

ABSTRACT
for the doctoral dissertation (PhD)
in the educational program “8D07103 –Thermal Power Engineering”

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“Improving the Corrosion Resistance of Boiler Heating Surfaces by Applying Cr_3C_2 -
NiCr-Based Coatings”

General description of the work. The dissertation is devoted to the production of Cr_3C_2 -NiCr protective coatings using detonation spraying and the investigation of their structural-phase state and tribological properties depending on process conditions. The work also presents the results of numerical modeling of the thermal state of boiler tubes and experimental studies confirming the effectiveness of the coatings under high-temperature operating conditions.

Relevance of the topic. Kazakhstan’s energy sector will remain closely tied to the use of coal in the coming years, with proven reserves amounting to 34 billion tons (approximately 4% of global reserves). Coal plays a leading role in the country’s fuel and energy balance, with 79% of electricity generated at thermal power plants (TPPs). More than half of the equipment at thermal power plants in the Republic of Kazakhstan has been in operation for over 30 years, leading to an increase in the number of failures due to equipment obsolescence. The main causes of boiler unit failures are pipe surface damage due to heating, which accounts for up to 70% of all damage. Heated surfaces operate under extreme conditions involving high temperatures (up to 600–1,200 °C), aggressive gaseous environments, and abrasive ash particles, which cause intense processes of high-temperature corrosion, erosion, and thermal cycling damage. The primary cause of degradation in superheater tubes made of heat-resistant steels (12KH1MF, 15KH5M, 20X3MVF, etc.) is the combined effect of oxidation and sulfidation processes occurring on their outer surface upon contact with fuel combustion products. These products contain sulfur, chlorine, vanadium, and alkali metals, which lead to accelerated degradation of the pipe material. At temperatures above 410–550 °C, loose multilayer oxide films form on their surfaces, losing their protective properties, which leads to accelerated growth of corrosion pits and metal loss.

One promising approach to improving the performance and service life of outdated equipment is the application of protective composite coatings on boiler heating surfaces. Of particular interest are Cr_3C_2 -NiCr coatings applied by gas-thermal methods, which provide reliable protection of steels against gas corrosion, sulfidation, and oxidation at temperatures up to 900–1000 °C. Despite numerous studies of the thermophysical properties of heat-resistant materials, no effective technology has yet been developed for applying protective coatings that improve the performance characteristics of heating surfaces in boiler units using non-combustible fuel. At the same time, the operational properties of heat-resistant steels used for pipe manufacturing have been studied in considerable detail, whereas the processes of heat conduction and degradation of pipes with protective coatings remain insufficiently studied. Research in this area is a pressing task closely linked to improving the

energy efficiency and reliability of boiler units. In this regard, conducting research aimed at studying the thermal conductivity, degradation, and improving the effectiveness of protective coatings for boiler unit components is a pressing task.

Thesis objective: to improve the operational properties of heating surfaces in TPP boiler units by developing and scientifically substantiating a technology for applying protective detonation coatings of $\text{Cr}_3\text{C}_2\text{-NiCr}$ with a gradient structure.

Research objectives:

- Development of a process for applying detonation-resistant coatings and investigation of the thermophysical and physicomachanical properties, structure, and characteristics of the resulting $\text{Cr}_3\text{C}_2\text{-NiCr}$ coating.

- Conducting electrochemical tests of protective coatings in aggressive environments and evaluating their corrosion resistance.

- Development of a prototype experimental test bench simulating the operating conditions of the radiation-convection section of a boiler and obtaining test results on the high-temperature oxidation of protective coatings;

Research object: $\text{Cr}_3\text{C}_2\text{-NiCr}$ detonation coatings on the surface of 12X1MF steel.

Research topic: Corrosion and thermophysical characteristics of boiler heating surfaces with $\text{Cr}_3\text{C}_2\text{-NiCr}$ coatings.

The scientific novelty lies in the following:

- For the first time, a mathematical model of the thermal-technical state of heating surfaces with $\text{Cr}_3\text{C}_2\text{-NiCr}$, based on the calculation of the linear heat flux density through a multilayer cylindrical wall in combination with numerical simulation using the finite element method in the ELCUT and SolidWorks software packages, allowing for a quantitative justification of the thermophysical properties of a 100- μm -thick gradient coating;

- For the first time, a method has been developed and experimentally validated for producing protective detonation coatings of $\text{Cr}_3\text{C}_2\text{-NiCr}$ with a gradient phase distribution by controlled variation of the barrel's explosive mixture filling volume (from 57% to 73%) using a single type of powder;

- A method and a laboratory test rig based on ASTM G76-04 have been developed for conducting accelerated tests for high-temperature oxidation and wear, allowing the simulation of the effects of high temperatures (up to 750° C), aggressive media (Na_2SO_4) and erosive particles (Al_2O_3), with maximum approximation to the operating conditions of radiation-convective boiler surfaces.

Connection of the work to research projects. The research topic corresponds to the priority areas of scientific development in the Republic of Kazakhstan for 2023–2029, “Energy, Advanced Materials, and Transportation,” as well as the provisions of the Concept for the Development of the Electric Power Industry of the Republic of Kazakhstan for 2023–2029, aimed at improving the efficiency, environmental friendliness, and reliability of power plants.

This work was carried out as part of project AP09261164 “Improving the resistance of steel components in thermal power plant boilers to corrosion and erosion wear” under the grant funding program for scientific and/or scientific-

technical projects for 2021–2023 (Ministry of Education and Science of the Republic of Kazakhstan) and project AP22683418 “Extending the service life of power equipment components operating under conditions of intense wear, erosion, and corrosion at elevated temperatures” under the “Zhas Galym” program for 2024–2026 (Ministry of Science and Innovation of the Republic of Kazakhstan).

Main scientific propositions to be defended:

- Varying the filling of the detonation chamber in the range of 57–73% allows for the formation of a gradient coating of $\text{Cr}_3\text{C}_2\text{-NiCr}$ coating with a phase transition from a metallic plastic matrix (Cr_3Ni_2 , Cr_3Ni_2) near the substrate to a solid carbide phase on the surface, which ensures an optimal balance of wear resistance and adhesion;

- Shifting of the stationary corrosion potential E_{corr} into the passivation region and reducing the corrosion rate to 0.287×10^{-4} mm/year ensures the absence of corrosion damage, as well as stability (mechanical strength limits are 1.9–2.1% higher) of samples with a protective $\text{Cr}_3\text{C}_2\text{-NiCr}$ coating after 4,320 hours in a high-pressure boiler;

- Applying a 100-micron-thick $\text{Cr}_3\text{C}_2\text{-NiCr}$ coating does not impair heat transfer (increase in thermal resistance $< 0.01\%$), while increasing the reliability of the tubes by reducing failure rates by 60% and ensuring resistance to cyclic high-temperature oxidation at 650 °C over 50 cycles.

Practical significance. The results obtained can be used to improve the operational properties of boiler heating surfaces. The developed methodology for bench testing of high-temperature gas erosion and corrosion allows for the reproduction of operating conditions in the radiation-convective and convective zones of a high-pressure boiler and can be used to evaluate the effectiveness of the protective properties of pipe surfaces. The results of the dissertation have been integrated into the educational process since 2024 and are applied at the National Autonomous University “Daulet Serikbayev East Kazakhstan Technical University” in the implementation of the educational program 6B07103 Thermal Power Engineering (elective courses: “PK4306 Boiler Room Design,” “TOE4309 Thermal-Mechanical Equipment of Power Plants,” “TPU4309 Thermal Technology Processes and Installations”) (Certificate of Use in the Educational Process dated September 2, 2024). As part of the dissertation research, a method for applying protective coatings using detonation spraying was developed, which is protected by a patent of the Republic of Kazakhstan for an invention (Appendix A – Method for producing wear-resistant coatings using detonation spraying, No. 36690, published on April 12, 2024).

Author’s personal contribution. In collaboration with the scientific advisor, the author defined the research objectives and formulated the research tasks; independently planned the experiments and obtained the bulk of the experimental results presented in the dissertation; analyzed the results; formulated the conclusions and propositions to be defended; and prepared publications on the dissertation topic.

Testing of the work .

As part of the dissertation and based on the results obtained, the following materials were published, presented, and discussed.

Impact-factor articles included in the international scientific database Scopus

1. **Dautbekov M.K.**, Rakhadilov B.K., Zhurero L.G., Kakimzhanov D.N., Elistratov S.L., Segeda T.A. A Technology for Applying Detonation Coatings to Power Equipment Components Made of 12Kh1MF Steel // Thermal Engineering. – 2022. – Vol. 69(12). – P. 989–995. DOI:10.1134/S0040601522120011 (Scopus CiteScore (2022) 1.5, 31st percentile #172/252 Energy Engineering and Power Technology Web of Science: Q3 quartile)

2. Rakhadilov B., Kakimzhanov D., **Dautbekov M.**, Sagdoldina Zh., Adylkanova M., Abylkalykova R. Influence of Spraying Parameters on the Structure and Tribological Properties of Cr3C2-NiCr Detonation Coatings // Advances in Tribology. – 2023. – Vol. 2023. – P. 9. DOI: <https://doi.org/10.1155/2023/6684656> (Scopus CiteScore (2023) 5.0, 72nd percentile #184/672 Mechanical Engineering, 64th percentile #48/132 Surfaces, Coatings and Films; Web of Science: Q2 quartile)

Articles in publications recommended by the Committee for Quality Assurance in Science and Higher Education of the Ministry of National Education and Science of the Republic of Kazakhstan:

3. **Dautbekov M.K.**, Zhurero L.G., Satbaeva Z.A., Magazov N.M. Improving the operational properties of power equipment components operating under load. Bulletin of Toraygyrov University. – Issue 2. – Pp. 79–93. DOI: <https://doi.org/10.48081/28007>.

4. B. K. Rakhadilov, **M. K. Dautbekov**, L. G. Zhurero, O. A. Stepanova, A. M. Akayev. Technology for producing coatings by detonation spraying on components of thermal power plant equipment Bulletin of Toraygyrov University Energy Series No. 2 (2023), pp. 282–394.

5. Kakimzhanov D.N., **Dautbekov M.K.**, Turabekov E.S., Kuanyshbay R.M., Rustemov A.S. Effect of varying the distance of pulsed plasma treatment on the properties of CR3C2-NICR detonation coatings. Bulletin of Shakhim University. Technical Sciences Series. 2024;1(4(16)):310–319.

6. B. K. Rakhadilov, D. N. Kakimzhanov, **M. K. Dautbekov**, O. V. Kolisnichenko Technology for applying duplex coatings to power equipment components Bulletin of Toraygyrov University Energy Series No. 3 (2023), pp. 306–318 <https://doi.org/10.48081/YBCY7199>

7. D. N. Kakimzhanov, B. K. Rakhadilov, Yu. N. Tyurin, O. V. Kolisnichenko, L. G. Zhurero, **M.K. Dautbekov** Influence of pulsed plasma treatment on the phase composition and hardness of Cr3C2-NiCr coatings Eurasian Journal of Physics and Functional Materials 2021. Vol. 5, No. 1(6), pp. 45–51

Conference proceedings, papers, and posters

8. **Dautbekov M.**, Sulyubayeva L., Magazov N. Improvement of Operational Properties of Power Equipment Parts Operating in a Loaded State //2024 IEEE 14th International Conference Nanomaterials: Applications & Properties (NAP). – IEEE, 2024. – pp. 1–4, doi:10.1109/NAP62956.2024.10739738

9. **Dautbekov, M.** Technology for Applying Detonation Coatings to Power Equipment Parts / M. Dautbekov // IV Annual International Conference of the Kazakh Physical Society (KPS), June 4–7, 2025. – Ust-Kamenogorsk, 2025;

10. **Dautbekov, M.** Application of protective NiCr-Cr₃C₂ coatings on parts of power equipment operating under stressed conditions / M. Dautbekov, L. Zhurerova, D. Kakimzhanov // Proceedings of the International Conference “Fundamental and Applied Problems of Modern Physics”. – Tashkent, 2023. – P. 18;

11. Magazov, N. M. Plasmatron for air plasma spraying of nitride coatings / N. M. Magazov, **M. K. Dautbekov** // World Conference on Materials Science and Nanotechnology (WCMSN-2022), November 7–8, 2022. – Bangkok, 2022. – P. 15

Patent

12. Patent for invention No. 360690., Method for producing wear-resistant coatings using detonation spraying., Date of registration in the State Register of Inventions: April 12, 2024., B.K. Rakhadilov, D.N. Kämizhanov, Zh.B. Sagdoldina, **M.K. Dautbekov**

Structure and scope of the dissertation . The dissertation includes an introduction, four chapters, a conclusion, a bibliography of 173 references, and 4 appendices; it is presented in 137 pages of typed text and contains 69 figures and 14 tables.