическое моделирование. — 1991. — № 5. — С. 29–48.

9   Hamanishi N. Time synchronization method by time distortion for VR training including rapidly moving objects / N. Hamanishi, J. Rekimoto // VRST '19: 25th ACM Symposium on Virtual Reality Software and Technology. — 2019. — P. 1–2. DOI: 10.1145/3359996.3364745.

10 Gil S. Emotional time distortions: The fundamental role of arousal / S. Gil // Cognition & emotion. — 2012. — Vol. 847. — P. 62. DOI: 10.1080/02699931.2011.625401.

11 Nosov P. Development of means for experimental identification of navigator attention in ergatic systems of maritime transport / P. Nosov, I. Palamarchuk, S. Zinchenko, I. Popovych, Y. Nahrybelnyi, H. Nosova // Bulletin of the university of Karaganda-Physics. — 2020. — No. 1(97). — P. 58–69. DOI: 10.31489/2020Ph1/58–69.

12 Nosov P.S. Diagnostic system of perception of navigation danger when implementation complicated maneuvers / P.S. Nosov, S.M. Zinchenko, I.S. Popovych, A.P. Ben, Y.A. Nahrybelnyi, V.M. Mateichuk // Electronics, Computer Science, Control. — 2020. — No. 1. — P. 146–161. DOI: 10.15588/1607-3274-2020-1-15.

13 Сорокина И.В. Оценка параметров многомерных возможностных распределений при заданном уровне риска / И.В. Сорокина, С.В. Сорокин // Нечеткие системы и мягкие вычисления. — 2015. — Т. 10, № 2. — P. 181–193.

14 Hong D.H. Parameter estimation of mutually T-related fuzzy variables / D.H. Hong // Fuzzy Sets and System. — 2001. — Vol. 123. — P. 63–71.

15 Zinchenko S. Automatic collision avoidance system with many targets, including maneuvering ones / S. Zinchenko, P. Nosov, V. Mateichuk, P. Mamenko, I. Popovych, O. Grosheva // Bulletin of the university of Karaganda-Physics. — 2019. — No. 4(96). — P. 69–79. DOI: 10.31489/2019Ph4/69–79.

16 Zinchenko S.M. Improving the accuracy and reliability in automatic ship motion control systems / S.M. Zinchenko, A.P. Ben, P.S. Nosov, I.S. Popovych, P.P. Mamenko, V.M. Mateychuk // Radio Electronics, Computer Science, Control. — 2020. — No. 2. — P. 183–195. DOI: 10.15588/1607-3274-2020-2-19

17 Shevchenko R. Research of psychophysiological characteristics of response to stress situations by future sailors / R. Shevchenko, V. Cherniavskyi, S. Zinchenko, M. Palchynska, S. Bondarevich, P. Nosov // Revista Inclusiones. — 2020. — Vol. 7. — P. 566–579.

18 Shevchenko R. Comparative analysis of emotional personality traits of the students of maritime science majors caused by long-time staying at sea / R. Shevchenko, I. Popovych, L. Spytska, P. Nosov, S. Zinchenko, V. Mateichuk, et al. // Revista Inclusiones. — 2020. — Vol. 7. — P. 538–554.

19 Александров П.С. Введение в теорию групп / П.С. Александров. — М.: Наука; Гл. ред. физ.-мат. лит-ры, 1980. — 144 с.

20 Malyutin A. Pretrees and Arborescent Convexities / A. Malyutin // Journal of Mathematical Sciences. — 2016. — Vol. 212. — P. 566–576. DOI: 10.1007/s10958-016-2689-1.

21 Nosov P. Approaches going to determination periods of the human factor of navigators during supernumerary situations / P. Nosov, A. Ben, A. Safonova, I. Palamarchuk // Radio Electronics, Computer Science, Control. — 2019. — Vol. 2, No. 49. — P. 140–150. DOI: 10.15588/1607-3274-2019-2-15.

22 Варшавский В.И. О поведении стохастических автоматов с переменной структурой / В.И. Варшавский, И.П. Воронцова // Автоматика и телемеханика. — 1963. — Т. 24. — С. 353–360.

23 Popovych I.S. Experimental research of effective «The ship's captain and the pilot» interaction formation by means of training technologies / I.S. Popovych, V.V. Cherniavskyi, S.V. Dudchenko, S.M. Zinchenko, P.S. Nosov, O.O. Yevdokimova, et al. // Revista ESPACIOS. — 2020. — Vol. 41, No. 11. — P. 30.

24 Kasianov V. Subjective entropy of preferences. Subjective analysis: monograph / V. Kasianov. — Warsaw, Poland: Institute of aviation, 2013. — 644 p.

25 Popova H. Assessment of professional competencies cognitive component in the maritime specialists training by LMS Moodle / H. Popova // Information Technologies and Learning Tools. — 2019. — Vol. 72, No. 4. — P. 106–120. DOI: 10.33407/itlt.v72i4.2467.

26 Yurzhenko A. The concepts of "Communicative competence" and "gamification of English for special purpose" in scientific discourse / A. Yurzhenko // Eureka: Social and Humanities. — 2018. — Vol. 6. — P. 34–38. DOI: 10.21303/2504-5571.2018.00803.

27 Прокопчук Ю.А. Набросок формальной теории творчества: моногр. / Ю.А. Прокопчук. — Днепр: ГВУЗ «ПГАСА», 2017. — 452 с.

28 Volkov Y. A study of decomposition of a group of ships for preliminary forecasting of dangerous approaching / Y. Volkov // Eastern-European Journal of Enterprise Technologies. — 2019. — Vol. 3. — P. 6–12. DOI: 10.15587/1729–4061.2019.165684.

29 Zinchenko S.M. Automatic collision avoidance with multiple targets, including maneuvering ones / S.M. Zinchenko, P.S. Nosov, V.M. Mateychuk, P.P. Mamenko, O.O. Grosheva // Radio Electronics, Computer Science, Control. — 2019. — No. 4. — P. 211–221. DOI: 10.15588/1607-3274-2019-4-20.

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Модельдік тәжірибеде навигатор уақытының бұрмалануын анықтау

Мақалада кемені басқару кезінде қиын жағдайларда теңіз көлігі навигаторларының уақытты қабылдауына формалды талдау жасалған. Эксперименттік деректердің талдауы және теңіз апаттарының зерттеуі көрсеткендей, көптеген жағдайларда навигаторлар күрделі маневр жасау кезінде, мысалы кемені арқандауда, сыртқы және ішкі факторлардың әсерінен типтік операцияларды орындау уақытын дұрыс қабылдамайды, бұл авариялардың ықтималдығын едәуір арттырады. Зерттеудің негізгі мақсаты сыни жағдайларда теріс адам факторының көрінісі көрсеткіші ретінде навигатор уақытының бұрмалануын (НУБ) анықтаудың ресми және автоматтандырылған құралдары мен әдістерін әзірлеу. Осы мақсатты орындау үшін НУБ қалыптастырудың жалпыланған моделі ұсынылды, кеменің физикалық траекториясын талдау кезінде НУБ-ның аралықтарын анықтауға арналған математикалық модельдер мен автоматтандырылған құралдар, сондай-ақ қиын жағдайларда жеке уақыт кодтарын қалыптастыру жүйесі жасалды. Navi Trainer 5000 сертификатталған навигациялық тренажерын қолдану арқылы эксперименттер жүргізілген, ұсынылған тәсілдердің тиімділігі мен практикалық құндылығын растады, бұл кемені басқару кезінде навигациялық вахтаны атқару қауіпсіздігін едәуір дәрежеде арттыруға мүмкіндік береді.

Кілт сөздер: эксперименттік деректер, навигатор уақытының бұрмалануы, эргатикалық және автоматтандырылған жүйелер.

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Идентификация дисторсии времени навигатора в модельном эксперименте

В статье проведен формальный анализ восприятия времени навигаторами морского транспорта в критических ситуациях при управлении судном. Анализ экспериментальных данных и расследования морских катастроф показал, что в широком ряде случаев навигаторы во время выполнения сложных маневров, на примере швартовки судна, неадекватно воспринимают время выполнения типовых операций в условиях влияния внешних и внутренних факторов, что значительно повышает вероятность возникновения аварий. В качестве основной цели исследования выступает разработка формальных и автоматизированных средств и методов определения дисторсии времени навигатора (ДВН) как показателя проявления негативного человеческого фактора в критических ситуациях. Для выполнения поставленной цели была предложена обобщенная модель формирования ДВН, разработаны математические модели и автоматизированные средства для идентификации интервалов ДВН при анализе физической траектории движения судна, а также система формирования индивидуальных временных кодов в критических ситуациях. Проведенные эксперименты с использованием сертифицированного навигационного тренажера Navi Trainer 5000 подтвердили результативность и практическую ценность предложенных подходов, что в значительной мере позволит повысить безопасность несения навигационной вахты при управлении судном.

Ключевые слова: экспериментальные данные, дисторсия времени навигатора, эргатические и автоматизированные системы.

References

1 Hancock, P. & Weaver, J. (2005). On time distortions under stress. *Theoretical Issues in Ergonomics Science, 6, 2,* 193–211. DOI: 10.1080/14639220512331325747.

2 Nosov, P.S., Popovych, I.S., Cherniavskyi, V.V., Zinchenko, S.M., Prokopchuk, Y.A. & Makarchuk, D.V. (2020). Automated identification of an operator anticipation on marine transport. *Radio Electronics, Computer Science, Control, 3,* 158–172.

3 COLREGS — International regulations for preventing collisions at sea. Retrieved from: http://www.jag.navy.mil/distrib/instructions/COLREG-1972.pdf.

4 Scheele, F., Haftor, D., & Pashkevich, N. (2019). Cognitive time distortion as a hidden condition of worker productivity. *Journal of Business Research,* 591–596. DOI: 10.1016/j.jbusres.2018.11.002.

5 Ogden, R., Henderson, J., Mcglone, F. & Richter, M. (2019). Time distortion under threat: Sympathetic arousal predicts time distortion only in the context of negative, highly arousing stimuli. *PLOS ONE, 14.* DOI: 10.1371/journal.pone.0216704.

6 El-Azhari, A., Haddar, S., Drago, R. & Gil, S. (2020). Similar time distortions under the effect of emotion for durations of several minutes and a few seconds. *Acta Psychologica,* 210. DOI: 10.1016/j.actpsy.2020.103170.

7 Ono, F., Horii, S., & Watanabe, K. (2012). Individual differences in vulnerability to subjective time distortion. *Japanese Psychological Research,* 54. DOI: 10.1111/j.1468–5884.2011.00497.x.

8 Molodtsov, D.A. (1991). Printsipy optimalnosti kak matematicheskaia model povedeniia cheloveka [Optimaly prynciples as personal's mathematical behaviour model]. *Matematicheskoe modelirovanie — Mathematical modeling, 1, 5,* 29–48 [in Russian].

9 Hamanishi, N., & Rekimoto, J. (2019). Time synchronization method by time distortion for VR training including rapidly moving objects. *VRST '19: 25th ACM Symposium on Virtual Reality Software and Technology,* 1–2. DOI: 10.1145/3359996.3364745.

10 Gil, S. (2012). Emotional time distortions: The fundamental role of arousal. *Cognition & emotion. 26,* 47–62. DOI: 10.1080/02699931.2011.625401.

11 Nosov, P., Palamarchuk, I., Zinchenko, S., Popovych, I., Nahrybelnyi, Y., & Nosova, H. (2020). Development of means for experimental identification of navigator attention in ergatic systems of maritime transport. *Bulletin of the University of Karaganda-Physics, 1(97),* 58–69. DOI: 10.31489/2020Ph1/58–69.

12 Nosov, P.S., Zinchenko, S.M., Popovych, I.S., Ben, A.P., Nahrybelnyi, Y.A., & Mateichuk, V.M. (2020). Diagnostic system of perception of navigation danger when implementation complicated maneuvers. *Radio Electronics, Computer Science, Control, 1,* 146–161. DOI: 10.15588/1607–3274–2020–1-15.

13 Sorokina, I.V., & Sorokin, S.V. (2015). Otsenka parametrov mnohomernykh vozmozhnostnykh raspredelenii pri zadannom urovne riska [Estimation of the parameters of multivariate possibility distributions for a given risk level]. *Nechetkie sistemy i miahkie vychisleniia — Fuzzy systems and soft computing, 10, 2,* 181–193 [in Russian].

14 Hong, D.H. (2001). Parameter estimation of mutually T-related fuzzy variables. *Fuzzy Sets and System, 123,* 63–71.

15 Zinchenko, S., Nosov, P., Mateichuk, V., Mamenko, P., Popovych, I., & Grosheva, O. (2019). Automatic collision avoidance system with many targets, including maneuvering ones. *Bulletin of the University of Karaganda-Physics, 4(96),* 69–79. DOI: 10.31489/2019Ph4/69–79.

16 Zinchenko, S.M., Ben, A.P., Nosov, P.S., Popovych, I.S., Mamenko, P.P., & Mateychuk, V.M. (2020). Improving Accuracy and Reliability in Automatic Ship Motion Control Systems. *Radio Electronics, Computer Science, Control, 2,* 183–195.

17 Shevchenko, R., Cherniavskyi, V., Zinchenko, S., Palchynska, M., Bondarevich, S., Nosov, P. et al. (2020). Research of psychophysiological characteristics of response to stress situations by future sailors. *Revista Inclusiones. 7,* 566–579.

18 Shevchenko, R., Popovych, I., Spytska, L., Nosov, P., Zinchenko, S., Mateichuk, V. et al. (2020). Comparative analysis of emotional personality traits of the students of maritime science majors caused by long-time staying at sea. *Revista Inclusiones, 7,* 538–554.

19 Aleksandrov, P.S. (1980). *Vvedenie v teoriiu hrupp [Introduction to group theory]*. Moscow: Nauka; Hlavnaia redaktsiia fiziko-matematicheskoi literatury [in Russian].

20 Malyutin, A. (2016). Pretrees and Arborescent Convexities. *Journal of Mathematical Sciences, 212,* 566–576. DOI: 10.1007/s10958–016–2689–1.

21 Nosov, P., Ben, A., Safonova, A., & Palamarchuk, I. (2019). Approaches going to determination periods of the human factor of navigators during supernumerary situations. *Radio Electronics, Computer Science, Control, 2, 49,* 140–150. DOI: 10.15588/1607–3274–2019-2-15.

22 Varshavsky, V.I., & Vorontsova, I.P. (1963). O povedenii stokhasticheskikh avtomatov s peremennoi strukturoi [On the behavior of stochastic automata with variable structure]. *Avtomatika i telemekhanika — Automation and telemechanics, 24, 3,* 353–360 [in Russian].

23 Popovych, I.S., Cherniavskyi, V.V., Dudchenko, S.V., Zinchenko, S.M., Nosov, P.S., & Yevdokimova, O.O., et al. (2020). Experimental research of effective «The ship's captain and the pilot» interaction formation by means of training technologies. *Revista ESPACIOS, 41, 11,* 30.

24 Kasianov, V. (2013). *Subjective entropy of preferences. Subjective analysis.* Warsaw, Poland: Institute of aviation.

25 Popova, H. (2019). Assessment of professional competencies cognitive component in the maritime specialists training by LMS Moodle. *Information Technologies and Learning Tools, 72, 4,* 106–120. DOI: 10.33407/itlt.v72i4.2467.

26 Yurzhenko, A. (2018). The concepts of "Communicative competence" and "gamification of English for special purpose" in scientific discourse. *Eureka: Social and Humanities, 6,* 34–38. DOI: 10.21303/2504–5571.2018.00803.

27 Prokopchuk, Yu.A. (2017). *Nabrosok formalnoi teorii tvorchestva [Sketch of the Formal Theory of Creativity]*. Dnepr: PSACEA Press, 452 [in Russian].

28 Volkov, Y. (2019). A study of decomposition of a group of ships for preliminary forecasting of dangerous approaching. *Eastern-European Journal of Enterprise Technologies, 3,* 6–12. DOI: 10.15587/1729–4061.2019.165684.

29 Zinchenko, S.M., Nosov P.S., Mateychuk, V.M., Mamenko, P.P., & Grosheva, O.O. (2019). Automatic collision avoidance with multiple targets, including maneuvering ones. *Radio Electronics, Computer Science, Control, 4,* 211–221. DOI: 10.15588/1607–3274–2019-4-20.

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Investigation of the effect of electro-hydraulic pulses on the combustion process of phosphorus sludge
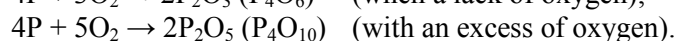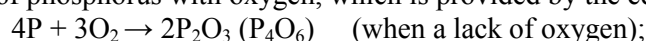
The article considers the influence of electro-hydraulic pulses on the combustion of phosphorus sludge. Electric discharges in the environment of phosphorus sludge are sources of shock waves, which destroying the structure of phosphorus sludge and contribute to the intensification of the combustion process. A distinctive feature of the electro-hydraulic effect is the ability to control the parameters of pressure waves over a fairly wide range using the characteristics of the electric discharge circuit. For determine the optimal productivity and purity of the final product of the electric discharge unit's operation mode, experiments were conducted on the effect of the discharge energy on the efficiency of the electric discharge method for extracting phosphorus from phosphorus sludge. The efficiency of the electric discharge process was estimated by the amount of phosphorus that was released after settling and expressed as a percentage of the total amount of phosphorus in a phosphorus sludge's portion. The experiments were conducted out for sludges of different structures, with different phosphorus content and were conditionally divided into three groups: "rich" with phosphorus content — 70 %, "medium" — 50 % and "poor" — phosphorus content — 30 %.

Keywords: electro-hydraulic pulses, combustion, phosphorus, phosphorus sludge, electro-hydraulic effect, electric discharge, charging voltage, interelectrode gap, capacitor banks.

Introduction

Sludge containing elemental phosphorus should not be disposed of not only for economic reasons, but also for environmental reasons. As a result, at factories producing phosphorus, there is an acute question of developing effective methods and means for processing sludge in order to eliminate the loss of a valuable product. The most perspective method is to burning them in furnaces with a special design, thus obtaining slime phosphoric acid in one stage of processing, which quality depends on the structure of burned phosphoric sludge.

The combustion reaction is a chemical reaction in which atoms from molecules of substances (fuel) are combined with an oxidizer (usually air oxygen) toformcombustion products. An example of a combustion reaction is the interaction of phosphorus with oxygen, which is provided by the equation:

$$4P + 3O_2 \rightarrow 2P_2O_3 \ (P_4O_6) \quad \text{(when a lack of oxygen)};$$
$$4P + 5O_2 \rightarrow 2P_2O_5 \ (P_4O_{10}) \quad \text{(with an excess of oxygen)}.$$

Here are the stoichiometric coefficients 4, 3, 2, 5 that denote the number of moles oxygen and phosphorus that participate in the combustion reaction of one mole of propane. Similar equations are used to describe molecular transformations, which are elementary stages (reactions) of a chemical process [1].

Elementary reactions correspond to real molecular events.

Phosphorus, which is a part of combustible substances of organic and mineral origin, oxidizes during combustion and forms phosphoric anhydride (P_2O_5). Phosphorus anhydride P_2O_5 (tetraphosphordecaoxide) is produced from the combustion of phosphorus under conditions of free access of air.

Experimental

The combustion process of phosphorus and phosphoric sludge is considered in a number of works [2, 3]. However, in these works, the electrophysical aspects of the combustion process of phosphorus and phosphorus sludge were not affected, and not in all works examined the effect of the concentration of impurities on the intensity of the combustion process.

Combustion is usually understood as a rapid physical and chemical redox process with the release of a large amount of heat, which is capable of self-propagation and often accompanied by a glow and the formation of a flame. A specific feature of combustion is the presence of electrophysical phenomena observed during the occurrence and development of the flame, associated with the appearance of a spatial distribution of charges in the flame. The consequence of this distribution is the existence of its own electric field, which is absent in ordinary plasma.

The effect of an earlier appearance of charged particles in comparison with a significant increase in temperature caused by non-equilibrium chemical reactions occurring during the period of self-ignition was found in the works. This effect was detected by using the probe method. The essence of this method is that a metal probe is introduced into the investigated point of the flame and the current-voltage characteristic is taken [4].

Results and Discussion

To study the thermophysical and electrophysical aspects of combustion, phosphorus sludge in the form of tablets with a diameter of 5 mm was placed in a cylindrical quartz glass reactor. For the manufacture of phosphorus sludge samples, were used several types of initial products. The first is pure phosphorus, the second is a sludge with a high phosphorus content (about 80 %), which is an emulsion of water in phosphorus, the third sludge with an average phosphorus content (about 50 %), which is an emulsification suspension of phosphorus in water, and the fourth sludge with a low phosphorus content (approx. 30 %) which is also an emulsification suspension of phosphorus in water. The temperature was measured through a chromel-copel thermocouple. The measurement procedure was consisted of heating and self-igniting sample in the reactor, recording the temperature and emerging electric potential.

Figure 1 shows the characteristic signals from the thermocouple and probe received by combustion the sludge tablet. The following main stages of burning are clearly visible on the graph: combustion; 1 — drop heating, water evaporation; 2 — pre-ignition stage; 3 — separation of volatile components of the mineral part of the sludge, as well as particles of the armor shell of phosphorus drops (in the sludge); 4 — the stage of stable combustion.
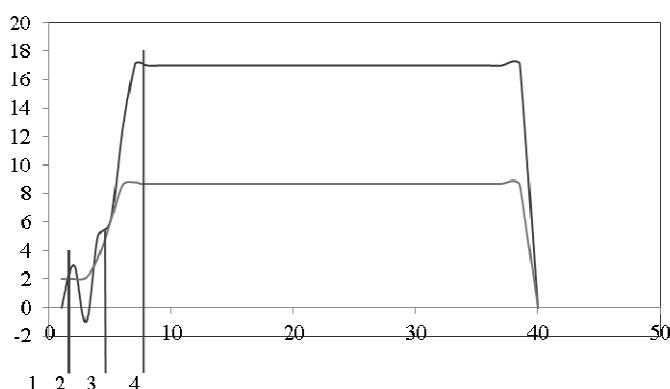
Figure 1. Characteristic signals from the thermocouple and probe

In the process of heating and combustion tablets of phosphorus sludge in the reactor volume is observed the so-called intra-furnace crushing of phosphorus droplets. This phenomenon was named microexplosion. The microexplosion is explained by the difference in the boiling points of water ($t_w = 100$ ºC) located inside the samples and phosphorus ($t_{ph} = 280$ C). The intra-furnace crushing of drops of phosphorus sludge emul-

sion not only increases the combustion surface, but also improves the mixture formation of phosphorus vapors with air. This in turn reduces the combustion time.

The effect of an earlier appearance of charged particles in comparison with a significant increase in temperature was detected, due to nonequilibrium chemical reactions occurring during the self-ignition period (stage 2 in Figure 1). This effect is expressed by recording the peak of the signal from the probe in the pre-ignition stage, which makes it possible to accurately record the moment of the beginning of the phosphorus combustion process in phosphorus sludge, and therefore, with a sufficient degree of accuracy, measure the combustion time of a certain sample of the burnt substance

The combustion of dispersed fuel systems (suspensions and emulsions) sprayed in a gaseous oxidizer stream in terms of basic characteristics significantly differs from the combustion of natural fuels (solid or liquid). Dispersed fuel systems based on widely used natural fuels are essentially new energy fuels, which in some cases are characterized by higher combustion rates than the initial. In the process of combustion a drop of phosphorus sludge when sprayed with nozzles during the evaporation of water and the emission of volatile (phosphorus vapors) in the droplet of the emulsion or emulsification, the intra-volume surface strongly develops. As a result, there is intra-porous oxidation of the sludge with explosive evolution and combustion of phosphorus vapor. The internal volume of the reaction surface is determined by the degree of dispersion of phosphorus particles in the emulsification suspension, as well as by the presence of an "armor" shell of phosphorus droplets [5].

Electric discharges in the environment of phosphorus sludge are sources of shock waves, which destroying the structure of phosphorus sludge and contribute to the intensification of the combustion process. During the passage of shock waves and compression waves, happens the destroying of the shell of the phosphorus droplets, the particles of the solid stabilizer break off from the phosphorus-water interface, but along with this, since phosphorus droplets are relatively easily deformable, due to the high pressure at the front of the shock wave, a dispersion process of phosphorus particles is possible. A distinctive feature of the electro-hydraulic effect is the ability to control the parameters of pressure waves over a fairly wide range (hydrodynamic characteristics of the discharge) using the characteristics of the electric discharge circuit (such as capacitance of capacitor banks, discharge voltage). In turn, the parameters of the shock wave, which is the main tool for influencing the structure of phosphorus sludge, make it possible to control the dispersion of phosphorus particles, thereby affecting the combustion process of atomized drops of phosphorus sludge [6].

Electro-hydraulic pulses, by destroying the structure of phosphorus sludge, contribute to the formation of "centers" with a higher content of phosphorus, free from the shell of mineral and organic impurities. The formation of "centers" with a high concentration of phosphorus can be effectively used in the burning of sludge to obtain thermal phosphoric acid. The aforementioned "centers" in this case can play the role of combustion centers. The intensification of combustion also contributes to the dispersion of phosphorus particles in the phosphorus sludge.

Next, experiments were carried out to measure the combustion time of samples of phosphorus sludge with different phosphorus contents: "rich" — 70 %, "medium" — 50 %, "poor" — 30 % phosphorus after processing electric discharges of various capacities. The discharge energy was regulated by the value of the initial voltage U_0, the capacitance of capacitor banks C, and the value of the working interelectrode gap l_{dg}.
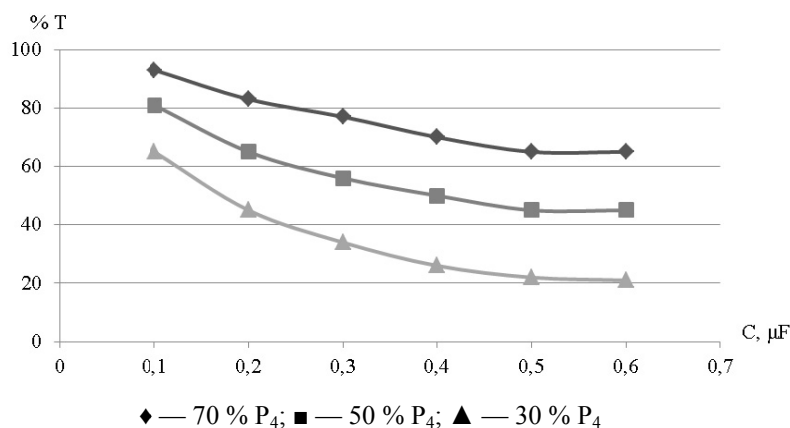

Figure 2. Dependence of the phosphorus combustion time on the capacity of the discharge circuit capacitor banks

Figure 2 shows the results of measurements of the combustion time of sludge tablets with different contents of P_4 depending on the capacitance of capacitor banks C. The initial voltage U_0 was 30 kV, and the interelectrode gap was l_{dg} = 12 mm.

Next, Figure 3 shows the dependence of the combustion time on the initial voltage U_0 of the generator at the capacitance of the capacitors C = 0.25 μF, the interelectrode distance l_{dg} = 12 mm.
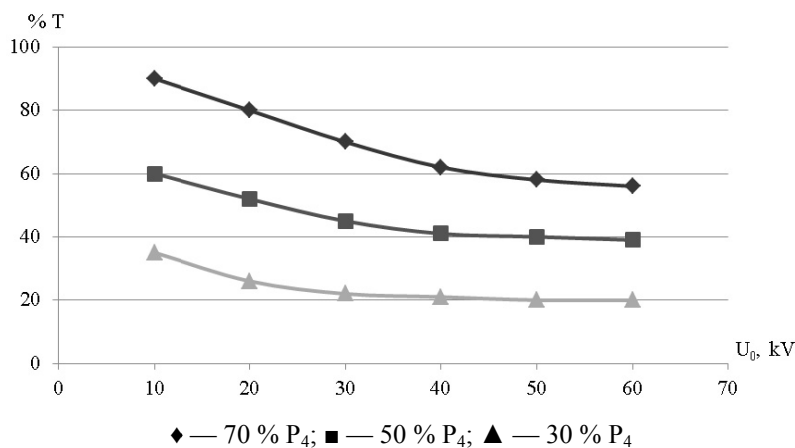

Figure 3. Dependence of the combustion time on the initial voltage of the generator

The third series of experiments on measuring the combustion time was carried out at the initial voltage U_0 = 30 kV, the capacity C = 0.25 μF, the interelectrode distance l_{dg} varied from 5 mm to 30 mm. The results are shown in Figure 4.
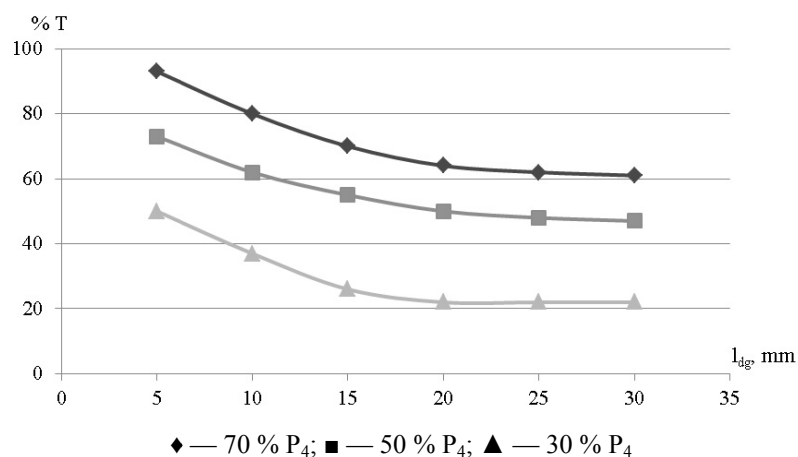

Figure 4. Dependence of the combustion time on the value of the interelectrode gap

In order to determine the optimal productivity and purity of the final product of the electric discharge unit's operation mode (to intensify the mass transfer of phosphorus), experiments were conducted on the effect of the discharge energy on the efficiency of the electric discharge method for extracting phosphorus from phosphorus sludge. The efficiency of the ED process was estimated by the amount of phosphorus that was released after settling and expressed as a percentage of the total amount of phosphorus in a phosphorus sludge's portion, previously determined by the results of iodometric chemical analysis.

The experiments were conducted out for sludgesof different structures, with different phosphorus content and were conditionally divided into 3 groups: "rich" with phosphorus content — 70 %, "medium" — 50 % and "poor" — phosphorus content — 30 %.

In Figure 5 shows the experimental results of the study of the ED treatment efficiency for various sludges depending on the capacity of capacitor banks.
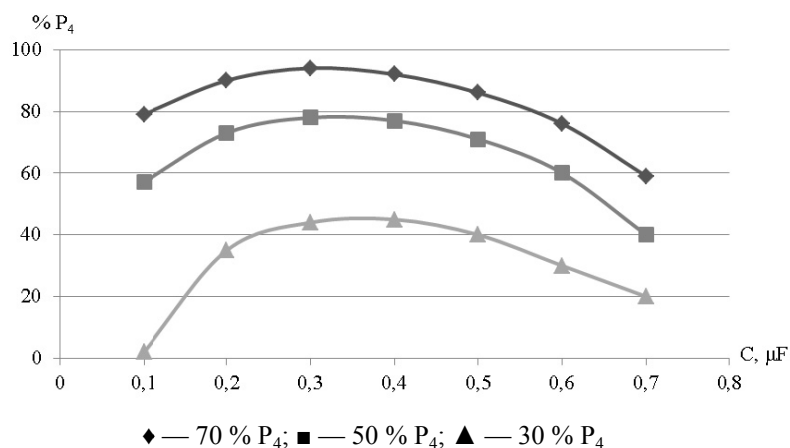
Figure 5. Dependence of the degree of phosphorus extraction on the capacity of capacitor banks

With a constant charging voltage of the ED pulse generator of 30 kV and the value of the interelectrode gap of 10 mm, the capacity varied within $C = 0.1$–0.5 µF. The dependence is extreme and the maximum value of the amount of phosphorus released is observed when the capacity of the capacitor bank is 0.25 µF. ♦ — 70 % P_4; ■ — 50 % P_4; ▲ — 30 % P_4.

Further, Figure 6 shows the results of similar experiments for the case of variation of the initial voltage U_0 in the range of 10–50 kV, while the capacity $C = 0.3$ µF, the value of the interelectrode distance l_{dg} is 10 mm. The maximum effect is observed at $U_0 = 30$ kV.
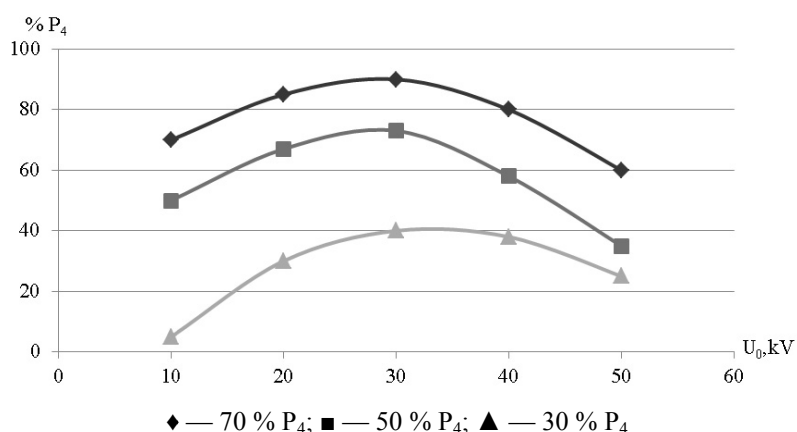

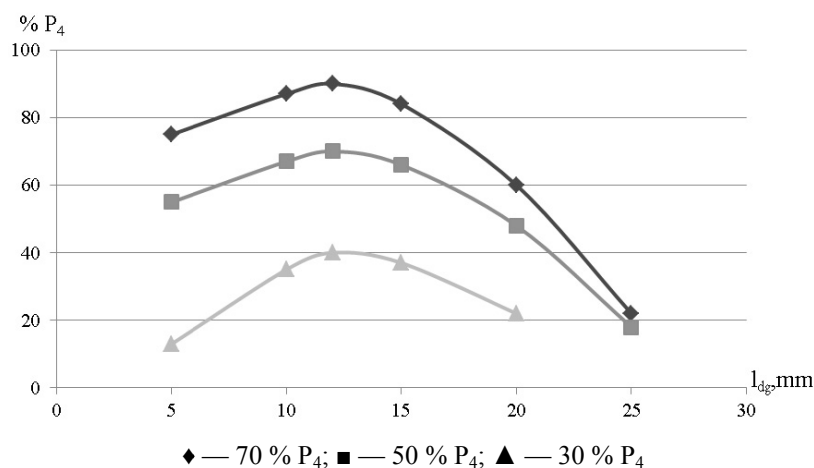Figure 6. Dependence of the degree of phosphorus extraction on the charging voltage

Figure 7. Dependence of the degree of phosphorus extraction on the value of the interelectrode distance

The third series of experiments was conducted with the following parameters of the discharge circuit $U_0 = 30$ kV, $C = 0.25$ µF. The value of the interelectrode gap varied within the range of $l_{dg} = 5$–25 mm. The results are shown in Figure 7 the maximum efficiency of the process was observed at $l_{dg} = 12$ mm.

Conclusions

We note that according to the results of laboratory experiments, the intensification of burning of phosphoric sludge is observed at the following parameters of an electric discharge installation — the initial voltage $U_0 = 35$ kV, the capacitance of capacitors $C = 0,4$ µF, the interelectrode distance $l_{dg} = 12$ mm. These results were used further in determining the parameters of the discharge circuit of a pilot plant for processing phosphoric sludge into phosphoric acid.

Based on the results of laboratory technological experiments, we can make the following conclusion. The maximum effect of using electric discharges to extract phosphorus from phosphorous sludge is observed at the following parameters of the discharge circuit of the high-voltage pulse generator: $U_0 = 30$ kV, $C = 0.3$ µF, $l_{dg} = 12$ mm.

The presence of maxima on the above dependencies is explained by the fact that when the pulse energy determined by the charging voltage, the capacitance of the capacitors, and the value of the interelectrode gap is less than the threshold, the extraction effect is not observed, since the pulse energy insufficient to destroy the structure of the emulsion. In addition, at a very high pulse energy, the effect of dispersion of phosphorus particles in the emulsion is observed and it becomes sedimentally and aggregatively stable.

References

1 Вильямс Ф.А. Теория горения / Ф.А. Вильямс. — М.: Наука, 2001. — 615 с.

2 Исламов М.Ш. Печи химической промышленности. — 2-е изд. / М.Ш. Исламов. — М.: Химия, 1975. — 432 с.

3 Бернадинер М.Н. Огневая переработка и обезвреживание промышленных отходов / М.Н. Бернадинер, А.П. Шурыгин. — М.: Химия, 1990. — 304 с.

4 Миронов В.Л. Основы сканирующей зондовой микроскопии: учеб. пос. для студ. ст. курсов высш. учеб. завед. — Нижний Новгород: РАН; Ин-т физики микроструктур, 2004. — 110 с.

5 Андронов В.И. Термическая фосфорная кислота, соли и удобрения на ее основе / В.И. Андронов, А.А. Бродский, Ю.А. Забелешинский. — М.: Химия, 1976. — 205 с.

6 Дормешкин О.Б. Исследование процесса гидравлической классификации фосфорного шлама с целью извлечения фосфора для производства глифосата / О.Б. Дормешкин, Г.С. Кенжибаева, С.С. Шалатаев, К.Т. Жантасов, Ш.К. Шапалов, Д.М. Жантасова // Изв. НАН РК. Сер. хим. и технол. — 2017. — № 6(426). — С. 97–102.

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Электрогидравликалық импульстардың фосфор шламының жану процесіне әсерін зерттеу

Мақалада электрогидравликалық импульстардың фосфор шламының жану процесіне әсері қарастырылған. Фосфорлық шламды ортадағы электрлік разрядтар фосфор шламының құрылымын бұзатын және жану процесінің күшеюіне ықпал ететін соққы толқындарының көзі. Электрогидравликалық әсердің ерекшелігі электрлік разряд тізбегінің сипаттамаларын қолдана отырып, қысым толқындарының параметрлерін жеткілікті кең ауқымда реттеу мүмкіндігі. Соңғы өнімнің өнімділігі мен тазалығы бойынша оңтайлы электроразрядты қондырғының жұмыс режимін анықтау үшін разряд энергиясының фосфор шламынан фосфорды алудың электроразрядты әдісінің тиімділігіне әсері бойынша тәжірибелер жүргізілді. Электроразряд процесінің тиімділігі тұндырудан кейін бөлінген фосфор мөлшерімен бағаланды және фосфор шламының құрамындағы фосфордың жалпы мөлшерінің пайызымен көрсетілді. Тәжірибелер әр түрлі құрылымдағы, құрамында фосфор мөлшері әр түрлі және шартты түрде үш топқа бөлінген үлгілер үшін жүргізілді: бар құрамында фосфор «мол» —70 %, «орташа» — 50 % және құрамында фосфор «аз» —30 %.

Кілт сөздер: электрогидравликалық импульстар, жану, фосфор, фосфор шламы, электрогидравликалық әсер, электр разряды, зарядтау кернеуі, лектрод аралық қашықтық, конденсаторлық батареялар.

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Исследование влияния электрогидравлических импульсов на процесс горения фосфорного шлама

В статье рассмотрено влияние электрогидравлических импульсов на процесс горения фосфорного шлама. Электрические разряды в среде фосфорного шлама являются источниками ударных волн, которые разрушают структуру фосфорного шлама и способствуют интенсификации процесса горения. Отличительной особенностью электрогидравлического эффекта является возможность с помощью характеристик электроразрядного контура регулировать параметры волн давления в довольно широких пределах. Для определения оптимального по производительности и чистоте конечного продукта режима работы электроразрядной установки были проведены опыты по влиянию энергии разряда на эффективность электроразрядного способа извлечения фосфора из фосфорного шлама. Эффективность электроразрядного процесса оценивалась количеством выделившегося фосфора после отстаивания и выражалась в процентах от общего количества фосфора в навеске фосфорного шлама. Опыты проводились для шламов различной структуры, с различным содержанием фосфора и условно разделенной на три группы: «богатый» с содержанием фосфора — 70 %, «средний» — 50 и «бедный» — содержание фосфора — 30 %.

Ключевые слова: электрогидравлические импульсы, горение, фосфор, фосфорный шлам, электрогидравлический эффект, электрический разряд, зарядное напряжение, межэлектродный зазор, конденсаторные батареи.

References

1   Williams, F.A. (2001). *Teoriia horeniia [Theory of combustion]*. Moscow: Nauka [in Russian].

2   Islamov, M. Sh. (1975). *Pechi khimicheskoi promyshlennosti [Furnaces of chemical industry]*. (2nd ed.). Moscow: Khimiia [in Russian].

3   Bernadiner, M.N., & Shurygin, M.N. (1990). *Ohnevaia pererabotka i obezvrezhivanie promyshlennykh otkhodov [Fire processing and neutralization of industrial waste]*. Moscow: Khimiia [in Russian].

4   Mironov, V.L. (2004). *Osnovy skaniruiushchei zondovoi mikroskopii [Fundamentals of scanning probe microscopy]*. Nizhny Novgorod: RAS; Institute of microstructure physics [in Russian].

5   Andronov, V.I., Brodsky, A.A., & Zabeleshinsky, Yu.A. (1976). *Termicheskaia fosfornaia kislota, soli i udobreniia na ee osnove [Thermal phosphoric acid, salts and fertilizers based on it]*. Moscow: Khimiia [in Russian].

6   Dormeshkin, O.B., Kenzhibayeva, G.S., Shalataev, S.S., Zhantasov, K.T., Shapalov, Sh.K., & Zhantasova, D.M. (2017). Issledovanie protsessa hidravlicheskoi klassifikatsii fosfornoho shlama s tseliu izvlecheniia fosfora dlia proizvodstva hlifosata [Investigation of the process of hydraulic classification of phosphorus slime to obtain the phosphorus for the production of glyphosates]. *Izvestiia Natsionalnoi akademii nauk Respubliki Kazakhstan. Seriia khimii i tekhnolohii — News of the National academy of sciences of the Republic of Kazakhstan. Series chemistry and technology, 6(426)*, 97–102 [in Russian].

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Model of forming a spatial-temporary radio frequency portrait of subscriber terminals in satellite communication systems monitoring

Currently, the development of satellite communications systems (SCS) is associated with the development of signals of complex structure. The popularization and distribution of software-defined radio systems (Software-defined radio, SDR) are noted, which leads to a decrease of quality of functioning of the SCS. Promising areas of countering the unauthorized use of the time-frequency resource of the KA repeater are methods aimed at determining the location of subscriber terminals (ST) and analyzing the service and semantic parts of the transmitted message. Accounting for changes of physical parameters requires the use of a large amount of heterogeneous a priori data; it is not achievable task in practice. According to the theory of mathematical statistics, the approximation is used at solving problems of sample analysis. The result of the approximation is a spatio-temporal radio-frequency portrait (STRFP) of an ST participating in the formation of a group signal. Thus, the aim of the research is to develop a model of changing the physical parameters of a radio signal and to study the possibility of approximating physical parameters in order to form a spatio-temporal radio-frequency portrait of an ST SCS.

Keywords: satellite communication system, group signal, non-energy parameter, communication channel, time division multiple access, satellite repeater, radio frequency portrait, sample.

Introduction

One of the directions in the development of satellite communications systems (SCS) is the use of signals with a complex structure that allow for the efficient use of the frequency-time resource. In particular, in SCS for various purposes (commercial and military), time division multiple access (TDMA) technologies are widely used [1]. It should be noted that the rapid development of SCS leads to an increase in the number of cases of unauthorized use of the time-frequency resource of the spacecraft-relay (SC-relay), which in turn leads to a decrease in the quality of functioning of the SCS.

In this situation, the forefront is the issue of ensuring hardware accessibility to the signals of individual subscriber terminals (ST), which is achieved by decomposition of a group signal.

A method for analyzing signals with a complex frequency-time structure (CFTS) is described, which allows the separation of STs without access to the semantic component of transmitted messages [2]. This method is based on the localization of the values of non-energy parameters of the signal of an individual ST in the parameter space.

The radio exchange in the SCS, operating through spacecraft — repeaters (SC–R) in the geostationary orbit (GSO), is characterized by a dynamic change in the physical parameters of the radio signals, due to a number of reasons in practice [3–7]. Moreover, the application of the known method [2] is not possible.

Accounting for changes in physical parameters requires the use of a large amount of diverse a priori data, such as the coordinates of the Astronomical radio source and SC–R; state of the ionosphere and troposphere; temperature of atmospheric layers, water content over the entire length of the radio path, etc. [8–9], which is not a solvable task in practice.

When solving problems of sample analysis, the approximation method is used in the theory of mathematical statistics; it is a description of the experimental points by some deterministic function. The studied complex object is replaced by a simpler object in order to study its properties.

The experimental estimates of the physical parameters of the radio signal with the frequency response are approximated by some deterministic function at the final stage of observation in relation to the described problem. The result of the approximation is a spatio-temporal radio-frequency portrait (STRFP) of an ST participating in the formation of a group signal. The STRFP is directly dependent on the transmission conditions and is unique, which allows for signal decomposition based on the analysis of the STRFP.

Thus, the aim of the article is to develop a model for changing the physical parameters of a radio signal and to study the possibility of approximating physical parameters in order to form an STRFP ST SCS.

Experimental

During the propagation of radio signals through the physical communication channel, they change under the influence of various factors, including the state of the ionosphere, ion concentration over the entire length of the radio path, troposphere, water content on the propagation path, and the length of the radio path, which changes due to the motion of the spacecraft — P and subscriber terminals, etc. Moreover, the value of each physical parameter depends to a certain extent on the distance between the SC–R and the ST, the state of the atmosphere and ionosphere, which continuously changes over time. The value of the kth physical parameter of the radio signal from the ST at a certain point in time is determined by the Equation (1):

$$v_k(t) = v_k(t_0) + v_k^{(R)}(t) + v_k^{(At)}(t) + v_k^{(Ion)}(t), \qquad (1)$$

where $v_k(t_0)$ is the base value of the parameter at time, t_0; $v_k^{(R)}(t)$ is change in the parameter due to a change in the distance between SC–R – ST — radio monitoring receiving station; $v_k^{(At)}(t)$ is change in parameter due to the influence of the atmosphere; $v_k^{(Ion)}(t)$ is change in the parameter due to the influence of the ionosphere.

Subscriber terminals operating in the same SCS can be located at geographically distant positions and, accordingly, communication channels from ST to SC–R, depending on their condition, will affect radio signals differently.

Figure 1 shows a simulation scheme for radio monitoring of ST SCS for the following conditions:
 − the period of functioning of the ST corresponded to 24 hours;
 − the SC repeater moved in the area at 62° E, according to the TLE obtained from open access for the SC–R «UFO–10»;
 − ST1 stationary object with coordinates 45.031° N and 41.6917° E;
 − ST2 is a mobile object that performs rectilinear movement with initial coordinates of 35.934° N and 101.614° E at a speed of 40 km/h towards the sub-satellite point;
 − ST3 is a mobile object that performs rectilinear movement with initial coordinates of –45.13° S and 95.66° E at a speed of 40 km / h towards the sub-satellite point;
 − ST4 is a mobile object that performs rectilinear movement with initial coordinates of –45.45° S and 41.318° E at a speed of 40 km/h away from the subsurface point;
 − the daily change in the total electronic content of the ionosphere on radio paths was obtained on the basis of data from the international reference model of the ionosphere [10].

The Doppler shift of the carrier frequency and the time delay with respect to the time-synchronous grid consider such as the main non-energy parameters.

In general the slant range between the ST and SC-R and the effect of the ionosphere on the propagation path of the radio signal are the main heterogeneous factors are influenced on the amount of time delay of the signals of various ATs relative to the reference time grid. The change of the time shift of the signals of individual antibodies relative to the time grid is caused by a change in these factors.

A change of the carrier frequency of the antibodies observed at the input of the receiver of the radio monitoring complex occurs due to the Doppler Effect, which, on the one hand, is caused by the movement of the SC-R on the GSO, and, on the other hand, by the movement of the mobile STs themselves, which carry out the movement during the radio communication session.
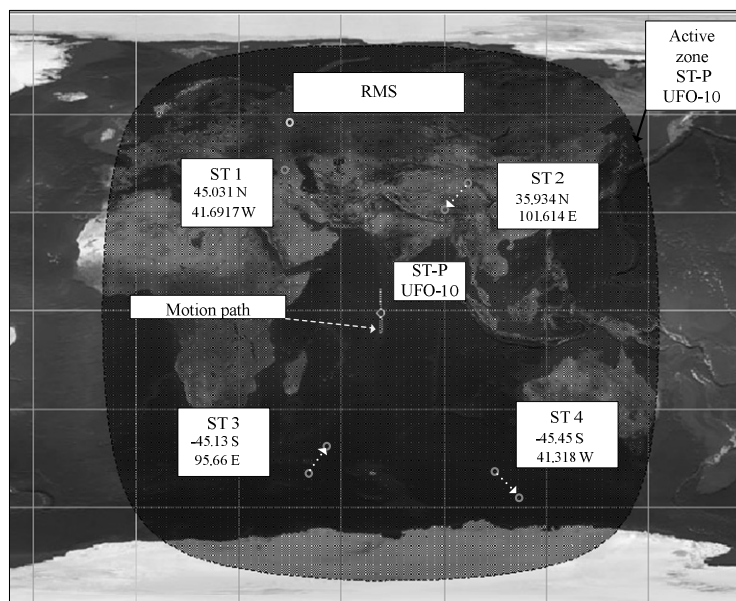
Figure 1. Scheme of the simulation of radio monitoring ST SCS

Figure 2 presents the graphs of changes of physical parameters obtained in the result of modeling.

The changes of the listed physical parameters take the form of a certain curve (Fig. 2). Moreover, two types of sections (namely, "quasilinear" and "quasiquadratic") are distinguished on each of the curves.

Polynomials of the second $y_{\mathrm{apr\_2}}(t) = b \cdot t^2 + c \cdot t + d$ and third orders $y_{\mathrm{apr\_3}}(t) = a \cdot t^3 + b \cdot t^2 + c \cdot t + d$ were used as approximants for studying the approximation error of changing physical parameter on a finite observation interval; the coefficients of them were found by the least squares method by minimizing the sum of the form.

The results illustrating the maximum value of the absolute error of the approximation (s) (ξ_2 and ξ_3) depending on the moment of the beginning of the observation t_0, the duration of the hour $t_{apr} = 1$ and the type of the approximating polynomial are summarized in Table 1.

When approximating a model of changing the time delay, the smallest approximation error is achieved using a third-order polynomial and does not exceed 0.68 μs $t_{apr} = 1$ for an hour (Table 1).

At the same time, it is necessary to take into account the mechanisms of noise impact in the conditions of data transmission to the SCS, operating through the spacecraft — R.
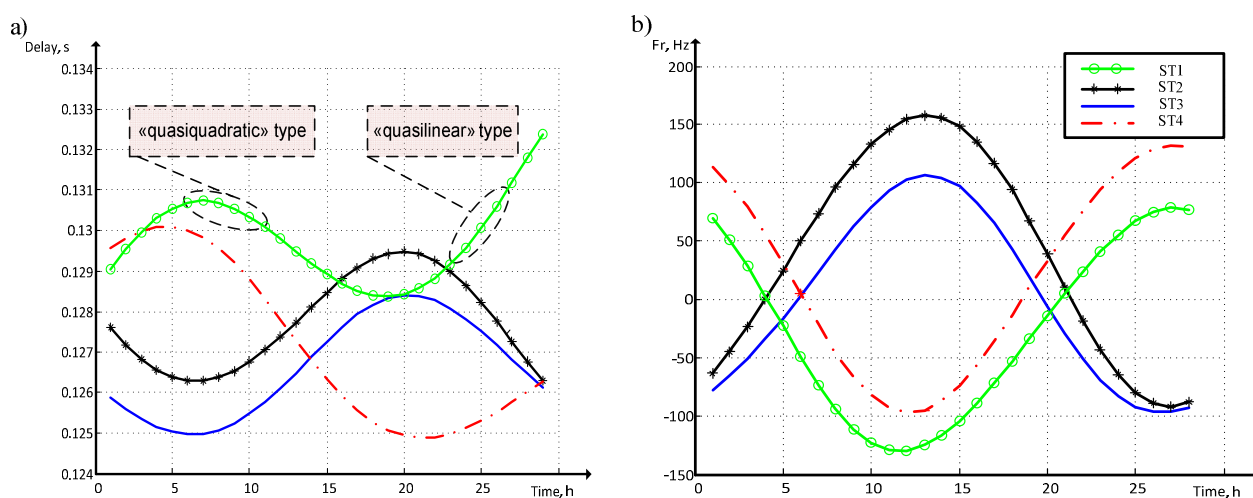

Figure 2. Change of physical parameters of the signal from subscriber terminals, where *a* is time delay relative to the reference time grid, *b* is the carrier frequency of the radio signal at the input of the receiver of the radio monitoring system

Maximum absolute approximation error delays by polynomials of the second and third

t_{apr} , [h]	1	2	3
ξ_2 , [s]	$2.655 \cdot 10^{-7}$	$14.377 \cdot 10^{-7}$	$48.059 \cdot 10^{-7}$
ξ_3 , [s]	$1.8035 \cdot 10^{-7}$	$2.1529 \cdot 10^{-7}$	$3.884 \cdot 10^{-7}$

According to [11], the potential accuracy of measuring non-energy parameters such as delay $y_t(t)$ and Doppler shift $y_f(t)$ against the background of Additive white Gaussian noise, expressed through standard deviation, are determined by the Equations:

$$\sigma_{ys} = \sqrt{\frac{1}{2 \cdot E / N_0 \cdot (2 \cdot \pi \cdot \Delta f_{ek})^2}}, \quad \sigma_{yf} = \sqrt{\frac{1}{2 \cdot E / N_0 \cdot (2 \cdot \pi \cdot \Delta t_{ek})^2}},$$

where Δf_{ek} is equivalent spectral width; Δt_{ek} is equivalent observation time.

The potential accuracy of estimating the delay and Doppler frequency shift is calculated taking into account the width of the spectrum of the radio signal $\Delta f = 9600$ Hz and accumulation interval of $T = 0.025$ s, that is, a radio signal base of 240.

The dependence of the potential accuracy of estimating the delay and carrier frequency on the signal-to-noise ratio is calculated based on the described parameters (Fig. 3).

Under the conditions for receiving a radio signal with a signal-to-noise ratio of 15 dB for the considered radio signal, the standard deviation of the delay and carrier frequency corresponds to 6.949 μs and 2.668 Hz, respectively.

The error in determining the value of physical parameters is a random variable. We assume that the error of determining the value of a physical parameter is distributed according to the normal law within the framework of the model under consideration [12–16]. A sample describing the effects of noise on each of the considered parameters is formed considering the obtained results.
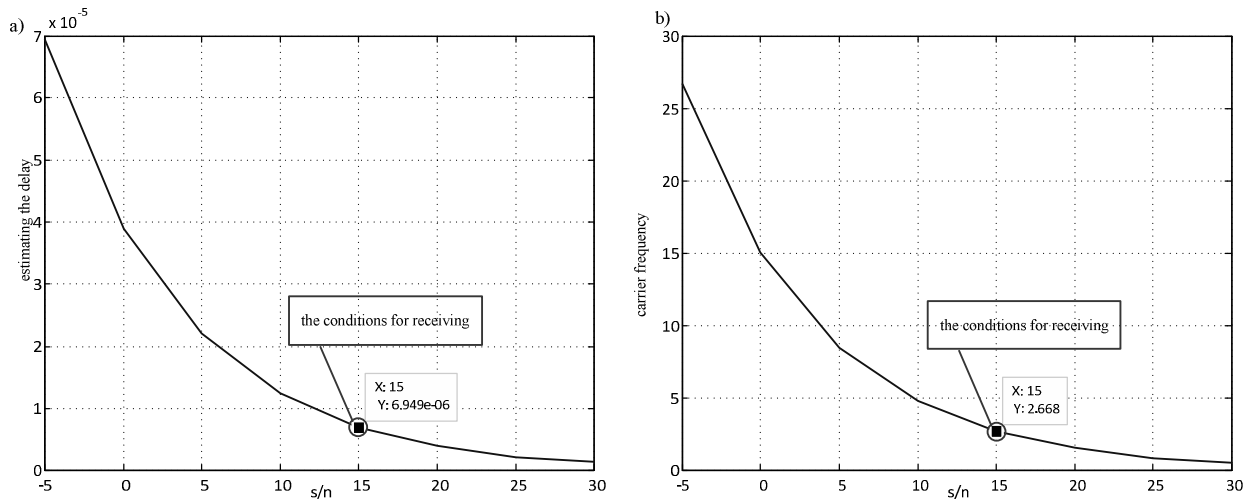

Figure 3. Dependence of the standard deviation of the parameter, where *a* is time delay on the signal-to-noise ratio; *b* is carrier frequency on the signal-to-noise ratio

The Equation describing k the physical parameter of the radio signal from the ST with the impact of noise will take the form:

$$v_k(t) = v_k(t_0) + v_k^{(R)}(t) + v_k^{(At)}(t) + v_k^{(Ion)}(t) + \hat{\delta}_k(t),$$

where $\hat{\delta}_k(t)$ is the effect of noise k on the value of the physical parameter of the radio signal from ST.

Results and Discussion

The error of approximation by polynomials of the second and third order under the influence of noise was studied based on the additive model (3). A «quasiquadratic» section was selected for the experiment.

A change in the time delay was simulated for a typical reception state with an SNR of 15 dB (Fig. 4).
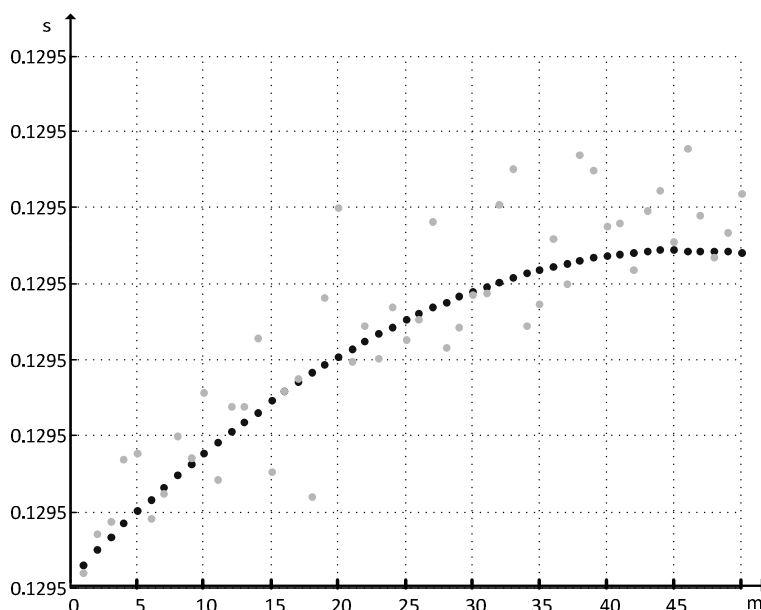

Figure 4. Change in time delay under noise at SNR = 15 dB

Based on the results of modeling the approximation by a polynomial of the second and third order of the time delay under the influence of noise in a sample of 1000 tests, the distribution density of the approximation errors is constructed (Fig. 5).
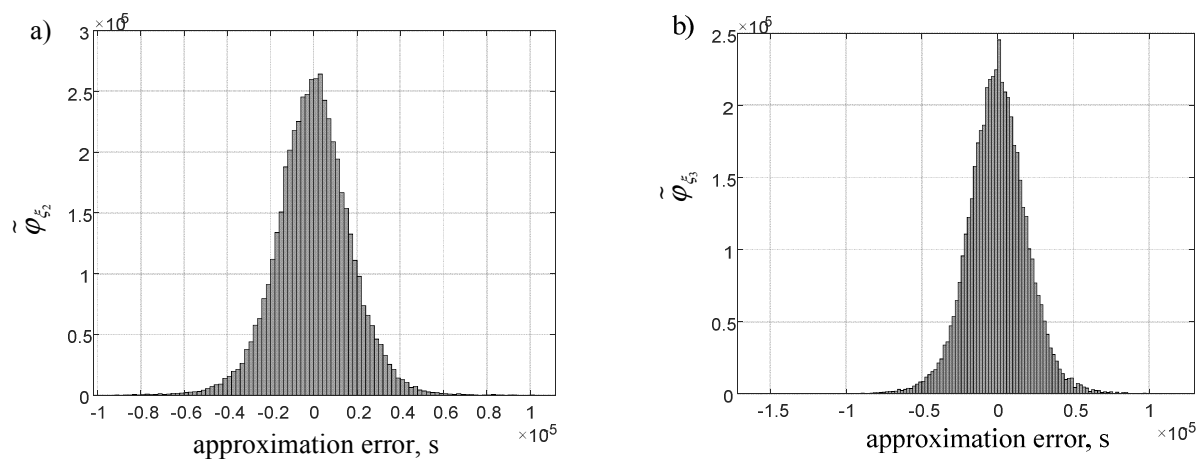

Figure 5. Probability density of approximation errors with a signal to noise ratio of 15 dB, where *a* is second-order polynomial; *b* is third-order polynomial

When analyzing the results obtained, the approximation error with a probability of 0.9 for various SNRs does not exceed the values presented in Table 2.

The value of the maximum absolute approximation error

Signal to noise ratio, [dB]	Standard deviation, time delay, [s]	ξ_2	ξ_3
5	$219.8 \cdot 10^{-6}$	$191 \cdot 10^{-6}$	$258 \cdot 10^{-6}$
10	$12.36 \cdot 10^{-6}$	$16.4 \cdot 10^{-6}$	$16.9 \cdot 10^{-6}$
15	$6.949 \cdot 10^{-6}$	$10 \cdot 10^{-6}$	$8 \cdot 10^{-6}$
20	$3.908 \cdot 10^{-6}$	$7 \cdot 10^{-6}$	$4 \cdot 10^{-6}$
25	$1.95 \cdot 10^{-6}$	$6 \cdot 10^{-6}$	$2 \cdot 10^{-6}$

Analysis of the data in Table 2 shows that the choice of the best polynomial for approximation is not obvious [17–20].

Figure 6 presents the results of the analysis and selection of conditions for the application of polynomials.
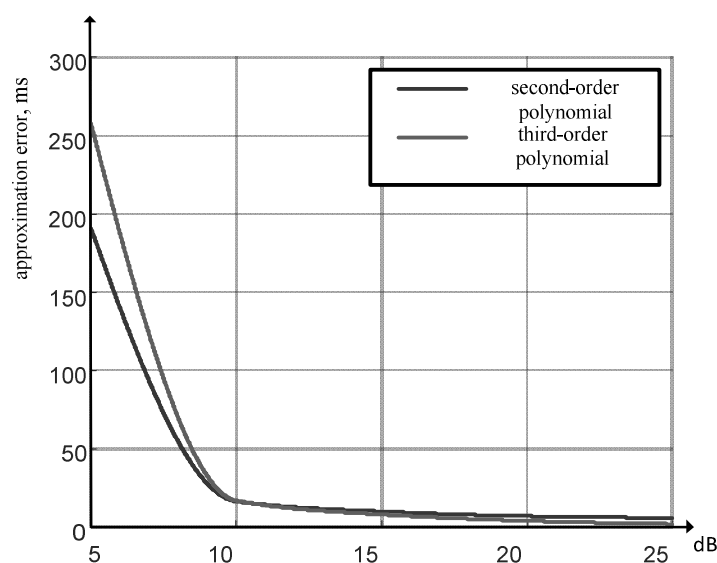

Figure 6 Dependence of the absolute approximation error on the SNR

Based on the simulation results, it was found that for the approximation of an arbitrary section it is advisable to use a second-order polynomial with an SNR of less than 10 dB, the use of which provides a significantly smaller error than when using a third-order polynomial. For SNR above 10 dB, it is preferable to use a polynomial of polynomial order.

Conclusions

Based on the model, changes in the physical parameters of the radio signal under the influence of the communication channel are studied. The quality of approximation of the change in the physical parameter of the signal by polynomials of the second and third order is investigated. The minimum error for the SNR of 15 dB is achieved by approximating the change in the delay by a second-order polynomial and is 38 μs. Application of the developed model makes it possible to use the spatio-temporal radio-frequency portrait of the ST, which in turn creates the prerequisites for the implementation of the method of decomposition of the ST SCS group signal during radio monitoring in the absence of access to switching and address parameters.

References

1 Еремеев И.Ю. Особенности организации спутниковых сетей связи с применением технологии многочастотного доступа с временным разделением каналов / И.Ю. Еремеев, К.В. Семенов // Наукоемкие технологии. — 2010. — № 9. — С. 36–43.

2 Богдановский С.В. Метод определения координат источников радиоизлучения на основе поляризационных измерений / С.В. Богдановский, К.Л. Овчаренко, А.Н. Симонов // Тр. Воен.-косм. акад. им. А.Ф. Можайского. — 2017. — № 657. — С. 38–43.

3 Цыганов А.С. Модель формирования кадровой структуры и информативный признак для оценивания периода кадра групповых сигналов с многочастотным множественным доступом с временным разделением / А.С. Цыганов, С.С. Старицин // Телекоммуникации. — 2017. — № 4. — С. 2–5.

4 Камнев В.Е. Спутниковые сети связи / В.Е. Камнев, В.В. Черкасов, Г.В. Чечин. — М.: Альпина Паблишер, 2004. — 536 с.

5 Эскобал П. Методы определения орбит / П. Эскобал. — М.: Мир, 1970. — 472 с.

6 Boev S.F. Determination technique of quasireference value of a carrier radio signal frequency of uncooperated onboard lighting source during radio monitoring / S.F. Boev, Y.M. Vikulova, I.V. Chebotar, M.T. Baldytchev, Y.N. Gaychuk, O.V. Galtseva // IOP Conference Series: Materials Science and Engineering. — 2018. — Vol. 457. — P. 012010, DOI: 10.1088/1757–899X/457/1/012010.

7 Балдычев М.Т. Решение задачи распознавания излучающих объектов на основе подхода к отождествлению их диаграмм направленности / М.Т. Балдычев, Ю.Н. Гайчук, С.В. Куликов, Р.А. Гудаев // Наукоемкие технологии. — 2015. — Т. 16, № 12. — С. 26–30.

8 Горбулин В.И. Методика распознавания типов космических объектов на основе совокупности радиотехнических признаков с учетом весовых коэффициентов / В.И. Горбулин, В.Д. Лиференко, С.В. Куликов, Р.А. Гудаев, М.Т. Балдычев // Успехи современной радиоэлектроники. — 2017. — № 9. — С. 57–65.

9 Кантор Л.Я. Спутниковая связь и проблема геостационарной орбиты / Л.Я. Кантор, В.В. Тимофеев. — М.: Радио и связь, 1988. — 168 с.

10 Рекомендация МСЭ — R P/1057–2. Распределение вероятностей, касающихся моделирования распространения радиоволн. — Женева: МСЭ, 2014. — 21 с.

11 Замарин А.И. Сравнительный анализ подходов к оцениванию задержки сигналов в условиях априорной неопределенности взаимного частотного сдвига / А.И. Замарин, И.Ю. Еремеев, К.Л. Овчаренко // Естественные и технические науки. — 2017. — № 2. — С. 126–130.

12 Овчаренко К.Л. Потенциальная точность оценивания задержки сигналов при наличии частотного рассогласования на основе вычисления взаимной корреляционной функции модифицированных комплексных огибающих / К.Л. Овчаренко // Успехи современной радиоэлектроники. — 2017. — № 7. — С. 39–44.

13 Куликов С.В. Решение задачи распознавания излучающих объектов на основе использования алгоритма сравнения спектральных портретов / С.В. Куликов, Р.А. Гудаев, А.В. Зеленков, М.Т. Балдычев, Ю.М. Викулова // Наукоемкие технологии. — 2016. — Т. 17, № 12. — С. 12–17.

14 Логинов А.А. Алгоритм вычисления функции неопределенности в задаче одновременной оценки частотно-временных характеристик сигналов / А.А. Логинов, Д.С. Марычев, О.А. Морозов, В.Р. Фидельман // Изв. высш. учеб. завед. Поволжский регион. — 2013. — № 3. — С. 62–73.

15 Ершов Р.А. Вычислительно-эффективный алгоритм оценки временной задержки широкополосных сигналов / Р.А. Ершов, О.А. Морозов, В.Р. Фидельман // Изв. Самар. науч. центра РАН. — 2014. — № 4. — С. 384–387.

16 Босый А.С. Метод определения местоположения земных станций по ретранслированным сигналам в условиях неопределенности координат космического аппарата-ретранслятора с применением беспилотного летательного аппарата / А.С. Босый, И.Ю. Еремеев, К.Л. Овчаренко, М.М. Тюстин, Е.Ю. Шиловский // Тр. Воен.-косм. акад. им. А.Ф. Можайского, 2019. — № 667. — С. 161–169.

17 Богдановский С.В. Пространственно-поляризационная обработка радиосигналов при пеленговании источников радиоизлучения с беспилотного летательного аппарата / С.В. Богдановский, А.Н. Симонов, С.Ф. Теслевич, З.Ф. Шайдулин // Наукоемкие технологии. — 2015. — Т. 16, № 12. — С. 50–55.

18 Петухов П.Е. Алгоритм формирования и обработки сигналов с модуляцией частоты вращения вектора поляризации / П.Е. Петухов, Ю.Е. Боровков, А.Н. Кренев, И.В. Чеботарь, М.Т. Балдычев // Наукоемкие технологии. — 2018. — Т. 19, № 10. — С. 15–18. DOI: 10.18127/j19998465-201810-03.

19 Боев С.Ф. Метод комплексного применения бортовых радиотехнических и радиолокационных средств для распознавания радиомолчащих воздушных объектов в условиях радиоэлектронного подавления / С.Ф. Боев, А.В. Тимошенко, И.В. Чеботарь, М.Т. Балдычев // Журн. радиоэлектроники. — 2017. — № 4. — С. 1–17.

20 Куликов С.В. Моделирование системы мониторинга воздушно-космического пространства / С.В. Куликов, Н.М. Епанешников, Р.А. Гудаев, И.В. Чеботарь, М.Т. Балдычев // Радиотехника. — 2020. — Т. 84, № 4(8). — С. 46–68.

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Спутниктік байланыс жүйелерінің мониторингі кезінде абоненттік терминалдардың кеңістіктік-уақытша радиожиілік портретін қалыптастыру моделі

Қазіргі кезде жерсеріктік байланыс жүйелерін (ЖБЖ) дамыту уақыт жиілігі ресурсын тиімді пайдалануды қамтамасыз етуге мүмкіндік беретін күрделі құрылымды сигналдарды дамытумен байланысты. Сонымен қатар, релелік ғарыш аппараттарының (СК-релесі) уақыттық жиіліктік ресурсын рұқсатсыз пайдалануға мүмкіндік беретін бағдарламалық қамтамасыз етуде (БҚЕ) танымал ету және тарату бар, бұл өз кезегінде ЖБЖ жұмысының сапасының төмендеуіне әкеледі. СА-

ретрансляторының уақыттық жиіліктік ресурсын рұқсатсыз пайдалануға қарсы тұрудың перспективалық бағыттары екі негізгі мәселені шешуге бағытталған әдістер болып табылады: абоненттік терминалдардың орналасуын анықтау және жіберілетін хабарламаның қызмет ету және мағыналық бөліктерін талдау. Физикалық параметрлердің өзгеруін ескеру үшін гетерогенді априорлы деректердің көп мөлшерін қолдануды қажет етеді және іс жүзінде бұл шешілетін мәселе емес. Математикалық статистика теориясы бойынша іріктемені талдау есептерін шешкен кезде жуықтау қолданылады. Зерттелген күрделі объект оның қасиеттерін зерттеу үшін қарапайым объектімен ауыстырылады. Сипатталған мәселеге қатысты күрделі жиіліктік құрылымы бар радиосигналдың физикалық параметрлерінің эксперименттік бағалары бақылаудың соңғы кезеңінде белгілі детерминирленген функциямен жуықтайды. Жақындаудың нәтижесі топтық сигналды құруға қатысатын АТ-ның кеңістіктік-уақыттық радиожиілік портреті (КУРЖП). КУРЖП тарату шарттарына тікелей байланысты және бірегей, бұл оның КУРЖП талдауы негізінде сигналды ыдыратуға мүмкіндік береді. Осылайша, зерттеудің мақсаты радиосигналдың физикалық параметрлерін өзгерту моделін жасау және АТ ЖБЖ кеңістіктік-уақыттық радиожиілік портретін қалыптастыру үшін физикалық параметрлерді жуықтау мүмкіндігін зерттеу болып табылады.

Кілт сөздер: спутниктік байланыс жүйесі, топтық сигнал, энергетикалық емес параметр, байланыс арнасы, уақытша бөлінуге көптеген мүмкіндік, ғарыш аппараты, ретранслятор, радиожиілік портреті, үлгі.

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Модель формирования пространственно-временного радиочастотного портрета абонентских терминалов при мониторинге спутниковых систем связи

В настоящее время развитие спутниковых систем связи (ССС) связано с разработкой сигналов сложной структуры, позволяющих обеспечить эффективное использование частотно-временного ресурса. Наряду с этим, отмечаются популяризация и распространение программно определяемых радиосистем (Software-defined radio, SDR), что приводит к снижению качества функционирования ССС. Перспективными направлениями противодействия несанкционированному использованию частотно-временного ресурса КА-ретранслятора являются методы, направленные на определение местоположения абонентских терминалов (АТ) и анализ служебной и семантической частей передаваемого сообщения. Учёт изменения физических параметров требует использования большого объема разнородных априорных данных и на практике является нерешаемой задачей. Согласно теории математической статистики, при решении задач анализа выборки применяется аппроксимация. Изучаемый сложный объект подменяется более простым объектом с целью изучения его свойств. Применительно к описанной задаче экспериментальные оценки физических параметров радиосигнала со сложной частотно-временной структурой аппроксимируются некоторой детерминированной функцией на конечном этапе наблюдения. Результат аппроксимации представляет собой пространственно-временной радиочастотный портрет (ПВРЧП) АТ, участвующих в формировании группового сигнала. ПВРЧП напрямую зависит от условий передачи и является уникальным, что позволяет осуществлять декомпозицию сигнала на основе анализа его ПВРЧП. Таким образом, целью исследования является разработка модели изменения физических параметров радиосигнала и исследование возможности аппроксимации физических параметров с целью формирования пространственно-временного радиочастотного портрета АТ ССС.

Ключевые слова: спутниковая система связи, групповой сигнал, неэнергетический параметр, канал связи, множественный доступ с временным разделением, космический аппарат, ретранслятор, радиочастотный портрет, выборка.

References

1   Eremeev, I. Yu., & Semenov, K.V. (2010). Osobennosti orhanizatsii sputnikovykh setei sviazi s primeneniem tekhnolohii mnohochastotnoho dostupa s vremennym razdeleniem kanalov [Features of satellite communication networks organization using multi-frequency access technology with time division of channels]. *Naukoemkie tekhnolohii — Journal Science Intensive Technologies, 9,* 36–43 [in Russian].

2   Bogdanovskii, S.V., Ovcharenko, K.L., & Simonov, A.N. (2017). Metod opredeleniia koordinat istochnikov radioizlucheniia na osnove poliarizatsionnykh izmerenii [Method for determining the coordinates of radio sources based on polarization measurements]. *Trudy Voenno-kosmicheskoi akademii imeni A.F. Mozhaiskoho — Proceedings of the Military Space Academy named after A.F. Mozhaysky, 657,* 38–43 [in Russian].

3   Cyganov, A.S., & Staricin, S.S. (2017). Model formirovaniia kadrovoi struktury i informativnyi priznak dlia otsenivaniia perioda kadra hruppovykh sihnalov s mnohochastotnym mnozhestvennym dostupom s vremennym razdeleniem [A model for form-

ing a frame structure and an informative feature for evaluating the frame period of group signals with multi frequency multiple access with time division]. *Telekommunikatsii — Telecommunications and Radio Engineering, 4*, 2–5 [in Russian].

4   Kamnev, V.E., Cherkasov, V.V., & Chechin, G.V. (2004). *Sputnikovye seti sviazi [Satellite communication networks]*. Moscow: Alpina Publisher [in Russian].

5   Eskobal, P. (1970). *Metody opredeleniia orbit [Methods for determining orbits]*. Moscow: Mir [in Russian].

6   Boev, S.F., Vikulova, Y.M., Chebotar, I.V., Baldytchev, M.T, Gavchuk, Y.N., & Galtseva, O.V. (2018). Determination technique of quasireference value of a carrier radio signal frequency of uncooperated onboard lighting source during radio monitoring. *IOP Conference Series: Materials Science and Engineering, 457*, 012010, DOI: 10.1088/1757–899X/457/1/012010.

7   Baldychev, M.T., Gajchuk, Yu.N., Kulikov, S.V., & Gudaev, R.A. (2015). Reshenie zadachi raspoznavaniia izluchaiushchikh obektov na osnove podkhoda k otozhdestvleniiu ikh diahramm napravlennosti [Solving the problem of recognizing radiating objects based on an approach to identifying their directional diagrams]. *Naukoemkie tekhnolohii — Telecommunications and Radio Engineering, 16(12)*, 26–30 [in Russian].

8   Gorbulin, V.I., Liferenko, V.D., Kulikov, S.V., Gudaev, R.A., & Baldychev, M.T. (2017). Metodika raspoznavaniia tipov kosmicheskikh obektov na osnove sovokupnosti radiotekhnicheskikh priznakov s uchetom vesovykh koeffitsientov [Method of recognition of types of space objects based on a set of radio technical features taking into account the weighting coefficients]. *Uspekhi sovremennoi radioelektroniki — Achievements of Modern Radioelectronics, 9*, 57–65 [in Russian].

9   Kantor, L.Ya., & Timofeev, V.V. (1988). *Sputnikovaia sviaz i problema heostatsionarnoi orbity [Satellite communications and the problem of geostationary orbit]*. Moscow: Radio i sviaz [in Russian].

10 Recommendation ITU — R P/1057–2. (2014). *Raspredelenie veroiatnostei, kasaiushchikhsia modelirovaniia rasprostraneniia radiovoln [Probability distributions concerning radio wave propagation modeling]*. Geneva: ITU [in Russian].

11 Zamarin, A.I., Eremeev, I.Yu., & Ovcharenko, K.L. (2017). Sravnitelnyi analiz podkhodov k otsenivaniiu zaderzhki sihnalov v usloviiakh apriornoi neopredelennosti vzaimnoho chastotnoho sdviha [A comparative analysis of approaches to the estimation of delay signals in conditions of a priori uncertainty of the mutual frequency shift]. *Estestvennye i tekhnicheskie nauki — Natural and technical sciences, 2*, 126–130 [in Russian].

12 Ovcharenko, K.L. (2017). Potentsialnaia tochnost otsenivaniia zaderzhki sihnalov pri nalichii chastotnoho rassohlasovaniia na osnove vychisleniia vzaimnoi korreliatsionnoi funktsii modifitsirovannykh kompleksnykh ohibaiushchikh [Potential accuracy of signal delay estimation in the presence of frequency mismatch based on the calculation of the mutual correlation function of modified complex envelopes]. *Uspekhi sovremennoi radioelektroniki — Achievements of Modern Radioelectronics, 7*, 39–44 [in Russian].

13 Kulikov, S.V., Gudaev, R.A., Zelenkov, A.V., Baldychev, M.T., & Vikulova, Yu.M. (2016). Reshenie zadachi raspoznavaniia izluchaiushchikh obektov na osnove ispolzovaniia alhoritma sravneniia spektralnykh portretov [Solving the problem of recognizing emitting objects based on the use of the spectral portrait comparison algorithm]. *Naukoemkie tekhnolohii — Science-intensive technologies, 17, 12*, 12–17 [in Russian].

14 Loginov, A.A., Marychev, D.S., Morozov, O.A., & Fidelman, V.R. (2013). Alhoritm vychisleniia funktsii neopredelennosti v zadache odnovremennoi otsenki chastotno-vremennykh kharakteristik sihnalov [Algorithm for calculating the uncertainty function in the problem of simultaneous estimation of the time-frequency characteristics of signals]. *Izvestiia vysshikh uchebnykh zavedenii. Povolzhskii rehion — Proceedings of higher educational institutions. Volga region, 3*, 62–73 [in Russian].

15 Ershov, R.A., Morozov, O.A., & Fidelman, V.R. (2014). Vychislitelno-effektivnyi alhoritm otsenki vremennoi zaderzhki shirokopolosnykh sihnalov [Computationally efficient algorithm for estimating the time delay of wideband signals]. *Izvestiia Samarskoho nauchnoho tsentra Rossiiskoi akademii nauk — Bulletin of the Samara Scientific Center of the Russian Academy of Sciences, 4*, 384–387 [in Russian].

16 Bosyi, A.S., Eremeev, I.Yu., Ovcharenko, K.L., Tiustin, M.M., & Shilovskii, E.Yu. (2019). Metod opredeleniia mestopolozheniia zemnykh stantsii po retranslirovannym sihnalam v usloviiakh neopredelennosti koordinat kosmicheskoho apparata-retransliatora s primeneniem bespilotnoho letatelnoho apparata [Method for determining the location of earth stations using relayed signals under conditions of uncertainty in the coordinates of a relay spacecraft using an unmanned aerial vehicle]. *Trudy Voenno-kosmicheskoi akademii imeni A.F. Mozhaiskoho — Proceedings of the Military Space Academy named after A.F. Mozhaisky, 667*, 161–169 [in Russian].

17 Bogdanovskii, S.V., Simonov, A.N., Teslevich, S.F., & Shaidulin, Z.F. (2015). Prostranstvenno-poliarizatsionnaia obrabotka radiosihnalov pri pelenhovanii istochnikov radioizlucheniia s bespilotnoho letatelnoho apparata [Spatial polarization processing of radio signals for direction finding of radio emission sources from an unmanned aerial vehicle]. *Naukoemkie tekhnolohii — Science-intensive technologies, 16, 12*, 50–55 [in Russian].

18 Petukhov, P.E., Borovkov, Yu.E., Krenev, A.N., Chebotar, I.V., & Baldychev, M.T. (2018). Alhoritm formirovaniia i obrabotki sihnalov s moduliatsiei chastoty vrashcheniia vektora poliarizatsii [Algorithm for the formation and processing of signals with modulation of the frequency of rotation of the polarization vector]. *Naukoemkie tekhnolohii — Science-intensive technologies, 19, 10*, 15–18. DOI: 10.18127/j19998465-201810-03 [in Russian].

19 Boev, S.F., Timoshenko, A.V., Chebotar, I.V., & Baldychev, M.T. (2017). Metod kompleksnoho primeneniia bortovykh radiotekhnicheskikh i radiolokatsionnykh sredstv dlia raspoznavaniia radiomolchashchikh vozdushnykh obektov v usloviiakh radioelektronnoho podavleniia [The method of complex application of airborne radio engineering and radar equipment for the recognition of radio silent air objects in conditions of electronic suppression]. *Zhurnal radioelektroniki — Radio Electronics Journal, 4*, 1–17 [in Russian].

20 Kulikov, S.V., Epaneshnikov, N.M., Gudaev, R.A., Chebotar, I.V., & Baldychev, M.T. (2020). Modelirovanie sistemy monitorinha vozdushno-kosmicheskoho prostranstva [Simulation of a monitoring system for aerospace]. *Radiotekhnika — Radio engineering, 84*, 4(8), 46–68 [in Russian].

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Development of the electronic physics textbook for students of secondary school

The work the results of using the developed electronic textbook on physics for organizing the independent work of secondary school students is analyzed. The possibilities of an electronic textbook are shown, the advantages of using the textbook in the learning process are noted. For the development of the electronic textbook, the C# programming language was used in the Microsoft Visual Studio software environment. The main idea of developing an electronic textbook is the relationship between theoretical teaching and practical skills. The electronic textbook provides two modes of operation: training mode and control mode, thus the electronic textbook contains a block of theoretical material and a module for interactive testing of students' knowledge. The theoretical material of the textbook has been developed in accordance with the standard curriculum for the subject "Physics". The interactive testing module includes standard physical problems of different degrees of complexity, as well as practice-oriented problems on physics. A set of practice-oriented problems has been developed, the use of which in the process of teaching physics will allow to ensure the formation of students' theoretical knowledge and practical skills, to prepare students for practical activities. The main advantage of an electronic textbook is interactivity. The novelty of the development of an electronic textbook is implementation in accordance with a new approach aimed at shaping students' knowledge about the practical applications of physics and developing their practical skills.

Keywords: electronic textbook, information and communication technologies, interactive testing, physical problems, pedagogical experiment.

Introduction

Electronic technology becomes an important component in all areas of social activity. Education is one of the most significant components in the process of personality formation and development of a man of to-day; therefore it needs constant improvement and modernization.

Modern education cannot be imagined without electronic technologies, since their use makes it possible to ensure the fulfillment of a number of important problems, such as providing access to educational materials as part of the implementation of distance learning programs, conducting online courses, and the use of innovative technologies contributes to the modernization of education.

The study of the concept of teaching by using information technology is one of the prospective lines of research today. The concept of e-learning is one of the main directions of research in educational technologies, and most scientific works on the e-learning education theme are devoted to the study of teaching and learning strategies, interactive learning environments, e-learning in education sector and massive open online courses [1]. This indicates an increase in interest in the study of the application of information and communication technologies in education sector, due to the development and dissemination of these technologies.

Information technologies make it possible to gain access to educational material at any time, simplify the transfer of information, provide greater clarity of the material and automate the process of knowledge control; make it possible to conduct virtual laboratory works. The textbooks created by using these technolo-

gies have a number of advantages and disadvantages. The advantages of electronic textbooks include the ability to fill the textbook with various visual aids, the ability to use hyperlinks and animations. The disadvantages of electronic textbooks include the complexity of development, the high cost of devices for reproducing educational material, the need to have an Internet connection, if necessary to display various elements of the textbook [2, 3]. Electronic textbooks on physics can be equipped with tools of self-control and testing of students, as well as tools for conducting virtual physical experiments, which will improve the quality of learning the material by students [4].

In work [5] authors investigated how elements of course structure influence the usage patterns of electronic textbooks (e-texts) in introductory physics courses. Found that course structure has a strong influence on how much of the e-texts students actually read, and when they do so.

The scientific and methodological basis of the use of the electronic textbooks and virtual laboratory works in the formation of an applied orientation in students were discussed in [6]. The article noted that conduction a physical experiment and frontal laboratory works by using virtual models and electronic books via computer, then can compensate the lack of equipment in the physics laboratory.

The theory of creating and using an electronic textbook, solving the requirements of innovative technologies and practical problems in the process of professional training of students, in particular, training future teachers with electronic textbooks, and also forms skills and abilities in practice, were discussed in [7]. The study is devoted to overcome the above contradictions by finding the best option for the creation and use of electronic textbooks illustrating its impact on the quality of education.

The structure and content of the electronic educational and methodological complex for students «Physics: social and humanitarian direction of specialized education» were described in [8]. The offered complex was developed on the basis of application software. Didactic and basic principles of organization of the electronic educational and methodical complex on the subject, which are the basis for the development of the author's complex, were highlighted.

The work [9] considers the organization matter of the training process in Physics with the "Educon" helping as an electronic support. The article noted that the practice of using electronic textbooks shows that students assimilate the material qualitatively. The development of the information and communication educational environment represented by electronic educational resources opens the way for new methods in physics studying, thereby improving the educational quality.

The purpose of the research in [10] is to identify students' preference for e-textbooks or analog, printed books, analyze the perception of student benefits and limitations of the medium, and investigate potential impacts of e-textbook use in educational process. The survey analyzed five beneficial and five limiting features of e-textbooks, confirming that eyestrain is the most problematic feature for e-textbook users, while ease of access was the most significant positive feature. Although the research does consider factors that may influence e-textbook preferences among students, there may be other factors that were not addressed in this research that may influence students' preferences for electronic texts and printed texts.

At the Department of Physics and Nanotechnology of the Physics and Technology of Faculty of the Karaganda University named after academician E.A. Buketov, work is underway to develop and use electronic teaching aids in the educational process [11–16]. At the principle of the concept of electronic edition developed by lecturers at the Department, much attention is paid to the methodological component, which allows using electronic educational resources as self-training for students and a simulator for self-testing.

According to the State Compulsory Standard of general secondary education [17], the purpose of general secondary education is to create an educational space to ensure the development of the following skills:

− functional and creative application of knowledge;
− critical thinking;
− carrying out research work;
− use of information and communication technologies;
− the use of various methods of communication;
− ability to work in a group and individually;
− problem solving and decision making.

This purpose can be achieved by using electronic teaching textbooks, since working with the textbook will improve the skills of using information and communication technologies among students, and can also contribute to the development of the above skills.

The purpose of this work is to develop the electronic textbook and practice-oriented problems on physics. To achieve the purpose of the work, the following tasks were set and solved:

− to develop the theoretical material of the textbook in accordance with the standard curriculum on physics [18];
− to develop practice-oriented problems on physics.

Practice-oriented problems were included in the textbook, since the preparation of students on physics, according to the State Compulsory Standard of general secondary education, involves the use of the knowledge gained to explain various physical processes and phenomena, the principles of operation of the most important technical devices. Solving applied problems helps to establish a connection between the studied theories and phenomena occurring in the real world, and contributes to the use of acquired skills in various life situations [19].

The electronic physics textbook

The electronic textbook was developed by using the C # programming language in a development environment «Microsoft Visual Studio» for Windows operating system. The main structural elements of the textbook are a block of theoretical material and a module for testing students' knowledge. The main menu of the program is shown in the Figure 1, where the structural elements of the textbook are indicated by numbers 1–3.
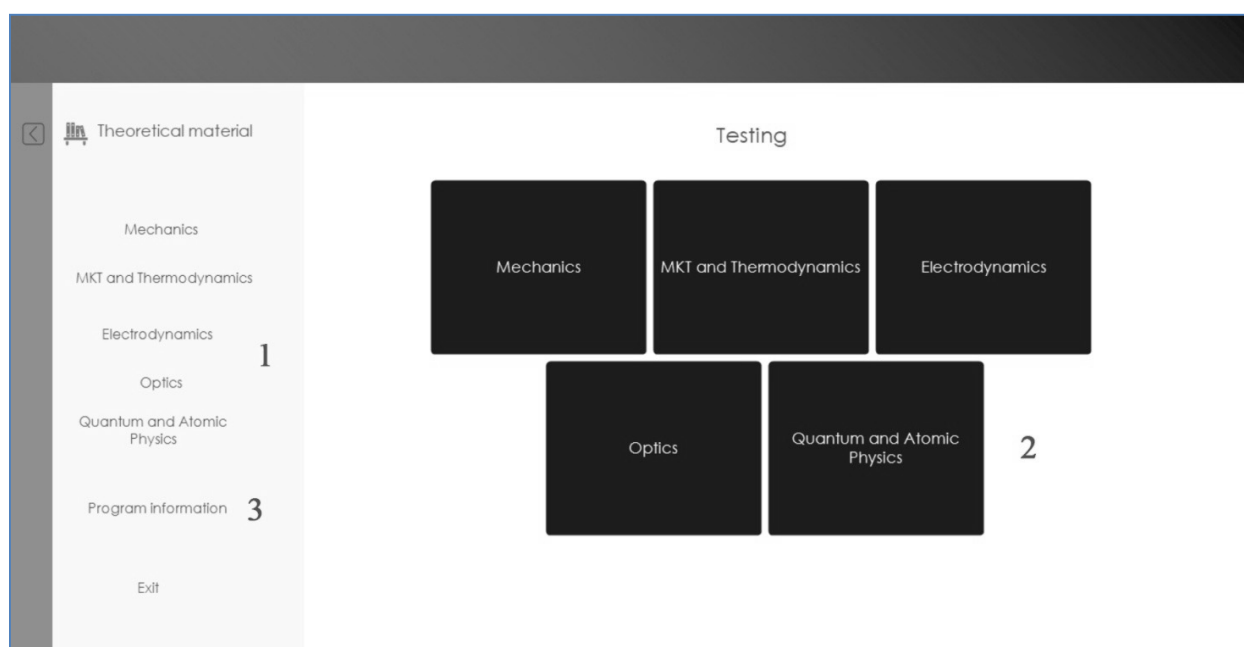
Figure 1. Main menu of the electronic textbook

Description of the structural elements of the electronic textbook:

1 — the block containing theoretical material on the sections of physics. The theoretical material is compiled on the main themes of a typical curriculum on physics;

2 — the testing module, when you click on a specific section, the test for the section opens in a separate window, the program window is hidden until testing is complete;

3 — the block containing information about the structure of the electronic textbook, when the button is pressed, this information is shown to the user.

All sections of the theoretical material are divided into subsections. For example, the "Electrodynamics" section includes the following subsections: electrostatics, direct current, magnetism, electromagnetic oscillations and waves. Each subsection is broken down into themes. On the themes included in the subsections, a brief reference material is presented, which is necessary for solving physical problems, supplemented by process diagrams and graphics, various figures that make the material more visual and improve its perception. The Figure 2 presents reference material on the themes "The motion of a body thrown at an angle to the horizon", included in the subsection "Kinematics".

Figure 2. Reference material on theme "Motion of a body thrown at an angle to the horizon"

The material is structured in such a way to make it easier to find the information you need. When you click on each of the subsections, a list appears containing all the theme of the subsection, clicking on the theme name from the splash list allows you to open the reference material. The non-linear structure of the material of textbook allows you to start studying it from a specific theme and return to previously studied material if necessary. The splash list also contains a link for passing testing by subsection. Testing is a set of problems with a choice of one answer out of five proposed, as well as problems with a choice of several correct answers out of eight proposed. All problems, including practice-oriented problems, were compiled according to the themes included in the subsection.

The table shows the concentration of gas molecules in identical closed vessels and the root mean square velocity of molecules

Gas	Concentration, m^{-3}	Root mean square velocity, m/s
Oxygen	$5,32 \cdot 10^{25}$	460
Nitrogen	10^{26}	550

Analyze the data and select the correct statements.
A) Oxygen pressure on the vessel walls is greater than 0.01 MPa
B) Nitrogen pressure on the vessel walls is greater than 0.4 MPa
C) At a pressure of 0.8 MPa, the root mean square velocity of oxygen molecules ≈ 920 m/s
D) The mass of the oxygen molecule is greater than $7.38 \cdot 10{-}26$ kg.
E) The mass of the nitrogen molecule is lesser than $4.2 \cdot 10{-}26$ kg.
F) Oxygen pressure on the vessel walls is lesser than 1.7 MPa
F) Oxygen pressure on the vessel walls is lesser than 1.7 MPa
G) Nitrogen pressure on the vessel walls is lesser than 0.3 MPa
H) At a pressure of 0.8 MPa, the root mean square velocity of oxygen molecules is lesser than 970 m/s

Finish testing

Figure 3. Testing window for the section "Molecular-kinetic theory and thermodynamics"

The testing module allows to testing the entire section. The testing window is shown in the Figure 3. Test tasks include tasks from testing on subsection. When generating a test variant, each task is selected randomly from a list of tasks of a certain number, generated from all testing variants on a subsection. This allows creating many different test variants and gives the ability to test multiple times. Each variant of the test consists of 12 tasks (9 tasks with a choice of one answer and 3 tasks with a choice of several correct answers). Tasks with a choice of one correct answer are evaluated at 1 point; tasks with a choice of several correct answers are evaluated from 0–2 points, depending on the selected answers. Thus, having completed all the tasks correctly, the student receives 15 points.

The information block of the textbook program contains information about the structure of the program, the structure of test tasks and the assessment of test items.

Results and its discussion

The approbation of the electronic physics textbook was carried out in the 10th grade of the secondary school. The students studied the theoretical material of the textbook, after which they completed the tasks from the test module of the textbook. When conducting a pedagogical experiment for students, test variants were created for the sections "Mechanics", "Electrodynamics", "Molecular-kinetic theory (MKT) and thermodynamics". The testing results are shown in the Table 1.

T a b l e 1

Student testing results

Section	Themes of section including in testing	Average score received by students
Mechanics	Uniformly accelerated motion. Relativity of motion. Graphical representation of movement. Uniform circular motion. Forces in nature. Newton's laws. The movement of a body thrown at an angle to the horizon. Body movement along an inclined plane. The law of conservation of momentum and energy. Work done by a constant force. Free and forced vibrations. Harmonic vibrations. Oscillations of mathematical and spring pendulums. Sound waves. Conditions for equilibrium of bodies. Archimedes' law. Hydrostatic pressure. Rule of moments.	10,1/15 (67,3 %)
MKT and thermodynamics	Fundamental principles of MKT. The amount of substance. Molar mass. Molecular speed. Isoprocesses in gases. Internal energy of gas. Ideal gas equation of state. Basic equation of MKT. I and II laws of thermodynamics. Heat balance equation. Heat engines. Humidity.	11,32/15 (75,46 %)
Electrodynamics	Electric charge. Conservation law of electric charge. Capacitors. Connection of conductors. Electric field. Electric current. Ohm's law for a section of circuit. Electromotive force. Electric current in various environments. A magnetic field. Magnetic induction. Ampere force. Lorentz force. Work and power of current.	11,68/15 (77,86 %)

These data show that the learning material was assimilated by the students, since the average score obtained as testing result on the sections is more than 67 % of the maximum possible score. The analysis of the students works showed that each of the students successfully solves at least 7 physical problems with the choice of one correct answer and at least 1 problem with the choice of several correct answers, which is 66.6 % of the number of proposed problems. These results indicate that the developed theoretical material of the textbook can be useful for students for independent study, repetition of previously studied themes, and the testing module can be used to practice the skills of solving physical problems. The analysis of the test results also showed that the greatest difficulties for students arise when solving problems on the following themes: "Body motion on an inclined plane", "Law of conservation of momentum and energy", "Rule of moments", "Magnetic induction", "Humidity". Students also had difficulties in solving practice-oriented problems. This can be attributed to the lack of students' experience in solving this type of problem.

Conclusion

The electronic physics textbook was developed for for students of secondary schools. For the development of the textbook, the Microsoft VisualStudio software development environment was used. The

theoretical material and tasks of the test part of the textbook were developed in accordance with the typical curriculum for the subject.

The results of the pedagogical experiment showed that each student successfully completes more than 66 % of the proposed test tasks. The presented electronic physics textbook can be useful for achieving various educational goals. The electronicphysics textbook can be used by students in the process of independent preparation to practice solving problems, repeating previously studied themes and consolidating theoretical material.

References

1   Valverde-Berrocoso J. Trends in Educational Research about e-Learning: A Systematic Literature Review (2009–2018) / J. Valverde-Berrocoso, M.C. Garrido-Arroyo, C. Burgos-Videla, M.B. Morales-Cevallos // Sustainability. — 2020. — Vol. 12, No. 12. — P. 5153.

2   Никитина Е.О. Электронные учебники как средство обучения в эпоху информатизации образования / Е.О. Никитина // Наука и школа. — 2013. — № 4. — С. 21–23.

3   Прутько А.С. Преимущества и недостатки использования электронных учебных пособий по курсу физики / А.С. Прутько // Научное сообщество студентов XXI столетия. Гуманитарные науки. — 2019. — № 11(83). — С. 85–89.

4   Гурин Н.И. Мультимедийный электронный учебник по дисциплине «Физика» (раздел «Физические основы механики») / Н.И. Гурин, В.В. Чаевский, И.И. Наркевич // Высшее техническое образование. — 2011. — № 8(146). — С. 169–171.

5   Seaton D.T. Analyzing the impact of course structure on electronic textbook use in blended introductory physics courses / D.T. Seaton, G. Kortemeyer, Y. Bergner, S. Rayyan, D.E. Pritchard // American journal of physics. — 2014. — Vol. 82, No. 12. — P. 1186–1197.

6   Usembayeva I.B. Electronic Resources in Physics as a Means of Formation Applied Orientation of Students / I.B. Usembayeva, A.N. Bahtibayev, K.M. Berkimbayev, A.Ch. Saribaeva // Procedia Social and Behavioral Sciences: 5th World Conference on Educational Sciences. — 2014. — Vol. 116. — P. 4310–4314.

7   Беркимбаев К.М. Электронный учебник как средство совершенствования профессиональной подготовки будущих учителей / К.М. Беркимбаев, А.Х. Сарыбаева, А.Л. Ташимова, А. Миндетбаева // Междунар. журн. эксперим. обр. — 2012. — Т. 8. — С. 13–16.

8   Myslitska N.A. Electronic teaching and methodological complex in physics for students of social and humanitarian type of studies / N.A. Myslitska, V.F. Zabolotnyi, I.Yu. Slobodianiuk // Information Technologies and Learning Tools. — 2019. — Vol. 74, No. 6. — P. 43–55.

9   Polovnikova L. Electronic textbook efficiency in studying physics at the technical university / L. Polovnikova, A. Novikova // Proceedings of 4th International Multidisciplinary Scientific Conference on Social Sciences and Arts SGEM 2017 (24–30 August 2017). — 2017. — Vol. 17, Book number 4. — P. 179–184.

10   Chang Lor. Benefits and Limitations of E-textbook Use [Электронный ресурс] / Lor Chang // Journal Student Research. — 2017. — Vol. 16. — P. 32–47. — URL: https://minds.wisconsin.edu/bitstream/handle/1793/77573/E-textbooks.pdf?sequence=1&isAllowed=y

11   Камбарова Ж.Т. Күрделілігі жоғары есептерді шығару әдістемесі. Молекулалық физика және термодинамика. Электронды оқу құралы. Свидетельство о внесении сведений в Государственный реестр прав на объекты, охраняемые авторским правом, № 3296 от 14 мая 2019 г.

12   Копбалина Қ.Б., Камбарова Ж.Т., Маженов Н.А. Электростатикалық өрісте зарядталған бөлшектердің қозғалысын компьютерлік модельдеу. Электронды оқу құралы. Свидетельство о внесении сведений в Государственный реестр прав на объекты, охраняемые авторским правом, № 3283 от 11 мая 2019 г.

13   Копбалина Қ.Б., Камбарова Ж.Т., Толекова М. Механика элементтері. Электронды оқу құралы. Авторское свидетельство о внесении сведений в Государственный реестр прав на объекты, охраняемые авторским правом № 11262 от 7 июля 2020 г.

14   Мусенова Э.К. Физика курсын оқытуда сандық ресурстарды қолданудың тиімділігі / Э.К. Мусенова, Т.Е. Сейсембекова, А.С. Утепова, Б.И. Казанкап // Қарағанды ун-тінің хабаршысы. Физика сер. — 2015. — № 3(79). — С. 116–121.

15   Ильина Л.Ф. Сравнительный анализ методики проведения занятий по электростатике в 8- и 10-х классах с использованием интерактивных технологий / Л.Ф. Ильина, А.Н. Колесникова // Вестн. Караганд. ун-та. Сер. Физика. — 2012. — № 3(67). — С. 66–71.

16   Ильина Л.Ф. Использование инновационных технологий при изучении магнитных явлений / Л.Ф. Ильина, Д.К. Тажибаева // Вестн. Караганд. ун-та. Сер. Физика. — 2010. — № 3(59). — С. 68–77.

17   Приказ Министерства образования и науки Республики Казахстан «Об утверждении государственных общеобязательных стандартов образования всех уровней образования». — URL: http://adilet.zan.kz/rus/docs/V1800017669.

18   Типовые учебные программы по общеобразовательным предметам общего среднего образования по обновленному содержанию. — URL: https://online.zakon.kz/m/document/?doc_id=33519278.

19   Ильясов В.Х. Направления развития методов преподавания и практико-ориентированный подход к преподаванию курса физики / В.Х. Ильясов, В.Н. Шамбулина // Балт. гуманит. журн. — 2018. — Т. 7, № 2(23). — С. 247–250.

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Орта мектеп оқушылары үшін физика пәні бойынша электрондық оқу құралын әзірлеу

Мақалада орта мектеп оқушыларының өздік жұмыстарын ұйымдастыруға арналған физика бойынша әзірленген электронды оқу құралын қолдану нәтижелері талданған. Электрондық оқу құралының мүмкіндіктері, оқу процесінде оқу құралды қолданудың артықшылықтары көрсетілген. Электрондық оқу құралын әзірлеу кезінде Microsoft Visual Studio бағдарламалық қамсыздандыру ортасында C# бағдарламалау тілі қолданылды. Ұсынылған электронды оқу құралын әзірлеудің негізгі ойы — теориялық оқыту мен практикалық дағдылардың өзара байланысы. Электрондық оқу құралы екі жұмыс режимін ұсынады: оқу режимі және бақылау режимі, яғни оқу құралы теориялық материалдар блогынан және оқушылардың білімін интерактивті тестілеу модулінен құрылады. Оқу құралының теориялық материалы «Физика» пәні бойынша типтік оқу бағдарламасына сәйкес әзірленген. Тестілеу модуліне тапсырмалар ретінде күрделілігі әр түрлі стандартты есептер, сонымен бірге физикадан практикаға бағытталған есептер енгізілген. Физиканы оқыту процесінде қолдану оқушылардың теориялық білімі мен практикалық дағдыларын қалыптастыруға, оқушыларды практикалық іс-әрекеттілікке дайындауға мүмкіндік беретін практикалық-бағытталған есептер кешені әзірленген. Электрондық оқу құралының басты артықшылығы оның интерактивтілігінде болып табылады. Электрондық оқу құралын әзірлеудің жаңалығы — оқушыларда физиканың практикалық қолданылуы туралы білімдерін қалыптастыруға және олардың практикалық дағдыларын дамытуға бағытталған жаңа әдіс-тәсілге сәйкес жүзеге асыру.

Кілт сөздер: электрондық оқу құралы, ақпараттық-коммуникативтік технологиялар, тестілеу бағдарламасы, физикадан есептер, педагогикалық эксперимент.

А.С. Прутько, А.С. Кудусов, Э.К. Мусенова, Ж.Т. Камбарова

Разработка электронного учебного пособия по физике для учащихся средней школы

В статье проанализированы результаты использования разработанного электронного пособия по физике для организации самостоятельной работы учащихся средней школы. Показаны возможности электронного учебного пособия, отмечены преимущества использования пособия в процессе обучения. При разработке электронного учебного пособия использован язык программирования C# в среде программного обеспечения Microsoft Visual Studio. Основная идея разработки электронного учебного пособия — взаимосвязь теоретического обучения и практических навыков. Электронное учебное пособие предусматривает два режима работы: режим обучения и режим контроля, таким образом пособие содержит блок теоретического материала и модуль интерактивного тестирования знаний учащихся. Теоретический материал пособия разработан в соответствии с типовой учебной программой по предмету «Физика». В модуль интерактивного тестирования учащихся в качестве заданий включены стандартные задачи различной степени сложности, а также практико-ориентированные задачи по физике. Разработан комплекс практико-ориентированных задач, использование которого в процессе обучения физике позволит обеспечить формирование у обучающихся теоретических знаний и практических умений, а также подготовку учащихся к практической деятельности. Основное преимущество электронного учебного пособия — интерактивность. Новизна разработки электронного учебного пособия заключается в ее выполнении в соответствии с новым подходом, направленным на формирование у учащихся знаний о практических применениях физики и развитие у них практических умений.

Ключевые слова: электронное учебное пособие, информационно-коммуникативные технологии, интерактивное тестирование, физические задачи, педагогический эксперимент.

References

1   Valverde-Berrocoso, J., Garrido-Arroyo, M.C., Burgos-Videla, C., & Morales-Cevallos, M.B. (2020). Trends in Educational Research about e-Learning: A Systematic Literature Review (2009–2018). *Sustainability*, *12*, *12*, 5153.

2   Nikitina, E.O. (2013). Elektronnye uchebniki kak sredstvo obucheniia v epokhu informatizatsii obrazovaniia [Electronic textbooks as a means of learning in the era of informatization of education]. *Nauka i shkola — Science and school*, *4*, 21–23 [in Russian].

3   Prutko, A.S. (2019). Preimushchestva i nedostatki ispolzovaniia elektronnykh uchebnykh posobii po kursu fiziki [Advantages and disadvantages of using e-learning manuals on physics course]. *Nauchnoe soobshchestvo studentov XXI stoletiia. Humanitarnye nauki — Scientific community of students of the XXI century. Humanitarian sciences, 11(83),* 85–89 [in Russian].

4   Gurin, N.I., Chaevskij, V.V., & Narkevich, I.I. (2011). Multimediinyi elektronnyi uchebnik po distsipline «Fizika» (razdel «Fizicheskie osnovy mekhaniki») [Multimedia electronic textbook on the discipline «Physics» (section «Physical foundations of mechanics»)]. *Vysshee tekhnicheskoe obrazovanie — Higher technical education, 8(146),* 169–171 [in Russian].

5   Seaton, D.T., Kortemeyer, G., Bergner, Y., Rayyan, S., & Pritchard, D.E. (2014). Analyzing the impact of course structure on electronic textbook use in blended introductory physics courses. *American Journal of Physics, 82(12), 1186–1197.*

6   Usembayeva, I.B., Bahtibayev, A.N., Berkimbayev, K.M., & Saribaeva, A.Ch. (2014). Electronic Resources in Physics as a Means of Formation Applied Orientation of Students. *Procedia Social and Behavioral Sciences: 5th World Conference on Educational Sciences, 116, 4310–4314.*

7   Berkimbaev, K.M., Sarybaeva, A.Kh., Tashimova, A.L., & Mindetbaeva, A. (2012). Elektronnyi uchebnik kak sredstvo sovershenstvovaniia professionalnoi podhotovki budushchikh uchitelei [An electronic textbook as means of professional training perfection of future teachers]. *Mezhdunarodnyi zhurnal eksperimentalnoho obrazovaniia — International Journal of Experimental Education, 8,* 13–16 [in Russian].

8   Myslitska, N.A., Zabolotnyi, V.F., & Slobodianiuk, I.Yu. (2019). Electronic teaching and methodological complex in physics for students of social and humanitarian type of studies. *Information Technologies and Learning Tools, 74, 6,* 43–55.

9   Polovnikova, L., & Novikova, A. (2017). Electronic textbook efficiency in studying physics at the technical university. *Proceedings of 4th International Multidisciplinary Scientific Conference on Social Sciences and Arts SGEM 2017 (24–30 August 2017), 17, 4,* 179–184.

10   Lor, Chang. (2017). Benefits and Limitations of E-textbook Use. *Journal Student Research, 16,* 32–47. Retrieved from: https://minds.wisconsin.edu/bitstream/handle/1793/77573/E-textbooks.pdf? sequence=1&isAllowed=y

11   Kambarova, Zh.T. (2019). Kurdeliligi zhogary esepterdi shygaru adistemesi. Molekulalyq fizika zhane termodinamika [Methods for solving problems of increased complexity. Molecular Physics and Thermodynamics]. *Electronic textbook.* Certificate of entering information into the state register of rights to objects protected by copyright, No. 3296 dated May 14, 2019 [in Kazakh].

12   Kopbalina, Q.B., Kambarova, Zh.T., Mazhenov, N.A. (2019). Elektrostatikalyq oriste zariadtalgan bolshekterdin qozgalysyn komputerlik modeldeu [Computer modeling of the motion of charged particles in an electrostatic field.]. *Electronic textbook.* Certificate of entering information into the state register of rights to objects protected by copyright, No. 3283 dated May 11, 2019 [in Kazakh].

13   Kopbalina, Q.B., Kambarova, Zh.T, Tolekova, M. (2020). Mekhanika elementteri [Elements of mechanics]. *Electronic textbook.* Certificate of entering information into the state register of rights to objects protected by copyright, No. 11262 dated July 7, 2020 [in Kazakh].

14   Mussenova, E.K., Seisembekova, T.Ye., Utepova, A.S., & Kazankap B.I. (2015). Fizika kursyn oqytuda sandyq resurstardy koldanudyn tiimdiligi [Efficiency of the use of electronic resources on lessons of physics]. *Qaragandy universitetinin khabarshysy. Fizika seriiasy — Bulletin of the University of Karaganda — Physics, 3(79)*, 116–121 [in Kazakh].

15   Ilyina, L.F., & Kolesnikova, A.N. (2012). Sravnitelnyi analiz metodiki provedeniia zaniatii po elektrostatike v 8- i 10-kh klassakh s ispolzovaniem interaktivnykh tekhnolohii [Comparative analysis of methods of conducting studies on electrostatics in the eighth and tenth grades, using interactive technologies]. *Vestnik Karahandinskoho universiteta. Seriia Fizika — Bulletin of the University of Karaganda — Physics, 3(67)*, 66–71 [in Russian].

16   Ilyina, L.F., & Tazhibayeva, D.K. (2010). Ispolzovanie innovatsionnykh tekhnolohii pri izuchenii mahnitnykh yavlenii [The using of innovation technologies during magnetic phenomenona study]. *Vestnik Karahandinskoho universiteta. Seriia Fizika — Bulletin of the University of Karaganda — Physics, 3(59)*, 68–77 [in Russian].

17   Prikaz Ministerstva obrazovaniia i nauki Respubliki Kazakhstan «Ob utverzhdenii hosudarstvennykh obshcheobiazatelnykh standartov obrazovaniia vsekh urovnei obrazovaniia» [Order of the Ministry of Education and Science of the Republic of Kazakhstan «On approval of state compulsory education standards at all levels of education»]. *adilet.zan.kz* Retrieved from: http://adilet.zan.kz/rus/docs/V1800017669 [in Russian].

18   Tipovye uchebnye prohrammy po obshcheobrazovatelnym predmetam obshcheho sredneho obrazovaniia po obnovlennomu soderzhaniiu [Standard curricula for general education subjects of general secondary education according to updated content]. *online.zakon.kz* Retrieved from: https://online.zakon.kz/m/document/? doc_id=33519278 [in Russian].

19   Ilyasov, V. Kh., & Shambulina, V.N. (2018). Napravleniia razvitiia metodov prepodavaniia i praktiko-orientirovannyi podkhod k prepodavaniiu kursa fiziki [The directions of development of methods of teaching and the practical-focused approach to teaching a course of physics]. *Baltiiskii humanitarnyi zhurnal — Baltic humanitarian journal, 7, 2(23),* 247–250 [in Russian].

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Formation of ICT competencies for future physics teachers

The article discusses effective ways to use IT-services in teaching future physics teachers. This reflects the mutual understanding between the teacher and the student based on the use of modern information technologies in the development of the modern educational process. Some IT-services in teaching meet modern requirements. But this does not mean the chaotic use of any platform, programs, and software applications, that is, it is necessary to take into account the specifics of the subject, the pedagogical and psychological state of students. Based on this, the article describes what digital competencies should be used in the training of future physics teachers. Video lectures and audio lectures, infographics, visual lectures made in Mindmap, and Vyond on the discipline "Methodological basis of solving physical tasks" have a great influence on the comprehensive search of students. The article analyzes the necessity and relevance of using information technologies in the educational process but also discusses ways to implement them practically. This creates skills for students to use digital competencies to expand their knowledge. There are also ways to conduct questionnaires, tests, and reflections in various formats that allow students to test their knowledge. The types of tasks created in the effective applications used in the teaching of physics are given.

Keywords: IT-services, ICT competencies, methods of teaching physics, platforms, interactive learning, infographics, requirements, tasks.

Introduction

Currently, there is a huge potential of modern information technologies. It is necessary to adapt the education system to the digital generation through the mass and effective use of innovative educational technologies and didactic models based on ICT, thereby allowing everyone to study with the help of any teacher, wherever they are, using the latest available devices (computer, laptop, tablet, phablet, smartphone, etc.). At the same time, it is necessary to actively use the research approach in teaching aimed at developing students' qualifications and skills of scientific research in the formation of creative thinking and creative abilities based on IT competence. But it should be noted that information and communication technologies are not the solutions to all problems in the education system, they are a tool that can make lectures and seminars more information accessible and attractive for the digital generation.

Teachers retain their crucial role in the interactive learning process, focused on the needs of students. Thus, the authority of the teachers and the effectiveness of his activities won't depend on the level of mastering the course content and their pedagogical abilities but also on the extent to which they used modern information and communication technologies for collecting, processing, and teaching specific educational material. In other words, education should be redefined and the educational paradigm should be changed in the digital age because students do not want to learn traditionally, and teachers should not continue to teach traditionally [1].

Methods

The main methods of the research are the theoretical analysis of the problem status on the basis of the literature and the study of normative documents, observation, conversation, and interview.

The purpose of the study is to study the effectiveness of the integrated use of digital resources and services in the discipline "Methodological foundations for solving physical tasks" in the formation of ICT skills of future physics teachers to achieve this goal, the following tasks were set:

− analysis of digital resources and services in physics, creating conditions for achieving learning outcomes in the discipline "Methodological foundations for solving physical problems";

− creation of digital teaching aids in the discipline «Methodological foundations for solving physical tasks»;

– experimental verification of the formation of ICT skills of future physics teachers in the process of studying the course «Methodological foundations for solving physical tasks».

In the education system of Kazakhstan, the issue of ICT competence of teachers is relevant, which can be discussed by analyzing the content of the adopted and developed regulatory legal acts in recent years, in particular, we are talking about the State Program "Digital Kazakhstan" [2].

UNESCO has developed the document "ICT Competence Framework for Teachers. UNESCO Recommendations, version 3". The recommendations include the competencies necessary for teachers in their professional activities, covering six main aspects of teachers' work: understanding the role of ICT in education, curriculum and assessment, pedagogical practices, ICT technical and software tools, organization and management of the educational process, professional development [3].

The concept of ICT skills in the scientific literature of G.V. Soldatova reflects modern requirements for the skills and abilities of members of the information society and is understood as based on the continuous mastering of competencies (knowledge, skills, motivation, responsibility) the ability of an individual to confidently, effectively, critically and safely choose and apply information and communication technologies in different spheres of life (information environment, communications, consumption, techno sphere), as well as his readiness for such activities [4].

Nowadays, Information Computer Technologies in educational institutions of the Republic of Kazakhstan are being implemented and actively implemented in the learning process through modern platforms and distance learning programs. For example, universities of the country use platforms such as Moodle (modular-oriented dynamic learning), Microsoft Teams — Microsoft office workspace, Zoom, Google Meet, and Google Hangouts. Let's focus on the characteristics and capabilities of these platforms.

Moodle (modular-oriented dynamic learning). This open web application is a free e-learning system designed to organize the teaching and learning process for students and teachers. In this system, you can use all formats of documents, images, video, and audio files, as well as the SCORM archive [5].

Moodle, combined with a functionally rich test module, also allows you to evaluate students' work through such elements of the course as "Task", "Forum", etc. The results of the task can be evaluated on scales selected independently or passed by the teacher. On the forum, together with other participants of the course, you can configure the wiki, glossary, evaluation of articles or responses.

Moodle has great opportunities in creating tests, conducting training, and control tests. The tests use a wide variety of questions, such as a variety of choices, matching, correct/incorrect, short answers, essays, etc. Moodle is equipped with flexible tools for statistical analysis of semi-automatic testing results, which makes it easier to process tests.

Microsoft Teams is a Microsoft office workspace. It is a corporate platform that combines conversations, meetings, notes, and attachments in a workspace and is designed for remote teamwork. A workspace that allows users to collaborate, edit files and add notes wherever they are, helping them create a team, collaborate, and communicate instead of email [6].

It also allows teams to group messages to track video conversations, so that group conversations are usually visible to the entire group, or move to individual conversations. During voice and video conferences, participants create documents, videos, and audio files in the workspace where can actively use emojis, stickers, GIFs.

Microsoft Teams platform allows creating a calendar plan, scheduling classes, creating thematic groups and channels and uploading and downloading data and documents.

Zoom platform provides video conferences, online meetings, and distance learning. A free account allows us to communicate via video conferencing for 40 minutes. Conferences of all sizes and up to 100 people have an unlimited duration [7].

The program is perfect for individual and group classes, students can log in both from a computer and a tablet by phone. Anyone with a link or conference ID can join the video conference. The event can be planned, as well as a duplicate link, that is, you can create the same login link for a regular lesson at a certain time.

Video and audio communication with each participant. The organizer can mute and turn on the microphone, as well as mute the video, also to start video with the only member of the conference with the right to review.

It is convenient to record a lecture both on a computer and in the cloud, and it can be paused by setting up the automatic recording. During the conference, there is an opportunity to assign a co-organizer with the

same features as the organizer: for individual students, changing the name to turn on and off the microphone and dividing the room will help to perform group work.

Google Meet, Google Hangouts, Discord. Previously, Hangouts is used as a meeting, the presence of a limit on the number of participants is not profitable to use this platform. Google Meet is a video conferencing solution for corporate groups provided by Google [8]. It's the Google version of Zoom, with three levels of Basic, Business, and Enterprise that match the G Suite levels. However, Google Meet is available to anyone who has a Google account, so it is free for the public, with no time limit for up to 100 participants. In Google Meet, Google sits next to chat as part of a business communication solution, and Google Chat is an alternative to a service like Slack.

At the technological stage of modern education, there are also enough programs that allow creating tasks in different forms to conduct questionnaires, tests, and reflection to test students' knowledge in different formats. Some of them should be particularly noted.

Using *Quizlet*, teachers can create quizzes for students to complete control tasks, fill out suggestions, compare images and information, or choose the right answers. It is very easy to use — in a few minutes understand the interface, as well as work on Android and iOS on smartphones and tablets [9].

Kahoot! allows to submit all educational materials in the form of questionnaires and tests. Combined with a more detailed test of knowledge in a game format around new topics in the form of simple questions and answers to establish feedback with students. Kahoot! represents a new generation of student-response systems that has a main focus on student motivation and engagement through gamification [10].

Kahoot! — the teacher displays the material on the main screen, during which students answer questions and discuss information using a special application for computers or a browser on smartphones (Android, iOS, Windows Phone). For accessing the virtual cabinet, students must enter a special code sent by the teacher. This service allows you to find out how each student answered questions or create an academic performance schedule for the entire class. They can track the results themselves in special tables. Kahoot! — free and fully available program after registration.

The main feature of Easy Test Maker is the ability to create tasks where the students need to select correct and false statements to format texts for easy reading on a tablet, or for testing in a traditional format .pdf. or download it in doc. formats [11]. This program can mix questions and answers to help students complete their tasks and allow them to create 25 Tests without the possibility of exporting the free version of Easy Test Maker to "paper" format.

In addition to creating questionnaires with different response formats in ClassMarker, students can also write an essay [12]. To get started, the teacher must create a virtual class and send invitation codes to students. ClassMarker stores the results of all tests performed, a statistical report. If the teacher has their own web page, they can add tests to it. In the free version, ClassMarker allows you to create no more than 100 Tests.

SurveyMonkey is a service for creating simple and small surveys, as well as distributing mass surveys, identifying trends, and creating large surveys [13]. The service allows you to create surveys, adjust their appearance, move questions, conduct two-answer A/B tests, conduct surveys on websites and social networks, create visual reports, protect data and combine MailChimp, GroSocial, CleverReach, and other tools.

Socrative is a tool for creating, finding, and distributing online tests for educational institutions, conducting tests [14]. Among the advantages, it is worth noting the simplicity and pleasant interface of development.

The analysis of scientific and methodological literature [15, 16] has shown that video lectures created in accordance with didactic requirements are not enough to organize training in the discipline "Methodological basis of solving physical tasks".

General didactic requirements for the volume of educational video lectures for use in the educational process, it is recommended to create video recordings of lectures, the playback time of which is no more than 10 minutes.

When creating a specially prepared training video, the following techniques were used to improve the perception of information, recommended in:

− Titles and sound savers fixing the semantic parts of the video lecture.
− Video materials that set the appropriate visual range (video illustrations, etc.).
− Close-ups of diagrams, images and use of infographics.
− Change of large and general plans of the lecturer to maintain attention to the emotions that the lecturer conveys through gestures and facial expressions.

The use of video lectures in teaching allows students to activate mental activity, change the channels of perception of information from auditory to visual and vice versa. This type of lecture is accompanied by demonstration materials: presentation, video on the topic under study, diagrams, mind-maps, infographics, which are additional sources of information.

When the amount of information that needs to be remembered is measured in several pages, then such a method of presenting information and at the same time a method of teaching as a mind map is used. They represent a tree-like structure in the center of which is the central concept (lecture topic, complex object, end result or solution). Branches of secondary concepts depart from the central block.

Infographics are a type of visual presentation of data that is very effective in explaining and presenting various processes. Its main advantage is its colorful and laconic presentation of information.

However, it is important that the teacher knows the individual characteristics of students' perception of information. It is necessary to give the student the opportunity to choose tasks on an informational and figurative basis of various types. It increases the level of perception of educational information by students and contributes to their assimilation of the content of the academic discipline. This will contribute to the practical and professional implementation of the acquired knowledge and skills.

You can record video and audio lectures in various programs, including Microsoft PowerPoint, oCam, Audacity, and Bandicam, according to how students perceive and master the material (Fig. 1).

Introductory lesson on the discipline «Methodological basis of solving physical tasks», created in Microsoft PowerPoint

Audio lecture developed in Audacity

video review created in oCam

Video course template created in Bandicam
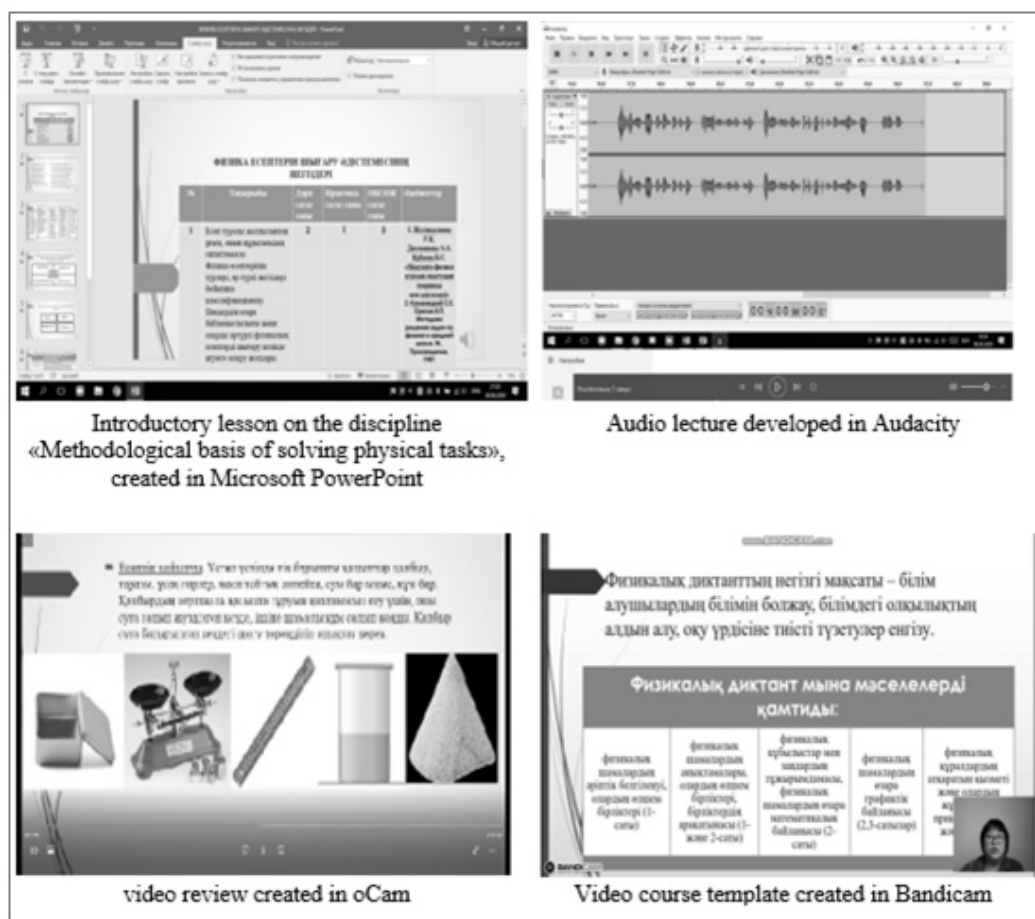
Figure 1. Video and audio training samples

Infographics are a graphical way of transmitting information [17]. Simply put, infographics allow you to organize the design of your educational materials so that they are easy and understandable to the student. This shows that infographics also include elements other than images, that is, they include text, diagrams, and blocks. In general, infographics are designed for fast, visual, and vivid delivery of material. For example, infographics are designed to explain the topic "algorithmization of methods for solving problems" is shown in Figure 2.

Figure 2. Infographics «Algorithmization of problem solving methods»

In fact, data can always be transmitted through text, tables, and numbers. But with the help of infographics, you can make sure that interpretation has the following advantages:

− infographics allow you to quickly convey to the audience a large number of materials in teaching physics. What you will have to read for a long time can be shown in one or more images;

− good infographics make information much clearer. Images are perceived by the human brain better than text;

− a bright, interesting picture will help attract the attention of the audience. Therefore, this format is used in public speaking, as well as in the media, and is used in modern textbooks.

In accordance with modern requirements, the updated curriculum can be clearly seen in physics textbooks of grades 7–11, created using infographics.

Mind-map-Intelligence Map or mind map. It reflects the opportunities for reflection, memory, memory, and the ability to demonstrate an effective way to solve creative problems, as well as to present and visually demonstrate internal processes of Information Processing, make changes to them and improve them.

In the discipline "Methodological basis of solving physical tasks" one of the ways to explain the topic "ways to solve text problems" was prepared on the Mind-map map. In the first step, you need to highlight the main point. The creation of a thought map begins precisely in the middle, that is, in the middle of it, "Ways to solve text problems" is written. This indicates that the main idea or goal is set. In the second step, it is necessary to highlight the topics that come from the main idea and differentiate the materials necessary for understanding. It is chosen "the mathematical path" and "experimental path" according to the topic. When drawing a map, you should use different colors. In the third step, select additional topics and highlight additional topics that will help you better understand or follow the main topic. At this time, methods were proposed, which are considered on the mathematical and experimental line. The fact that all of them lead to the main idea can be clearly seen on the map (Fig. 3). The general Mind-map should be designed at any time in the center, at the edge of the eye, so that everything else is noticed and every detail is remembered.
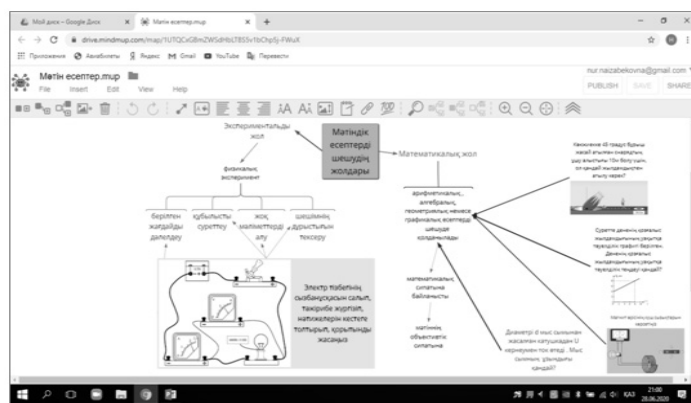
Figure 3. Mind-map on the topic "Ways to solve text problems"

You can also use interactive features, including in the Vyond program, to create educational material in the form of "sketch animation" (Fig. 4). It not only increases the student's interest but also allows you to independently create moving scenes, i.e. animations. The free sample is saved only for 14 days.
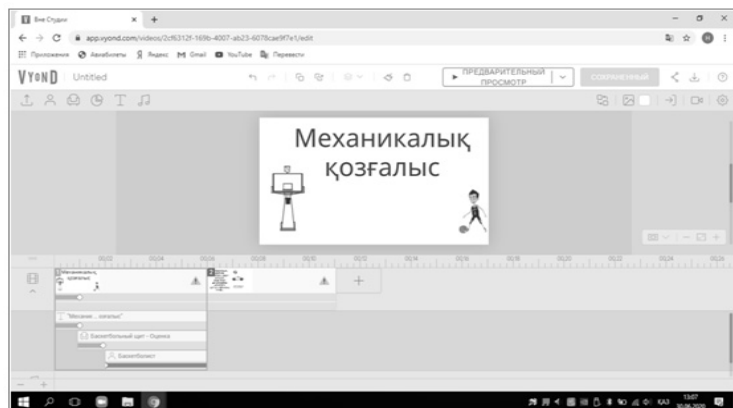
Figure 4. Sketch animation on the topic «Mechanical movement»

You can use the elements and resources of the electronic course for self-preparation of students. You can download lectures, presentations, videos, and test tasks on the discipline "Methodological basis of solving physical tasks" (Fig. 5). It will also be possible to adjust the time interval and determine the results of the training.
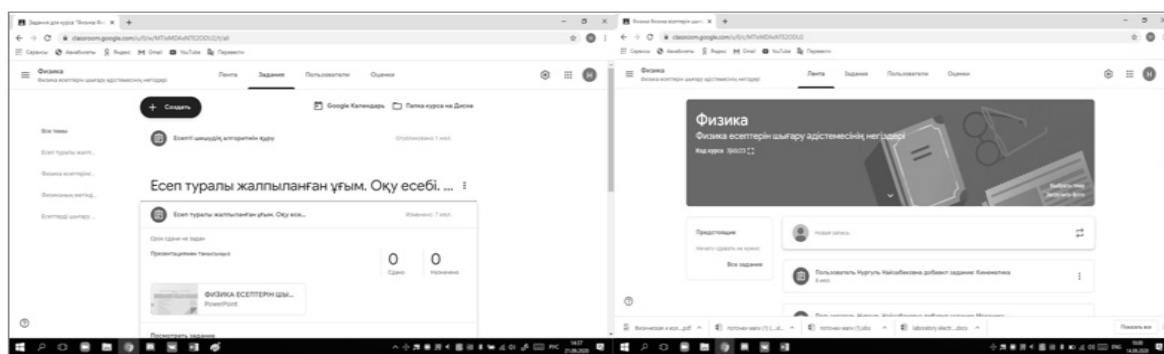
Figure 5. Elements of the electronic course on the discipline "Methodological basis of solving physical tasks"
https://classroom.google.com/u/0/c/MTIxMDAxNTE2ODU2

To determine the level of knowledge of students, it is more effective to use the Survey Monkey and Socrative applications. Because in teaching physics, formulas, graphs, and demonstration of practical tasks are difficult to implement in other applications such as Kahoot, Class Marker, Easy Test Maker, and Google Forms. And these programs can only be used to test theoretical questions and tasks with answers such as "true" and "false".

It is very effective to conduct online and offline physics classes, quizzes, test tasks, and competitions through Socratic. In this app, you can create a lot of text and logical questions and provide feedback, which can be implemented using applications for mobile devices that do not require registration. In addition to getting an instant result for the teacher and student, it can store tests and their results in the app, mail, and computer.

During the period of the diagnostic experiment at Kokshetau State University, the level of ICT competencies of students of future physics teachers was assessed. To assess the level of students' ICT competencies, an interactive test was developed, in which students were asked to complete various tasks, answer questions related to the search, processing, and presentation of information. 59 students of Kokshetau State University took part in the test, the test was carried out among 3-year bachelor students in 2019–2020 full-time and distance learning. The indicator of the formation of students' ICT competencies is a low level of 18 %, an average level of 34 %, and a high level of 48 % (Fig. 6).
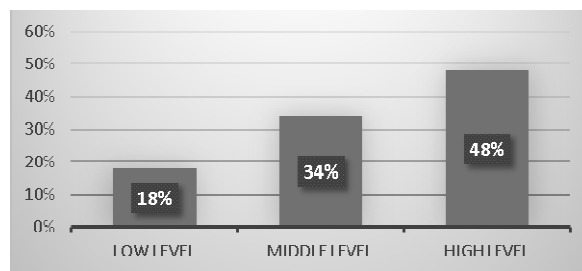
Figure 6. Levels of formation of ICT competencies

The results obtained in the course of diagnosing the level of ICT competencies of future physics teachers allowed us to conclude that the level of formation of ICT competencies is low.

An experimental check of the formation of IT competencies, in the course of studying the course "Methodological Foundations of Solving Physical tasks", was carried out on the basis of assessment tools developed in the Survey Monkey and Socrative applications.

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It is very effective to conduct online and offline physics classes, quizzes, test tasks, and competitions through Socrative (Fig. 7). In this app, you can create a lot of text and logical questions and provide feedback, which can be implemented using applications for mobile devices that do not require registration. In addition to getting an instant result for the teacher and student, it can store tests and their results in the app, mail, and computer (Fig. 8).

Sample of the test on the "Thermodynamics" serveymonkey
(https://RG.surveymonkey.com/create/?cm=св2 лфксонвуынх9ы65к_2б_2686б861дддедвуг_3д&tablke=1)

Test tasks created in the Socrative app
https://b.socrative.com/teacher/#quizzes
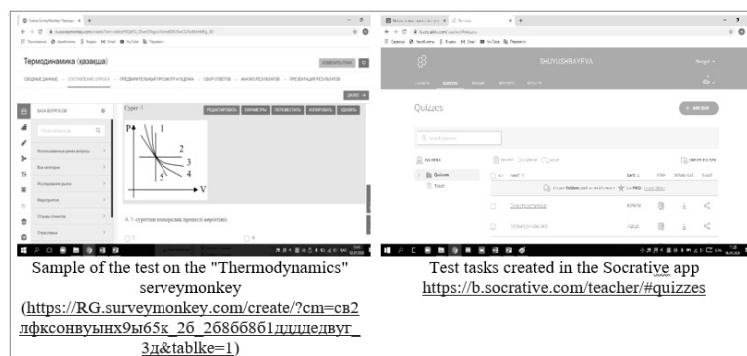
Figure 7. Shows the test results obtained from students in the Socrative app.
In a short time, the assessment of students' knowledge was carried out
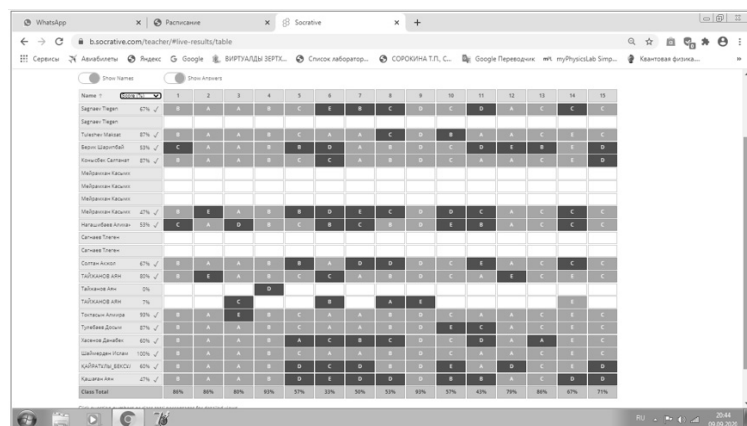
Figure 8. Test results obtained from students in the Socrative app

As part of the experiment to determine the formation of IT competencies, in the course of studying the course "Methodological foundations for solving physical tasks", a survey was conducted, which showed that social networks and mobile messengers are the most popular means of communication among the respondents, therefore, they also have good potential as a platform for communication for educational purposes, for instant notification, dissemination of information among a group of users.

Many students, future physics teachers have shown a high willingness to master the techniques of working with information and information technologies, since a sufficient understanding of the capabilities of Kahoot, Class Marker, Easy Test Maker, and Google Forms, Survey Monkey and Socrative, incl. and for self-education, about the possibilities of automating various educational activities. The communicative component was also formed at a sufficient level, the students gained experience of participating in videoconferences, webinars, streams, and gained knowledge about the culture of Internet communication. Students willingly undergo training, participate in forum discussions, in group work, high daily attendance of distance learning.

Conclusion

The use of the above computer programs, services created by the authors of the video lectures in the course "Methodological foundations for solving future physics teachers of physical tasks" increased the interest of students in the use of digital technologies in educational activities, intensified the independent work of students using various electronic means of educational and developmental purposes; stable skills of using computer technology and skills of working with it were formed.

Finally, the conditions in the modern world meet various modern requirements of society, as a result of the use of advanced information and communication, electronic, digital, and computer technologies and models of life in cyberspace, there is a need for a high level of literacy that meets the needs of the information society. They should contribute to increasing the intellectual activity of future physics teachers, the formation of creative and mental abilities, the development of a worldview of the individual, which will allow him to take a strong position in the information society. Thus, the use of IT-services in teaching physics has a huge impact on students' self-education.

References

1 Жоғары және жоғары оқу орнынан кейінгі білім беру жүйесін цифрлық ұрпаққа бейімдеу тұжырымдамасы [Электронды ресурс]. — URL: https://www.enu.kz/downloads/yanvar-2020/hiedtech-kontseptsiya-kaz.pdf

2 State program "Digital Kazakhstan" [Electronic resource]. — URL: https://digitalkz.kz/razvitie-chelovecheskogo-kapitala/

3 UNESCO ICT Competency Framework for Teachers [Electronic resource]. — URL: https://iite.unesco.org/ru/publications/3214694-ru/

4 Солдатова Г.У. Психологические модели цифровой компетентности российских подростков и родителей / Г.У. Солдатова, Е.И. Рассказова // Нац. психол. журн. — 2014. — Т. 2(14). — С. 27–35.

5 Manyakhina V. Description of setting up and using Moodle / V. Manyakhina, A. Zolochevsky [Electronic resource]. — URL: https://docs.altlinux.org/ru-RU/archive/4.1/html-single/school-server/moodle/index.html

6 Microsoft Teams [Electronic resource]. — URL: https://techexpert.ua/products/microsoft-teams/

7 Archibald M.M. Using Zoom Videoconferencing for Qualitative Data Collection: Perceptions and Experiences of Researchers and Participants / M.M. Archibald, R.C. Ambagtsheer, M.G. Casey, M. Lawless // International Journal of Qualitative Methods. — 2019. — Vol. 18. — P. 1–8.

8 Google Meet [Electronic resource]. — URL: https://gsuite.google.ru/intl/ru/products/meet/

9 What is Quizlet? [Electronic resource]. — URL: https://quizlet.com/ru/teachers

10 Wang A.I. The effect of points and audio on concentration, engagement, enjoyment, learning, motivation, and classroom dynamics using Kahoot! / A.I. Wang, A. Lieberoth // Proceedings of the European Conference on Games-based Learning (2016, January). — 2016. — P. 738–746.

11 Easy Test Maker [Electronic resource]. — URL: https://easytestmaker.com/

12 The Best Quiz Maker for Business & Education [Electronic resource]. — URL: https://www.classmarker.com/

13 SurveyMonkey [Electronic resource]. — URL: https://www.surveymonkey.ru/

14 Badanov A.G. Socrative Teacher manual / A.G. Badanov // Google Presentation [Electronic resourse]. — URL: https://docs.google.com/presentation/d/11q6_blwNxL-G8A8v4Q0WAtT9qXvOHd38cqQKiEpJql8/edit#slide=id.p

15 Garnaeva G.I. Information and communication technologies competence formation of the future teacher of physics / G.I. Garnaeva, E.I. Nizamova, E.D. Shigapova // European Proceedings of Social and Behavioural Sciences: 4th International Forum on Teacher Education (2018, September). — 2018. — P. 221–227.

16 Nekrasova G.N. Preparing Technology Teachers for Professional Activities in the Information Space of Technological Education / G.N. Nekrasova, N.N. Novikova // 5th International Forum on Teacher Education (IFTE) (2019, May). — 2019. — P. 473–485.

17 Ferreira J. Infographics: An introduction. Technical Report [Electronic resourse] / J. Ferreira. — Coventry University, 2014. — URL: https://www.researchgate.net/publication/266082644

Н.Н. Шуюшбаева, С.К. Дамекова, Н.К. Танашева, Г.С. Алтаева

Болашақ физика мұғалімдерінің цифрлық құзыреттіліктерін қалыптастыру

Мақалада болашақ физика мұғалімдерін оқытуда цифрлық сервистерді қолданудың тиімді жолдары қарастырылған. Бұл қазіргі заманғы білім беру үрдісін дамытуда заманауи ақпараттық технологияларды қолдану негізінде оқытушы мен студент арасындағы өзара түсіністікті көрсетеді. Оқытудағы кейбір цифрлық сервистер қазіргі заман талабын қанағаттандырады. Бірақ бұл кез келген платформа, бағдарламалар және бағдарламалық қосымшаларды бейберекет пайдалану дегенді білдірмейді, яғни пәннің ерекшелігіне, білім алушылардың педагогикалық-психологиялық жағдайларын ескеруді қажет етеді. Осы айтылғандар негізінде мақалада болашақ физика мұғалімдерін оқытуда қандай цифрлық сервистерді қолдану қажеттігі баяндалған. «Физика есептерін шығару әдістемесінің негіздері» пәні бойынша видеодәрістер мен аудиодәрістердің, инфрографикалардың, Mindmap және Vyond-та жасалған көрнекі дәрістердің студенттердің жан-жақты ізденуіне зор ықпал ететіні келтірілген. Мақалада оқыту үдерісінде ақпараттық технологияларды қолданудың қажеттілігі мен өзектілігі талданып қана қоймай, практикалық түрде іске асыру жолдары қарастырылған. Бұл студенттерге өз білімдерін кеңейту мақсатында цифрлық сервистерді пайдалану дағдыларын қалыптастырады. Сонымен қатар білім алушылардың білімін тескеруге мүмкіндік беретін әр түрлі форматта сауалнамалар, тесттер, рефлексия өткізудің жолдары айтылған. Физиканы оқытуда қолданылатын тиімді қосымшаларда жасалған тапсырмалардың түрлері келтірілген.

Кілт сөздер: ақпараттық технологиялар, цифрлық құзыреттіліктер, физиканы оқыту әдістемесі, платформалар, интерактивті оқыту, инфографика, талаптар, тапсырмалар.

Н.Н. Шуюшбаева, С.К. Дамекова, Н.К. Танашева, Г.С. Алтаева

Формирование цифровых компетенций будущих учителей физики

В статье рассмотрены эффективные способы использования цифровых сервисов в подготовке будущих учителей физики. Это отражает взаимопонимание между учителем и учеником, основанное на использовании современных информационных технологий в развитии современных образовательных процессов. Некоторые цифровые компетенции в обучении соответствуют современным требованиям. Однако это не означает хаотичного использования какой-либо платформы, программ и программных приложений, то есть необходимо учитывать специфику дисциплины, педагогическое и психологическое состояние студентов. Исходя из этого, авторами отмечено, какие цифровые сервисы следует использовать при подготовке будущих учителей физики. Кроме того, видеолекции и аудиолекции по дисциплине «Методические основы решения физических задач», инфографика, наглядные лекции по Mindmap и Vyond имеют большое влияние на комплексный поиск студентов. В статье не только проанализирована необходимость и актуальность использования информационных технологий в учебном процессе, но и предложены способы их реализации на практике, способствующие развитию у студентов навыков использования цифровых сервисов для расширения своих знаний. Также представлены способы проведения анкет, тестов, размышлений в различных форматах, позволяющих проверить знания и навыки студентов. Приведены типы заданий, созданные в эффективных приложениях, используемых в преподавании физики.

Ключевые слова: информационные технологии, цифровые компетенции, методика преподавания физики, платформы, интерактивное обучение, инфографика, требования, задачи.

References

1 Zhohary zhane zhohary oqu ornynan keiinhi bilim beru zhuiesin tsifrlyq urpaqqa beiimdeu tuzhyrymdamasy [The concept of adaptation of higher and postgraduate education to the digital generation]. *www.enu.kz* Retrieved from https://www.enu.kz/downloads/yanvar-2020/hiedtech-kontseptsiya-kaz.pdf [in Kazakh].

2 State program "Digital Kazakhstan". *digitalkz.kz* Retrieved from https://digitalkz.kz/razvitie-chelovecheskogo-kapitala/

3 UNESCO ICT Competency Framework for Teachers. *iite.unesco.org* Retrieved from https://iite.unesco.org/ru/publications/3214694-ru/

4   Soldatova, G.U., & Rasskazova, E.I. (2014). Psikholohicheskie modeli tsifrovoi kompetentnosti rossiiskikh podrostkov i roditelei [Psychological models of digital competence in Russian adolescents and parents]. *Natsionalnyi psikholohicheskii zhurnal — National Psychological Journal, 2(14)*, 27–35 [in Russian].

5   Manyakhina, V., & Zolochevsky, A. Description of settings and use of Moodle. *docs.altlinux.org* Retrieved from https://docs.altlinux.org/ru-RU/archive/4.1/html-single/school-server/moodle/index.html

6   Microsoft Teams. *techexpert.ua* Retrieved from https://techexpert.ua/products/microsoft-teams/

7   Archibald, M.M., Ambagtsheer, R.C., Casey, M.G., Lawless, M. (2019). Using Zoom Videoconferencing for Qualitative Data Collection: Perceptions and Experiences of Researchers and Participants. *International Journal of Qualitative Methods*, *18*, 1–8.

8   Google Meet. *gsuite.google.ru* Retrieved from https://gsuite.google.ru/intl/ru/products/meet/

9   What is Quizlet? *quizlet.com* Retrieved from https://quizlet.com/ru/teachers.

10   Wang, A.I., & Lieberoth, A. (2016) The effect of points and audio on concentration, engagement, enjoyment, learning, motivation, and classroom dynamics using Kahoot! *Proceedings of the European Conference on Games-based Learning*, (pp. 738–746).

11   Easy Test Maker. *easytestmaker.com* Retrieved from https://easytestmaker.com/

12   The Best Quiz Maker for Business & Education. *www.classmarker.com* Retrieved from https://www.classmarker.com/

13   SurveyMonkey. *www.surveymonkey.ru* Retrieved from https://www.surveymonkey.ru/

14   Badanov, A.G. Socrative Teacher manual. *docs.google.com* Retrieved from https://docs.google.com/presentation/d/11q6_blwNxL-G8A8v4Q0WAtT9qXvOHd38cqQKiEpJql8/edit#slide=id.p.

15   Garnaeva, G.I., Nizamova, E.I., & Shigapova, E.D. (2018) Information and communication technologies competence formation of the future teacher of physics. *European Proceedings of Social and Behavioural Sciences: 4th International Forum on Teacher Education (2018, September)*. (pp. 221–227).

16   Nekrasova, G.N. &Novikova, N.N. (2018) Preparing Technology Teachers for Professional Activities in the Information Space of Technological Education. *5th International Forum on Teacher Education (IFTE) (2019, May)*. (pp. 473–485).

17   Ferreira, J. (2014). Infographics: An introduction. Technical Report. Coventry University. *www.researchgate.net* Retrieved from: https://www.researchgate.net/publication/266082644

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Жоғары оқу орындарының жаратылыстану-ғылыми және техникалық мамандықтары бойынша оқитын студенттерінің зерттеушілік қабілеттіліктерін дамыту

Жоғары оқу орындарында студенттердің ғылыми-зерттеушілік іс-әрекеттілігін ұйымдастыру мәселесі өзекті міндет, себебі ол құзыретті маман даярлау кезінде маңызды құрал болып табылады. Мақала ЖОО-да студенттердің ғылыми-зерттеушілік іс-әрекеттілігін ұйымдастыру жүйесінің ерекшеліктерін зерттеуге арналған. Оқу іс-әрекеттілігімен қатар, ғылыми-зерттеушілік іс-әрекеттілік студенттердің зерттеушілік кәсіби құзыреттіліктерін қалыптастыруға ықпал етеді, ал бұл өз кезекте таңдалған мамандыққа деген қызығушылықты арттырады. Студенттердің ғылыми-зерттеушілік жұмысы болашақ мамандардың қазіргі жағдайда кәсіби ұтқырлыққа дайындығын қалыптастыруда қажетті құрамдас бөлігі болып табылады. Мақалада ғылыми-зерттеу жұмысын ұйымдастыру мәселелері қарастырылып, ЖОО-да студенттердің ғылыми-зерттеушілік іс-әрекеттілігін дамыту үшін мақсаттар мен міндеттер белгіленді. Студенттердің ғылыми-зерттеушілік іс-әрекеттілігін белсендіруге мәліметтерді модельдеу мен талдаудың заманауи компьютерлік технологияларын пайдалануымен, интерактивті әдістер ықпал етеді. Студенттер нақты мәселелерді шешуде өз білімдерін қолдана білуі, өз тәжірибесінде қолданбалы зерттеулер жүргізе білуі, жаңа стратегиялар құра білуі қажет. Зерттеу жұмысын ұйымдастырудың факультеттегі ағымдық жағдайды бағалау үшін бітіруші курс студенттері арасында сауалнама жүргізілді. Физика-техникалық факультетте жүргізілген зерттеулердің үш кезеңінің жалпыланған нәтижелері ұсынылған. Студенттер көзімен бакалавриат студенттерінің ғылыми-зерттеушілік іс-әрекеттілігін дамытудың заманауи жағдайларына бағалау жүргізілді, студенттердің ғылыми-зерттеушілік іс-әрекеттілігіне деген қызығушылығы зерттелген. Жүргізілген сауалнама нәтижелері студенттердің ғылыми-зерттеушілік іс-әрекеттілігіне айтарлықтай жоғары қызығушылығын көрсетті. Студенттерді ғылыми-зерттеушілік іс-әрекеттілігіне даярлау кезінде оқытушының рөлі және оның студенттердің ғылыми-зерттеу жұмыстарын жетекшілік етуге деген қызығушылығы маңызды екендігі көрсетілген.

Кілт сөздер: зерттеушілік қабілеттіліктер, заманауи білім беру үрдісі, зерттеушілік құзыреттілік, ғылыми-зерттеушілік жұмыс, мамандарды даярлау.

Кіріспе

Қоғам дамуының қазіргі таңдағы кезеңі адам өмірінің барлық салаларына әсер ететін өзгерістермен сипатталуда. Республикамыздағы әлеуметтік-экономикалық өзгерістерінің жылдам қарқыны, қоғамдағы құндылық бағдарларының ауысуы, ақпарат көлемінің ұлғаюы және кәсіби қызметте басқару функцияларының кеңею тенденциясы болашақ мамандарды даярлау мәселелерінде жоғары кәсіптік білім беру жүйесіне қоғамның қоятын талаптарының өзгеруіне әкелді. Болашақ маманның өмірдегі күрделі жағдайларды адекватты түрде қабылдау, оларды дұрыс бағалай білу, бар ақпаратты мақсатты түрде қайта өңдеу, жетіспейтін ақпаратты іздеу және толықтыру, өзінің зияткерлік және шығармашылық әлеуетін қолдана отырып, іс-әрекеттіліктің нәтижелерін болжау қабілеті ерекше практикалық мәнге ие болды.

Болон процесіне сәйкес жоғары білімнің бәсекеге қабілеттілігі артып отыруы тиіс, себебі білім тез ескіреді, бұл қарама-қайшылықты ілімді білім беру жүйесінің көмегімен ғана жеңуге болады. Оқытудың әрбір деңгейінде студенттердің шығармашылық ойлауын, зерттеушілік іскерлігін дамыту қажет. Осыған байланысты, ғылыми-зерттеушілік іс-әрекеттілік үлкен маңызға ие болып, болашақ маманның кәсіби даярлаудың негізгі құраушыларының біріне айналуда [1].

«Студенттердің ғылыми-зерттеушілік жұмысы» дәстүрлі түрдегі ұғымы студенттерді кафедра-лардың және зертханаларының ғылыми жұмысына, оқу-зерттеушілік жұмыстарын, курстық және дипломдық жұмыстарды орындауға, конференцияларға, семинарларға, конкурстарға, көрмелерге және т.б. қатысуға тарту формаларымен тығыз байланысты.

Көптеген авторлардың жұмыстарын талдаудан студенттердің ғылыми-зерттеушілік жұмысының тиімділігінің анықтаушы жағы оны ұйымдастыру және басқару болып табылатындығы анықталды. Жүйе ретінде студенттердің ғылыми-зерттеушілік жұмысты ұйымдастырудың жетекші принциптері — ғылыми және оқу процестерінің негізгі бірлігі, сонымен бірге осының негізінде мамандарды даярлау сапасын арттыру, ғылымның өндіріспен байланысын күшейту және т.б. болып табылады [2].

Оқу уақытының аясында оқу процесін ұйымдастырудың дәстүрлі формаларын сапаландыру кезінде студенттердің ғылыми-зерттеушілік іскерліктері мен қабілеттерін дамыту келесі дамыта оқыту құралдарын қолданған жағдайда мүмкін болады: проблемалық, зерттеушілік, жобалық және т.б. Осыған байланысты студенттерді ғылыми шығармашылыққа тартудың нысандары мен әдістерін екіге бөлуге болады:

– оқу жоспарлары мен жұмыс бағдарламаларына сәйкес оқу процесіне енгізілген және оқу уақытында жүргізілетін ғылыми-зерттеу жұмыстары;

– студенттердің сабақтан тыс уақытта жүргізілетін ғылыми-зерттеушілік жұмыстары.

Оқу үрдісінде студенттермен жүргізілетін ғылыми-зерттеу жұмыстарға курстық жұмыстарды және дипломдық жұмыстарды жатқызуға болады. Курстық жұмысты орындау кезінде студент ғылыми шығармашылыққа алғашқы қадамдарды жасайды, ғылыми әдебиеттермен жұмыс істеуге үйренеді, қажетті ақпаратты іріктеу және талдау дағдыларын меңгереді [3].

Әдістеме

Ғылыми-зерттеушілік әрекеттілік барысында студенттердің аналитикалық ойлауы күшейеді, ақпаратты іздеу және оны қолдану қабілеттері қалыптасады; жиналған материалды талдауға, есеп берулерді жазуға, зерттеу презентацияларын жасауға және т.б. үйренеді. ЖОО-да студенттердің ғылыми-зерттеушілік іс-әрекеттілігін дамыту мақсаттарын жүйелендіруге талпыныс жасадық, 1-кестеде оған сәйкесті міндеттер бөліп көрсетілген.

1 - к е с т е

ЖОО-да студенттердің ғылыми-зерттеушілік іс-әрекеттілігін дамытудың мақсаттары мен міндеттері

Мақсаттары	Міндеттері
Зерттеушілік іс-әрекеттілікке деген қабілеттіліктеріне ие дарынды студенттерді анықтау және оларды ғылыми-зерттеушілік іс-әрекеттілікке тарту	– кіші курстардың студенттері арасында факультеттегі студенттердің ғылыми үйірмелерінің, орталықтарының, зертханаларының презентацияларын жасап, таныстыру; – студенттерді ғылыми-зерттеушілік жұмысты жүргізу әдістерін қолдануға оқып-үйрету, жобалық және эксперименттік іс-әрекеттілікті іске асыру; – факультет немесе университет шеңберінде студенттер арасында ғылыми жұмыстар конкурстарын өткізу; – факультеттерде немесе университет деңгейінде студенттік ғылыми конференцияларды, пән олимпиадаларын өткізу
Студенттердің гранттық іс-әрекеттілігін жоғарылату	– әр түрлі стипендия және гранттар конкурстарына құжаттарды дайындау бойынша тренингтер жүргізу; – көпшілік алдында сөз сөйлеу мәдениеті бойынша тренингтер өткізу; – студенттерге әр түрлі гранттар мен стипендияларының өзекті конкурстары туралы үнемі хабарлау
Студенттердің жарияланымдық белсенділігін жоғарылату	– студенттерге өзекті конференциялардың өткізілуі және ғылыми еңбектер жинағын дайындауы туралы хабарламаларды жеткізу; – факультетте ғылыми мәтінді жазу технологиясы бойынша тренинг өткізу; – университеттік студенттік ғылыми басылымдар шығару
Студенттерді инновациялық іс-әрекеттілікке даярлау	– студенттерге арналған стартап-жобалар байқауларына құжаттарды дайындау бойынша тренинг жүргізу; – студенттерді қолданбалы ғылыми-жұмыстарға тарту; – студенттерді стартап–жобалар байқауларына қатыстыруды ұйымдастыру
Байланыстарды кеңейту	– әр түрлі деңгейдегі (қалалық, аймақтық, республикалық, халықаралық) ғылыми іс-шараларды ұйымдастыру; – студенттерді басқа ЖОО-дың ғылыми іс-шараларына қатыстыруды ұйымдастыру

ЖОО-да әр студенттердің ғылыми-зерттеушілік іс-әрекеттілігінің әр түрлі формалары жүзеге асырылады. Оқу жоспарлары мен бағдарламаларына сәйкес орындалатын және оқу процесіне енгізілген студенттердің ғылыми-зерттеушілік іс-әрекеттілігі келесілерден құрылады:

- ғылыми зерттеушілік элементтері бар тапсырмаларды, зертханалық жұмыстарды орындау, курстық және дипломдық жұмыстарды (жобаларды) жазу;
- оқу және өндірістік практикаларды өту кезеңінде ғылыми-зерттеушілік сипаттағы нақты тапсырмаларды орындау;
- ғылыми-зерттеулер әдістемесінің теориялық негіздерін меңгеру, ғылыми зерттеулерді ұйымдастыру және орындау, ғылыми эксперементті жоспарлау және ұйымдастыру, ғылыми мәліметтерді өңдеу.

Ал оқу процесін толықтыратын студенттердің ғылыми-зерттеушілік іс-әрекеттілігі мына түрде ұйымдастырылады:

- ғылыми-оқу зертханаларындағы, ғылыми-проблемалық және зерттеушілік топтардағы жұмыс;
- нақты ғылыми жетекшінің басшылығымен жеке ғылыми зерттеулерді орындау;
- әр түрлі деңгейдегі студенттік ғылыми іс-шараларға (ғылыми семинарлар, конференциялар, жобалар конкурстары, пәндер мен бағыттар бойынша олимпиадалар) қатысу;
- ғылыми іс-әрекеттілікке ынтасы бар студенттер топтарымен арнайы курстарды, бағдарламаларды ұйымдастыру, сабақтарды өткізу.

Физика-техникалық факультетте студенттердің ғылыми-зерттеушілік іс-әрекеттілігін ұйымдастыру үшін барлық жағдайлар жасалған деп айтуға болады. Факультетімізде көптеген озық ғылыми институттар, орталықтар мен зертханалар жұмыс істейді. Онда студенттер ғылыми-зерттеулермен айналысады, мемлекеттік грантпен қаржыландыратын ғылыми жобалар бойынша қызмет атқарады. Факультет кафедраларында ғылыми мектептер құрылған, ондаған ғылыми үйірмелер жұмыс жасауда. Ғылыми бағыттардың жетекшілері — профессорлық-оқытушылық құрамына кіретін ғалымдар болып табылады.

Нәтижелер мен оларды талдау

Төменде 2019–2020 оқу жылының аяғында физика-техникалық факультетінде жүргізілген зерттеудің үш сатысының жалпыланған нәтижелері келтірілген. Алынған нәтижелерді талдай отырып, факультеттегі жағдайларды талдау үшін сәйкесті тұжырымдамалар бөліп көрсетілді. 2-кестеде 4 курс студенттері арасында жүргізілген сауалнама нәтижелері келтірілген.

2 - к е с т е

Факультеттегі ағымдық жағдайды бағалау — студенттердің ғылыми-зерттеушілік іс-әрекеттілікке деген қызығушылығын арттыру

Тұжырымдамалар	Келісемін	Ішінара келісемін	Келіспеймін
1	2	3	4
Оқу процесінде белсенді танымдық процестер ынталандырылады: ақпаратты іздеу, нәтижені шығармашылықпен түсіндіру, рефлексия	72 %	24 %	4 %
Студенттер ғылыми-зерттеушілік іс-әрекеттілікке қатысу мүмкіндіктерімен танысады	48 %	42 %	10 %
Оқытуды ұйымдастыру формасы студенттердің ғылыми-зерттеушілік іс-әрекеттілігіне қызығушылығын анықтайды	44 %	50 %	6 %
Ғылыми-зерттеушілік іс-әрекеттілікке қызығушылық, шын мәнінде, тек міндетті оқу міндеттермен байланысты (мысалы, курстық жұмыс немесе дипломдық жұмыс)	50 %	35 %	15 %
Көбінесе зерттеулерді «ғылымға талпынған студенттер» сапалырақ жүргізеді	45 %	35 %	20 %
Студенттер ғылыми-зерттеушілік іс-әрекеттілігіне аса қызығушылық танытпайды	49 %	25 %	26 %
Студенттер ғылыми-зерттеушілік іс-әрекеттілігіне әлсіз тартылған	44 %	37 %	19 %

1	2	3	4
Студенттер пәндерді зерттеушілер ретінде зерттейді, туындаған сұрақтарға жауап іздейді.	30 %	40 %	30 %
Оқу үрдісінде студенттердің ғылыми-зерттеушілік іс-әрекеттілігіне үлкен көңіл бөлінеді	30 %	46 %	24 %
Студенттер зерттеу жобаларына қатысады	20 %	50 %	30 %
Университет студенттердің ғылыми-зерттеушілік іс-әрекеттілін көтермелейді және қолдайды	50 %	45 %	5 %
Студенттердің ғылыми-зерттеушілік іс-әрекеттілігіне деген қызығушылығы оқу бағдарламаларының шамадан тыс жүктелуімен төмендейді, себебі дағдыларды дамыту мен зерттеулерді жүргізуге аз уақыт қалады	29 %	35 %	36 %
Оқу үдерісінде студенттердің ғылыми-зерттеушілік іс-әрекеттілігі өте белсенді дамуда	13 %	43 %	44 %
Көптеген студенттер зерттеулерге қызығушылық танытады	13 %	39 %	48 %
Студенттер оқу үдерісінде ғылыми-зерттеушілік іс-әрекеттілігіне әрдайым қызығушылық танытады	10 %	40 %	40 %
Оқытушылардың көпшілігі студенттердің ғылыми-зерттеушілік іс-әрекеттілігіне тартуға қызығушылық танытпайды	40 %	30 %	30 %

2-кестедегі мәліметтер факультеттегі жағдайлардың кең спектрін қамтиды: оқу процесінің ерекшеліктері, студенттерді зерттеу жобаларына қатыстыруды ынталандыру және т.б. Кестеден көрінетіндей, студенттер ғылыми-зерттеушілік іс-әрекеттілікке деген қызығушылық көптеген факторлардан тәуелді екендігін білдірді: оқытушының өзінің студенттердің ғылыми-зерттеушілік іс-әрекеттілікке қызығушылық танытуы; факультетте тиісті жағдайлардың болуы, оқу процесінде белгілі бір әдістердің қолданылуы (проблемалық оқыту, зерттеушілік оқыту, біріккен оқыту және т.б.). 3-кестеде бакалавриат студенттерінің ғылыми-зерттеушілік іс-әрекеттілігін дамытудың заманауи жағдайларын бағалау үшін жүргізілген сауалнама нәтижелері келтірілген.

Бакалавриат студенттерінің ғылыми-зерттеушілік іс-әрекеттілігін дамытудың заманауи жағдайларын бағалау

Тұжырымдамалар	Келісемін	Ішінара келісемін	Келіспеймін
Оқытушылар студенттерге қызықтыратын зерттеу тақырыбын таңдауға көмектеседі	75 %	15 %	10 %
Студенттер ғылыми семинарларға, жобаларға, конференцияларға қатысуға мүмкіндіктері бар	89 %	9 %	2 %
Студенттердің ғылыми-зерттеушілік іс-әрекеттілігін жүргізу үшін лайықты материалдық-техникалық база бар	81 %	19	0 %
Студенттер үнемі ғылыми зерттеулерге қатысуға тартылады	48 %	44 %	8 %
Студенттердің ғылыми-зерттеу жұмыстары жақсы ұйымдастырылған	71 %	29 %	1 %
ЖОО студенттердің ғылыми-зерттеушілік, іс-әрекетілік жұмыстарына қаржы бөледі (конференцияларға іс-сапарлар және т.б.	80 %	20 %	0 %

3-кестеде келтірілген нәтижелерден студенттердің ғылыми семинарларға, жобаларға және конференцияларға қатысуға мүмкіндігі бар екенін, оқытушылар студенттерге қызықтыратын зерттеу тақырыбын таңдауға көмектесетінін көрсетті. Алынған нәтижелердің бәрі оң деп айтуға болмайды. Себебі бір фактор теріс әсер етеді деп айтуға болады: студенттер елу пайыздан жоғары бөлігі ғылыми зерттеулерге қатысуға үнемі тартылмайды деген пікірде.

4-кестеде бакалавриат студенттерінің қызығушылығы туралы жүргізілген сауалнама нәтижелері келтірілген. Сауалнамада студенттердің аты-жөндері көрсетілмеген. 4-кесте нәтижелері студенттердің ғылыми-зерттеушілік іс-әрекеттілігіне деген қызығушылықтары жеткілікті дәрежеде

екенін көрсетеді. Бірақ студенттердің 47 пайызы мұндай іс-шаралар іс жүзінде қызықтырмайтынын білдірген. Бір жағынан, мұндай студенттерді тек оқу нәтижелері, яғни оқу пәндерінен үлгерімділік қана қызықтыратынын ескеру қажет. Ал басқа жағынан студенттердің ғылыми-зерттеушілік іс-әрекеттілігіне қызығушылық танытпауының негізгі себебі — ынтаның болмауы болуы мүмкін.

4 - к е с т е

Студенттердің ғылыми-зерттеушілік іс-әрекеттілігіне деген қызығушылығын бағалау

Өте қызық	Қызық	Аздап қызығушылық таныттым	Қызығушылық жоқ
7 %	46 %	24 %	23 %

Мұндай нәтижелерге студенттерді карантин жағдайында қашықтықтан оқыту кезінде сауалнама онлайн режимінде жүргізілгені себеп болуы мүмкін. Шынында да, COVID-19 коронавирус инфекциясының пандемия салдарынан мәжбүрлі оқшаулану жағдайында және оқытушылармен, ғылыми жетекшілермен бетпе-бет сөйлесу, қатынасу мүмкін еместігі — оқу материалдарды меңгеруде, курстық және дипломдық жұмыстарды жазуда әдеттегі оқу процесіндегі жағдайлармен салыстырғанда қосымша қиындықтардың туындауына алып келді. Студенттердің ғылыми-зерттеу жұмыстарына жетекшілік ету тек онлайн режимінде жүргізілді, студенттерді алға қойған мақсаттар мен міндеттерді орындау үшін интернет-ресурстарды, компьютерлік технологияларды, оның ішінде қолданбалы бағдарламалар пакеттерін қолданды. Егер бұл факторлар қатарын ескеретін болсақ, онда сауалнама нәтижелері қанағаттанарлық деп есептеуге болады.

Сонымен бірге студенттердің ғылыми-зерттеу іс-әрекеттілігіне ықпал ететін оқытушының үлесі де бар. Ғылыми-зерттеушілік іс-әрекеттілік студенттерден еңбексүйгіштікті, шығармашылықты талап етеді. Сондықтан оқытушылардың студенттердің ғылыми-зерттеушілік қабілеттерін дамытуға қосатын үлесі өте маңызды.

Жоғары оқу орындарда студенттердің белсенді ғылыми жұмыстары үшін қолайлы жағдайлар жасалған. Студенттердің ғылыми-зерттеушілік іс-әрекеттілігіне белсенді қатысуына көптеген факторлар әсер етеді: оқу процесін ұйымдастырудағы стратегиялар мен әдістер [4–7], студенттерді ынталандыру, оқытушылардың белсенді рөлі және студенттермен ынтымақтасуға деген ұмтылысы, ғылыми-зерттеушілік іс-әрекеттілігін ұйымдастыруға арналған арнайы жағдайлар және материалдық база. Тәжірибе көрсеткендей, физика-техникалық мамандықтар студенттерінің ғылыми-зерттеушілік іс-әрекеттілігін белсендіру электронды оқу-әдістемелік құралдар, мәліметтерді өңдеудің компьютерлік технологиялары, екі және үш өлшемді модельдеудің интерактивті пакеттері және т.б. ықпал етеді. Сонымен қатар, реконструктивті-вариативті зерттеу жұмысы білім алушыға қойылған мәселені шешудің мазмұнын, мақсаттарын, міндеттерін, әдістері мен құралдарын өз бетінше анықтауға, күрделілігі жоғары есептерді шешудің стандартты емес әдістерін қолдануға мүмкіндік береді [8–11].

Студенттер жоғары білімі бар кәсіби маман болу үшін алған білімдерін практикада қолдана білуді ғана емес, сонымен бірге өзінің практикалық іс-әрекеттілігінде қолданбалы зерттеулерді жүргізе білу, жаңа стратегияларды құру, кәсіби қызметтің мәнін тереңірек білу және т.б. қажет. Ал бұл ғылыми-зерттеушілік іс-әрекеттілігімен тығыз байланысты.

Қорытынды

Сонымен, болашақ мамандарды ғылыми жұмысқа даярлау процесі студенттерді ғылыми-зерттеушілік іс-әрекеттілігінің әр түрлі формаларына қатыстырған жағдайда тиімді болады. Сондықтан оқу процесінде студенттерді ғылыми іс-әрекеттілікке тарту жүйелі және мақсатты түрде жүзеге асыру қажет, ғылыми мәселелерді шешу кезінде студент-зерттеушілердің шығармашылық іс-әрекеттілігін және дербестігін көтермелеп, қолдау қажет.

Оқытушылар студенттерді зерттеу жұмыстары мен жобаларына қатыстыруға өздері қызығушылық танытуы тиіс. Оқытушылар мен студенттердің арасында ғылыми ынтымақтастықты дамыту маңызды, себебі соның нәтижесінде студенттер ғылыми зерттеулерге белсенді қатысу, тәжірибе жинау мүмкіндіктеріне ие болады. Бұл студенттердің ынтасын арттырады. Оқу процесінде студенттер ғылыми шындықты тану әдісін игеруге көмектесетін қосымша тапсырмаларды орындау қажет: талдау, жалпылау, жүйелеу, ойлау, болжам жасау және жауап іздеу.

Инновациялық үрдістерді ескере отырып, кафедра мен ЖОО-ның қызметін ұйымдастыру, студенттердің ғылыми-зерттеу жұмысын ұйымдастыру кезінде тұлғаға бағытталған тәсілді және жүйелі қызметті пайдалану, білім алушылардың жетістіктеріне тұрақты мониторинг жүргізу студенттердің белсенділігін арттыруға, олардың ғылыми қызметтің әр түрлі түрлеріне қатысуына ықпал етеді, жағымды жеке уәждеменің және кәсіби өзін-өзі дамытуға мүдделіліктің өсуіне әкеледі.

Әдебиеттер тізімі

1 Вакуленко В.О. Роль научно-исследовательской работы студентов вуза в подготовке будущих специалистов / В.О. Вакуленко // В лабораторию ученого. — 2015. — С. 95–100.

2 Демченко З.А. Научно-исследовательская школа студента-исследователя / З.А. Демченко // Высшее образование в России. — 2010. — № 12. — С. 155–158.

3 Ефанов А.В. Организация научно-исследовательской работы студентов в вузе: учеб.-метод. пос. / А.В. Ефанов, В.А. Федоров, Л.С. Приходько, А.С. Зуева, К.В. Комарова; науч. ред. В.А. Федоров. — Екатеринбург: Изд-во ГОУ ВПО «Рос. гос. проф.-пед. ун-т», 2009. — 144 с.

4 Мусабекова А.М. Оқушылардың функционалдық сауаттылығын дамытуға бағытталған физиканы оқытудағы инновациялық тәсілдер / А.М. Мусабекова, Р.И. Жуманова, Ж.Т. Камбарова // Қарағанды ун-тінің хабар. Физика сер. — 2015. — № 2(72). — Б. 92–98.

5 Мусенова Э.К. Эффективность использования электронных ресурсов на уроках физики / Э.К. Мусенова, Т.Е. Сейсембекова, А.С. Утепова, Б.И. Казанкап // Вестн. Караганд. ун-та. Сер. Физика. — 2015. — № 3(79). — С. 116–121.

6 Сақыпова С.Е. «Газ заңдары» тақырыбын оқытуда инновациялық технологияларды қолдану әдістемесі / С.Е. Сақыпова, Р.И. Жұманова, Ж.Т. Қамбарова, Ф.Б. Әбілжанова // Қарағанды ун-тінің хабар. Физика сер. — 2011. — № 3(63). — Б. 57–63.

7 Sakipova Sh.E. Innovative and educational technologies applied in high education as objective reality / Sh.E. Sakipova // Journal of International Scientific Publications. Bulgaria. — 2013. — Vol. 11. — P. 116–120.

8 Польшакова Н.В. Организация научно-исследовательской работы студентов [Электронный ресурс] / Н.В. Польшакова, Е.В. Александрова // Современные проблемы науки и образования. — 2020. — № 5. — URL: https://science-education.ru/ru article/view?id=30112. DOI 10.17513/spno.30112

9 Камбарова Ж.Т. Күрделілігі жоғары есептерді шығару әдістемесі. Молекулалық физика және термодинамика: оқу құр. / Ж.Т. Камбарова. — Қарағанды: ҚарМУ баспасы, 2019. — 153 б.

10 Камбарова Ж.Т. Физика сабақтарында құзыреттілікті — бағдарланған әдіс — тәсілді қолдану ерекшеліктері / Ж.Т. Камбарова, С.Е. Сакипова, Қ.Б. Копбалина, П.А. Жанбирбаева // Хаос и структуры в нелинейных системах. Теория и эксперимент: материалы XI Междунар. науч. конф. (22–23 ноября 2019 г.). — Караганда: Изд-во КарГУ, 2019. — С. 404–407.

11 Шуюшбаева Н.Н. Физикадан компьютерлендірілген зерттеу жұмыстарын ұйымдастыру / Н.Н. Шуюшбаева, Р.Г. Қожабаев, А.А. Мейрманова, т.б. // Хаос и структуры в нелинейных системах. Теория и эксперимент: материалы XI-й Междунар. науч. конф. (22–23 ноября 2019 г.). — Караганда: Изд-во КарГУ, 2019. — С. 431–435.

С.Е. Сакипова, Ж.Т. Камбарова, Н.К. Танашева, Ш.Е. Сакипова

Развитие исследовательских способностей студентов естественнонаучных и технических специальностей вузов

Проблема организации научно-исследовательской деятельности студентов в вузах выступает актуальной задачей, так как является важнейшим инструментом при подготовке компетентного специалиста. Статья посвящена изучению особенностей системы организации научно-исследовательской деятельности студентов в вузе. Наряду с учебной, научно-исследовательская деятельность способствует формированию исследовательских профессиональных компетенций студентов, что формирует повышение интереса к выбранной профессии. Научно-исследовательская работа студентов является необходимой составляющей в формировании готовности будущих специалистов к профессиональной мобильности в современных условиях. В статье рассмотрены проблемы организации научно-исследовательской работы, выделены цели и задачи для развития научно-исследовательской деятельности студентов в вузе. Активизации научно-исследовательской деятельности студентов способствуют интерактивные методы с использованием современных компьютерных технологий моделирования и анализа данных. Студентам необходимо уметь применять свои знания при решении конкретных задач, проводить прикладные исследования в своей практике, создавать новые стратегии. Для оценки текущего состояния организации исследовательской работы на факультете проведен опрос среди студентов выпускного курса. Представлены обобщенные результаты трех этапов исследований, проведенных на физико-техническом факультете. Дана оценка современных условий развития научно-исследовательской деятельности студентов бакалавриата глазами студентов, изучен интерес студентов к научно-исследовательской деятельности. Результаты проведенного опроса показали достаточно

высокую заинтересованность студентов к научно-исследовательской деятельности. Показано, что при подготовке студентов к научно-исследовательской деятельности важна роль преподавателя и его заинтересованность в руководстве научно-исследовательской работой студентов.

Ключевые слова: исследовательские способности, современный образовательный процесс, исследовательская компетентность, научно-исследовательская работа, подготовка специалистов.

S.E. Sakipova, Zh.T. Kambarova, N.K. Tanasheva, Sh.E. Sakipova

Development of research abilities of students of natural-scientific and technical specialties of universities

The problem of organization the research activities of students in universities is an relevant objective, since it is the most important tool in the preparation of a competent specialist. The article is devoted to the study of the features of the system of organization the research activities of students at the university. Along with educational activities, research activities contributes to the formation of research professional competencies of students, to an increase in interest in the chosen profession. The research work of students is a necessary component in the formation of the readiness of future specialists for professional mobility in modern conditions. The article discusses the problems of organizing research work, identifies purpose and objectives for the development of research activities of students at the university. Interactive methods by using modern computer technologies for modeling and data analysis contribute to the revitalization of students' research activities. Students need to be able to apply their knowledge in solving specific problems, conduct applied research in their practice, and create new strategies. For assess the current state of the organization of research work at the faculty, a survey was conducted among graduate students. The generalized results of three stages of research carried out at the Faculty of Physics and Technology are presented. The assessment of the modern conditions for the development of research activities of undergraduate students by the eyes of students is carried out, the interest of students in research activities is studied. The results of the survey showed a rather high interest of students in research activities. It is shown that in preparing students for research activities, the role of the teacher and his interest in academic advising of students' research work are important.

Keywords: research abilities, modern educational process, research competence, scientific research work, training of specialists.

References

1   Vakulenko, V.O. (2015). Rol nauchno-issledovatelskoi raboty studentov vuza v podhotovke budushchikh spetsialistov [The role of research work of University students in training future specialists]. *V laboratoriiu uchenoho — To the scientist's lab,* 95–100 [in Russian].

2   Demchenko, Z.A. (2010). Nauchno-issledovatelskaia shkola studenta-issledovatelia [Research school of the research student]. *Vysshee obrazovanie v Rossii — Higher education in Russia, 12*, 155–158 [in Russian].

3   Efanov, A.V., Fedorov, V.A., Prikhodko, L.C., Zueva, A.C., & Komarova, K.V. (2009). Orhanizatsiia nauchno-issledovatelskoi raboty studentov v vuze [Organization of research work of students at the University]. Ekaterinburg: Izdatelstvo HOU VPO «Rossiiskii hosudarstvennyi professionalno-pedahohicheskii universitet» [in Russian].

4   Musabekova, A.M., Zhumanova, R.I., & Kambarova, Zh.T. (2015). Oqushylardyn funktsionaldyq sauattylygyn damytuga bagyttalgan fizikany oqytudagy innovatsiialyk tasilder [Innovative approaches to the teaching physics aimed to the development of functional literacy of pupils]. *Qaragandy universitetinin khabarshysy. Fizika Seriiasy — Bulletin of the university of Karaganda — Physics, 2(78)*, 92–98 [in Kazakh].

5   Mussenova, E.K., Seisembekova, T.E., Utepova, A.S., & Kazankap, B.I. (2015). Effektivnost ispolzovaniia elektronnykh resursov na urokakh fiziki [Efficiency of the use of electronic resources on lessons of physics]. *Vestnik Karahandinskoho universiteta. Seriia Fizika — Bulletin of the university of Karaganda — Physics, 3(79)*, 116–121 [in Russian].

6   Sakipova, Sh.E., Zhumanova, R.I., Kambarova, Zh.T., Abilzhanova, F.B. (2011). «Gaz zandary» taqyrybyn oqytuda innovatsiialyq tekhnologiialardy qoldanu adistemesi [Methodology of application of innovative technologies in teaching the topic «Gas laws»]. *Qaragandy universitetinin khabarshysy. Fizika Seriiasy — Bulletin of the university of Karaganda — Physics,* 3(63), 57–63 [in Kazakh].

7   Sakipova, Sh.E. (2013). Innovative and educational technologies applied in high education as objective reality. *Journal of International Scientific Publications. Bulgaria, 11*, 116–120.

8   Polshakova, N.V., & Aleksandrova, E.V. (2020). Orhanizatsiia nauchno-issledovatelskoi raboty studentov [The organization of scientific-research work of students]. *Sovremennye problemy nauki i obrazovaniia — Modern problems of science and education, 5*. Retrieved from: https://science-education.ru/ru article/view?id=30112. DOI 10.17513/spno.30112 [in Russian].

9   Kambarova, Zh.T. (2019). *Kurdeliligi zhogary esepterdi shygaru adistemesi. Molekulalyk fizika zhane termodinamika [Methodology for solving problems of high complexity. Molecular physics and thermodynamics]*. Qaragandy: QarMU baspasy [in Kazakh].

10   Kambarova, Zh.T., Sakipova, S.E., Kopbalina, K.B., & Zhanbirbaeva, P.A. (2019). Fizika sabaqtarynda quzyrettilikti — bagdarlangan adis-tasildi koldanu erekshelikteri [Features of using a competency-oriented approach in physics lessons]. Proceedings

from Chaos and structures in nonlinear systems. Theory and experiment: *11 Mezhdunarodnaia nauchnaia konferentsiia (22–23 noiabria 2019 hoda) — 11th International scientific conference (November, 22–23, 2019)* (p. 404–407). Karaganda: KarSU [in Kazakh].

11 Shuiushbaeva N.N., Kozhabaev R.G., Meirmanova A.A. Fizikadan kompiuterlendirilgen zertteu zhumystaryn uiymdastyru [Organization of computerized research work in physics]. Proceedings from Chaos and structures in nonlinear systems. Theory and experiment: *11 Mezhdunarodnaia nauchnaia konferentsiia (22–23 noiabria 2019 hoda) — 11th International scientific conference (November, 22–23, 2019)* (p. 431–435). Karaganda: KarSU [in Kazakh].

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