Technological Efficiency of Different Moisture Concentrators and their Influence on the Intensity of Precipitation Formation for the Purpose of Protecting Wind Turbine Blades

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Abstract
The global wind energy industry is characterized by rapid growth, consisting in technical and technological improvement of wind energy systems. An urgent task is to increase the reliability and efficiency of wind turbines operating in difficult external meteorological conditions. In this paper, an assessment of adverse meteorological phenomena that can reduce the energy potential of the air flow, disrupt the operation of wind turbines (cause erosion, icing on the blades), thereby reducing the resource of the blades. One of the determining atmospheric phenomena that has a significant impact on the performance and service life of wind turbines is precipitation. In the presence of precipitation in the form of rain, snow, hail, fog, the air flow can be considered dispersed and special approaches to modeling dispersed flows can be used. A study of the icing process of the surface of wind turbine blades was carried out in the Star-CCM+ hydrodynamic modeling package using the Dispersed Multiphase and Multiphase Interaction models based on mathematical modeling and numerical calculation methods. The influence of various moisture concentrators on the processes of precipitation formation intensification is considered in order to reduce the negative impact on wind turbine blades.

Keywords: Precipitation, Wind Turbine Blade, Dispersed Flow, Multiphase Interaction

1. Introduction
One of the most important tasks of researchers in wind energy today is to solve the problem of "icing" and erosion of wind turbine blades. Modern wind turbines with a height of 200 meters and higher can reach low stratus clouds, which can lead to atmospheric icing and the formation of ice on the wind turbines surfaces. The problem of icing of the blade surface remains relevant, the issues of protecting blades from icing are devoted to the works [1].

Icing of the working blades has an extremely negative effect on the operation of wind turbines, there is a deterioration in the aerodynamic characteristics of the blade, an increase in the mechanical load on the blades and abnormal vibration, a decrease in the output power of the wind turbine, which ultimately causes significant economic losses and reduces the service life of the wind turbine components. According to estimates [2], reducing the power of a wind turbine can reach up to 30%. In addition, there is a problem with the safety of the operation of wind turbines, ice falling from the surface of the blades can seriously injure people.

Currently, anti-icing methods are mainly divided into active and passive [1]. Active anti-icing methods include blade heating, mechanical anti-icing, chemical anti-icing, physical anti-slip, etc. Passive methods include the use of special anti-icing coatings. For example, in [3, 4] it is proposed to protect blades from icing by applying special hydrophobic anti-icing coatings to the surface to change the physicochemical properties of the blade surfaces, for example, an E51 mixture with the addition of spherical SiO2 nanoparticles, spraying antifreeze, which can lower the freezing temperature and reduce the adhesion strength of ice to the surface. Several passive bionic methods are known for the application of blade protection, such as borrowing the non-wetting properties of lotus leaves, butterfly wings, shark scales and duck feathers, for example in [5, 6].

Recently, as the size of wind turbine blades increases, and as a result, the peripheral speed of rotation of the blade tips, the erosion of their leading edge due to the impact of raindrops has become quite a serious problem. Rain erosion occurs due to the summation of the free fall speed of a drop and the rotation speed of the blades; at the moment of impact with the leading edge of the blade, the speed can reach 250-300 km/h. At the same time, this impact falls on a rather small area, so at the moment of impact there is a strong pressure on the blade edge. Erosion of the leading edge of wind turbine blades is a major factor in the loss of energy production by wind farms and maintenance costs [5]. One of the methods for combating erosive processes is nanocomposite epoxy coatings reinforced with fillers from Al_2O_3, ZrO_2 and CeO_2 nanoparticles [3]. In [7, 8], a 5 W wind turbine and the effect of rain erosion on it were experimentally studied. The erosion of the leading edge of the blade resulted in an annual loss of energy production of up to 4%, and the first failure of the wind turbine due to erosion was observed after 2 years [7].

Due to the significant dependence of the efficiency of wind turbines and wind farms in general on physical processes occurring in the atmosphere, it is necessary to analyze hazardous meteorological phenomena and the possibility of their control. A promising method of influencing hydrometeorological processes is artificial management of precipitation in the wind farm location area. The impact can be carried out by introducing moisture concentrators into clouds using aircraft or ground methods to control the precipitation zone and its amount. It is known that by creating additional ice crystals in clouds (cloud seeding), it is possible to control cloud development, either increasing the efficiency of precipitation processes or reducing them [9]. Currently, a large number of substances and chemical compounds are known that can be used to influence supercooled clouds, such as coolants (carbon dioxide CO_2, liquid nitrogen N_2), ice-forming reagents (silver iodide AgI), hygroscopic reagents (sodium chloride NaCl), coarse powder reagents (construction cement, diatomite, bentonite, white clay, copper oxide, sand). This approach has found application in precipitation management tasks for crop preservation, fire extinguishing [7], but there is virtually no information on the use of the artificial precipitation management method in the wind energy industry. In this regard, it is necessary to study the effect of various moisture concentrators on precipitation processes and perform a comparative analysis of their effectiveness in reducing the negative impact of precipitation on wind turbine blades.

2. Unfavorable Meteorological Phenomena for Wind Power Facilities

An assessment of adverse meteorological phenomena that may disrupt the operation of the wind farm and adjust load schedules has been made. The following meteorological phenomena have been identified:

(1) Very strong wind, squall. When the wind speed during gusts reaches at least 25 m/s, or an average speed of at least 20 m/s (35 m/s and 30 m/s, respectively, for mountainous areas and sea coasts). A critical load on the blades occurs, an emergency shutdown of the wind farm is carried out;

(2) Hurricane wind. Wind, when reaching a speed of 33 m/s or more, exerts a critical load on the blades, mast, and connecting parts. An emergency shutdown and unscheduled inspection of wind turbines is required;

(3) Large hail. If hail with a diameter of 20 mm or more falls, deep erosion of the surface of the hub and blades of the wind turbine may occur;

(4) Severe sandstorm. When sand or dust is carried by a strong wind (at least 15 m/s) and the meteorological visibility is no more than 500 m for at least 12 hours, erosion of the surfaces of the wind turbine blades may occur;

(5) Heavy ice and frost deposits. When ice appears - more than 5 mm thick, rotor imbalance, vibration, ice damage, erosion of the blade surface may occur;

(6) Severe frost/heat. If during the corresponding periods for 5 days or more the value of the average daily air temperature is lower/higher than the climatic norm by 7 °C or more, degradation of composite materials (blades) and a reduction in their service life are possible;

(7) Rain, freezing rain. As a result of prolonged rain exposure to the leading edges of wind turbine blades, rain erosion on the surface of the blades may occur. This type of erosion is underestimated and less studied.

3. Mathematical Modeling of the Blade Surface Icing Process

When a wind turbine rotates under the influence of an oncoming air flow containing droplets of supercooled liquid water, the droplets can hit the blade surface and form layers of ice. In this paper, icing of the blade surface of the Vestas wind turbine is simulated using the STAR-CCM+ software. The Dispersed Multiphase model was used to simulate liquid droplets.

Physical statement of the problem: an unsteady, turbulent, two-phase flow of a viscous incompressible flow in a rectangular tunnel with a three-bladed horizontal wind turbine is considered. The length of the tunnel before the wind turbine is 360 m, after the wind turbine - 360 m. The radius of the wind turbine is 60 m. The thermophysical properties of the carrier medium are constant: density $\rho = 1.176$ kg/m^3; kinematic viscosity $\nu = 1.576 \cdot 10^{-5}$ m^2/s; Prandtl number Pr = 0.712. Initial temperature 258.4 K, constant flow velocity u = 12.9 m/s. Thermophysical properties of the dispersed phase are also constant: density $\rho = 997.1$ kg/m^3; kinematic viscosity $\nu = 0.862 \cdot 10^{-6}$ m^2/s; Prandtl number Pr = 6.07.

A single turbulence model is used to calculate the turbulence of all phases by solving the turbulence quantity transport equations using mixture properties and mixture velocities. To simulate the turbulent flow regime of the carrier medium in the area of the wind turbine, a $k-\varepsilon$ mixture turbulence model was used to take into account the influence of wind turbines according to [10].

The transport equations for the mixture turbulent kinetic energy and the mixture turbulent dissipation rate are given by:

$$\frac{\partial}{\partial t}(\rho_m k_m) + \nabla \cdot (\rho_m k_m \bar{v}_m) = \nabla \cdot \left[\left(\mu_m + \frac{\mu_m'}{\sigma_k} \right) \nabla k_m \right] + P_m^k - \rho_m (\varepsilon_m - \varepsilon_0) + S_m^k \quad (1)$$

$$\frac{\partial}{\partial t}(\rho_m \varepsilon_m)+\nabla\cdot(\rho_m \varepsilon_m \bar{v}_m)=\nabla\cdot\left[\left(\mu_m+\frac{\mu_m^{'}}{\sigma_\varepsilon}\right)\nabla\varepsilon_m\right]+\left[\frac{1}{t_m^e}C_{\varepsilon 1}P_m^\varepsilon-C_{\varepsilon 2}f_2\rho_m\left(\frac{\varepsilon_m}{t_m^e}-\frac{\varepsilon_0}{t_m^0}\right)+S_m^\varepsilon\right] \quad (2)$$

where ρ_m is the mixture density, kg/m^3; k_m is the turbulence kinetic energy, m^2/s^2; $\bar{v}_m$ is the average mixture velocity, m/s; μ_m is the mixture turbulent eddy viscosity, Pa·s; $\mu_m^{'}$ is the phase turbulent viscosity, Pa·s; P_m^k, P_m^ε are the turbulence energy generation, m^2/s^3; t_m^e is the mixture large eddy time scale.

To simulate liquid droplets of the dispersed phase, the Dispersed Multiphase model integrated into the Star-CCM+ was used in combination with the Eulerien phase. The Fluid Film model was used to simulate the liquid film formation on the surface, the Multiphase Interaction model was used to model the interphase interaction, and the melt-solidification model was used to simulate the ice growth on a three-dimensional rotating blade. In this case, the continuous phase of the airflow interacts with the dispersed phase through drag force and heat transfer, and the dispersed phase interacts with the liquid film phase through impact. The Morpher tool is used to adapt the computational grid to the thickening of the ice on the blade surface. When simulating the ice thickness growth, STAR-CCM+ calculates the solidified film (ice) thickness at each time step.

Figure 1 shows the area where droplets impact the leading edge of a wind turbine blade, as well as the total amount of ice formed on the leading-edge surface of the blade.

The results show that blade icing occurs linearly along the span direction and is mainly concentrated on the leading edge of the blade, the thickness of the formed ice was about 2 cm. Figure 1 shows a scene with a color indication of the area where water droplets hit the surface, the maximum impingement rate was observed on the leading edge of the blade. Analyzing the dynamic parameters of the wind turbine, it can be noted that after icing, the lift coefficient decreases up to three times.

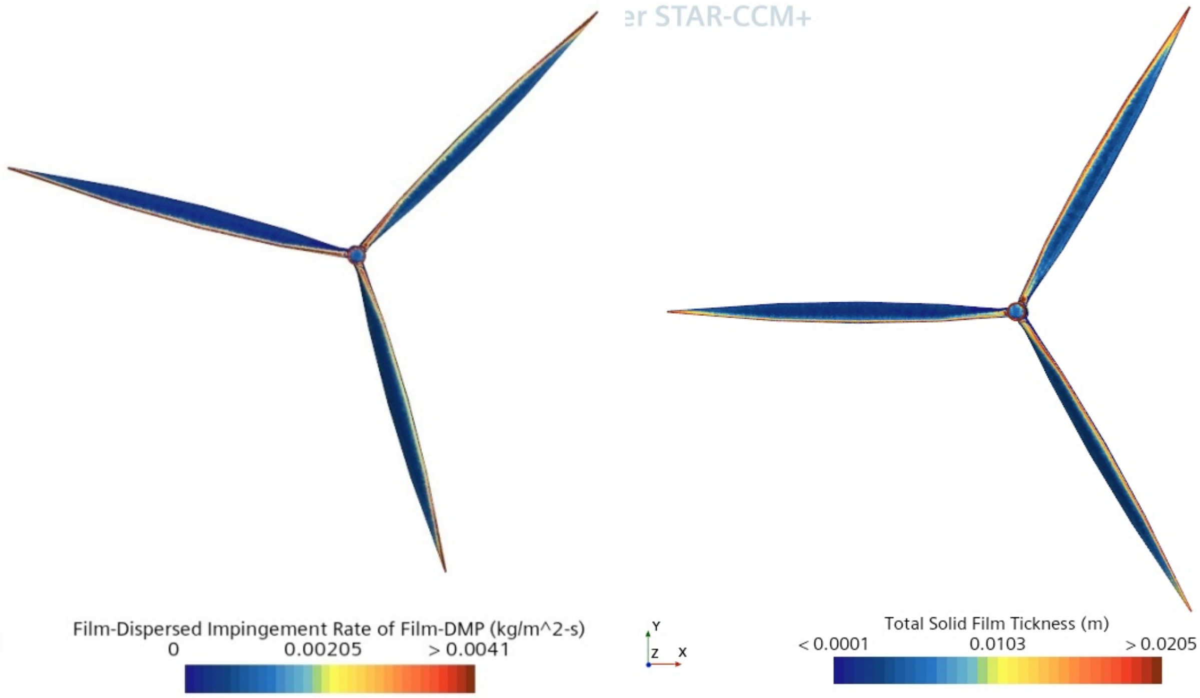

Figure 1: Results of modeling the icing process of wind turbine blades

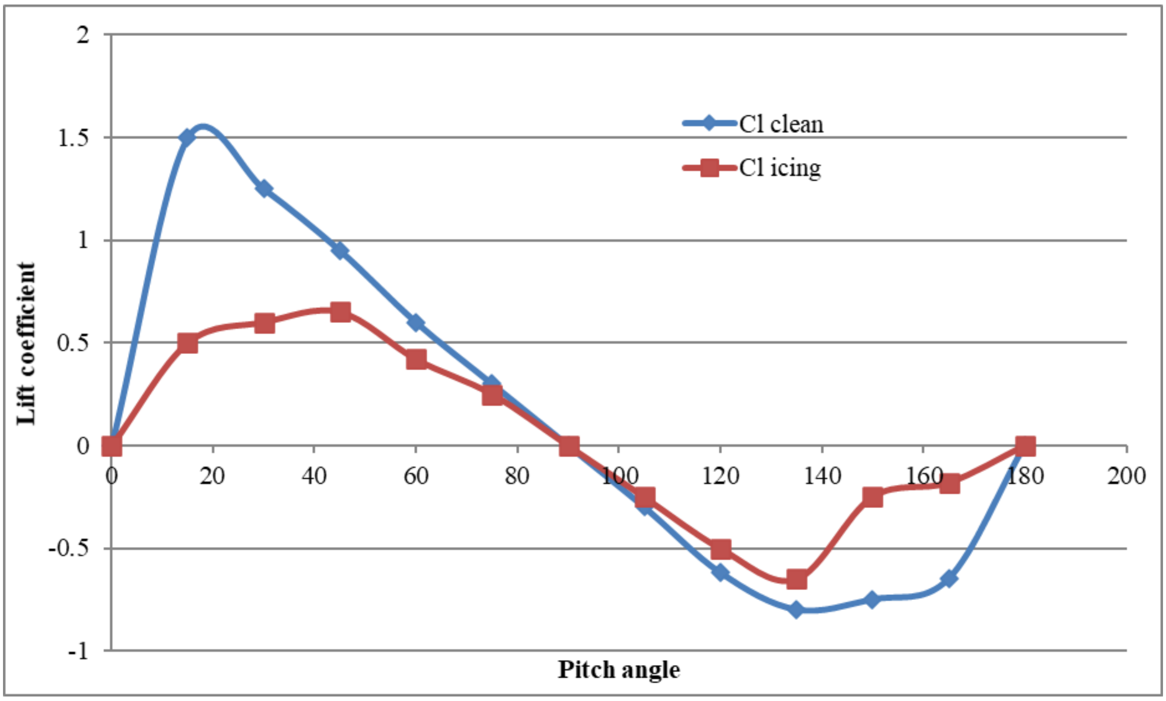

Figure 2: Blade lift coefficient with and without icing

Ice formation on wind turbine blades changes the aerodynamic properties of the blade, causing a more than threefold decrease in lift, which leads to a decrease in output power, thereby causing the wind turbine to stop working in more serious cases, which ultimately leads to significant economic losses. In this case, an artificial method of influencing precipitation processes in the area of wind turbines will solve a number of problems associated with the adverse effects of precipitation on the operation of wind turbines.

4. The Influence of Various Moisture Concentrators on the Processes of Sedimentation Intensification

The main condition for the possibility of implementing the precipitation management process is the existence of instability in the atmosphere during the development of physical processes. In most cloud structures, the formation of precipitation particles occurs ineffectively, while the mechanisms of particle thickening and the transition of one phase state of matter to another occurring in clouds can be used to regulate the processes of cloud and precipitation formation depending on the tasks being solved [7, 8].

Currently, there are many substances that can be used as moisture concentrators (reagents) for artificial precipitation management in cloud structures. According to the mechanism of ice particle formation, they can be divided into two main classes: coolants (substances that lower the temperature of the cloud environment, which leads to the formation of ice crystals) and ice-forming reagents (substances that create ice crystals directly on their aerosol particles in a supercooled cloud environment).

The principle of operation of refrigerants is based on their evaporation and the creation of strong cooling inside the cloud. During the evaporation of 1 g of solid carbon dioxide, more than a thousand ice particles are generated. In this case, the temperature threshold of solid carbon dioxide activity is -3 ... - 4 °C. Solid carbon dioxide is used mainly in the form of granules with a diameter of 8-10 mm and a length of 10-30 mm.

The amount of silver iodide AgI ice particles formed depends on the temperature and the amount of reagent introduced. The temperature threshold for silver iodide activity is 4–6 °C. Cloud seeding is performed from aircraft using specially developed pyrotechnic cartridges. The ice-forming activity of pyrotechnic compositions is more than five thousand nuclei per 1 g at a temperature of –10 °C. One pyrotechnic cartridge contains on average 30–50 g of pyrotechnic composition.

The introduction of a coarsely dispersed aerosol of insoluble substances into an unstable stratified cloud creates conditions for the development of coagulation. The interaction of reagent particles with cloud elements leads to the formation of a significant number of large particles (10 kg of reagent contains about a thousand particles with sizes from 5 to 80 µm). To create a downward flow in convective clouds with a height of 5 to 12 km, 10 to 100 kg of coarsely dispersed and highly dispersed powdered reagent are required.

One of the fundamental moments that largely determines the implementation of the IUO procedure is the choice of clouds. Natural precipitation is produced by clouds of the Ns (stratus-nimbi)–As (altostratus) type at a temperature of –4 °C and below and a thickness of 100 m. Clouds of the Sc (stratus-cumulus), St (stratus), Ac (altocumulus) types do not produce precipitation, but can be used for seeding for the purpose of precipitation formation if they have a temperature of –4 °C and a sufficient amount of moisture to start the process. In this case, their thickness should be at least 500 m.

Thus, an increase in precipitation during seeding is observed only if it coincides with the period of development of a cloud region with a stable ascending flow. Cloud seeding can lead to the opposite effect during dissipation of the cloud cell.

As a result of studying cloud structures and conducting various experiments on cloud dispersion, it was found that it makes sense to influence only Ns–As clouds with a thickness of more than 500–700 m and a water content of more than 100 g/m².

The water content of a cloud can be determined using the formula:

$$q = W \Delta H \qquad (3)$$

where W is the water content, g/m^3, and ΔH is the thickness (power) of the cloud layer, m.

The conducted research allowed to develop clear rules for the use of artificial precipitation, which led to the creation of a regulatory document. In accordance with this document, the amount of precipitation is determined numerically by the formula:

$$Q = \frac{4}{3}\left(\pi \rho_{H_2O} r_k^3 N\right) \qquad (4)$$

where ρ_{H_2O} is the density of water, kg/m^3; r_k is the radius of a drop when it falls from a cloud, µm; N is the number of reagent particles per 1 cm^2 of cloud area.

The dependence of the amount of precipitation on the reagent concentration is shown in Figure 3.

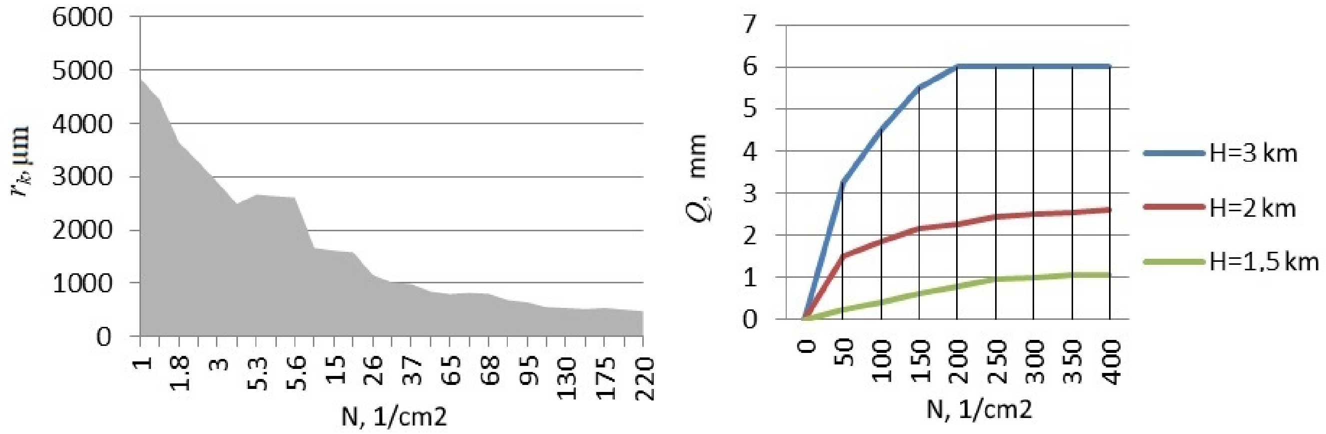

Figure 3: Dependence of the amount of precipitation on the concentration of introduced particles for different sizes of precipitation drops from the cloud r_k, and for different cloud altitudes H

5. Conclusions

This article assesses adverse meteorological events that can disrupt the operation of wind turbines; the Star-CCM+ hydrodynamic modeling package investigates the icing process of wind turbine blade surfaces and shows a more than threefold decrease in the blade lift coefficient in the presence of icing on the surface. The authors conduct a comparative analysis of methods for actively influencing hydrometeorological processes by artificially managing precipitation in the area of a wind turbine, and also consider the effect of various moisture concentrators on precipitation processes and compare their effectiveness in reducing the negative impact on wind turbine blades.

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References

1. Narges Tabatabaei Impact of Icing on Wind Turbine Aerodynamics. Fluid Mechanics. Luleå University of Technology Department of Engineering Sciences and Mathematics Division of Fluid and Experimental Mechanics. December 2018, 226 p.
2. Zhi Xu Numerical Simulation of Icing Characteristics on a Blade Airfoil for Vertical-axis Wind Turbine under Various Icing Conditions. Wind Turbine Icing, 2023, 18 p. DOI: https://doi.org/10.5772/intechopen.112398
3. Lin-Bo Zhang, Han-Xuan Zhang Nano-silica anti-icing coatings for protecting wind-power turbine fan blades. Journal of Colloid and Interface Science 630 (22). 2023, 1-10
4. Zhiyuan Liu, Yingwei Zhang Superhydrohobic coating for blade surface ice-phobic properties of wind turbines: review. Progress in Organic Coatings. V. 187, 2024. 108-145
5. U. Haryanto, R.D. Goenawan, D. Harsanti. Development of Hygroscopic Cloud Seeding Flare in Indonesia // 10 WMO Sci. Conf. on Weather Modification, Bali Indonesia, 4–7 October 2011.
6. Belyaev V.P., Zasepina L.P. Some Results of Experiments on the Destruction of Multicellular Convective Clouds. Works of the CAO. 1987, V. 164, 3-10.
7. Alessio Castorrini, Valerio F. Barnabei Impact of meteorological data factors and material characterization method on the predictions of leading edge erosion of wind turbine blades. Alessio Castorrini. Renewable Energy 227. 2024, 18 p.
8. Javier Contreras, Athanasios Kolios A wind turbine blade leading edge rain erosion computational framework. Renewable Energy 203 (10). 2022, 20 p.
9. Kachurin L.G. The Physical Basis of the Impact on Atmospheric Processes. – L.: Gidrometeoizdat. 1990. – 336 p.

10. Kornilova M.I., Kovalnogov V.N., Fedorov R.V. Numerical Study of the Atmospheric Boundary Layer and Aerodynamic Wakes in the Wind Farm Area. Modern High-tech Technologies. 2024. – №5, 50-56.