ABSTRACT

to the thesis research, submitted for the PhD degree in the educational program
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INCREASING THE EFFICIENCY OF A SMALL-CAPACITY INDUSTRIAL HEATING BOILER THROUGH THE IMPROVEMENT OF THE COMBUSTION CHAMBER DESIGN FOR BURNING SOLID FUEL IN A FIXED BED

In the global fuel and energy balance, coal accounts for one third of the world's primary energy and about 40% of the energy used for electricity generation among fossil fuels. Kazakhstan holds 3.3% of the world's industrial coal reserves. The coal industry of the Republic is one of the major sectors of the economy, providing more than 70% of electricity production, full capacity utilization of coke-chemical production, and fully meeting the fuel needs of the municipal and household sector as well as the population. The proven coal reserves in the country amount to nearly 34 billion tons. In this regard, Kazakhstan ranks among the top ten leading countries globally. The sector provides tens of thousands of jobs and generates export revenues for the country.

Coal is also widely used in the mining and heavy industries, as well as in other sectors related to the extraction of mineral resources. The shares of metallurgy and other industries in the total coal consumption structure account for approximately up to 20% of the total consumption, with a figure typical for the municipal and household sector. Coal constitutes about 1% of Kazakhstan's total exports.

Kazakhstan possesses all types of coal, from lignite to hard coal. The total geological coal reserves of Kazakhstan are estimated at 150-160 billion tons. Of the proven reserves, the majority consists of lignite (62%), while hard coal makes up 38%. Kazakhstan has a real potential to meet the demand for energy coal both in the domestic and foreign markets, as the proven coal geological resources and the capacity of coal enterprises are enormous.

The overwhelming majority of coal reserves are located in the Central Kazakhstan deposits, which include the Karaganda, Ekibastuz, and Maikuben coal basins, as well as the Shubarkol, Borly, Kuu-Chekin, and Yubileynoye (Karajira) coal fields. In the central part of the country, there is the large Turgai lignite basin, which has several major deposits suitable for open-pit mining and promising for future development.

The largest coal producers in Kazakhstan are enterprises located in the Pavlodar region: LLP "Bogatyr Access Komir" (30.7% of the total national production), LLP "North Pit" (21.7%), JV "Maikuben-West" (2.3%, including 91.9% of the national lignite production), and enterprises in the Karaganda region — JSC "Mittal Steel Temirtau" (13.1%) and JSC "Borly" of LLP "Kazakhmys Corporation"

(8.8%). With the current coal production rates, the reserves in the country will be sufficient for at least the next 300 years.

Thus, coal accounts for more than 60% of primary energy consumption in Kazakhstan. Although in the long-term perspective the relative share of coal in the total consumption structure is expected to decrease, coal will still maintain its leading position in the country's energy balance.

The low population density and vast territory of Kazakhstan complicate the process of gasification across all settlements in the country, although this program is being implemented in areas close to settlements located near gas extraction sites and mineral deposits. This territorial feature and the availability of significant coal reserves force a considerable part of the population and energy facilities in Kazakhstan to depend on the consumption of fossil coal as an energy source.

Relevance of the Research. In most rural areas of the Republic of Kazakhstan, low-capacity boilers are used that operate by burning solid fuel (coal) in a fixed bed, utilizing a grate-based air supply system. Therefore, reducing harmful emissions and improving the efficiency of low-capacity boilers during solid fuel combustion remains one of the most critical challenges in the coming years.

The importance of this issue arises from the abandonment of centralized heating systems due to their inefficiency and the installation of individual heating boilers in buildings. These include: separate industrial enterprises; automobile and tractor fleets; boarding schools; and others. The feasibility of this approach for small and medium-sized enterprises is driven by the desire to reduce heating and hot water supply costs by eliminating losses during the transportation of the heat carrier. However, the lack of effective solid fuel combustion technologies in low-capacity industrial boilers results in a certain high level of ground-level concentration of toxic pollutants, exceeding environmental standards.

To address this issue, most developed countries, including those in the European part, took a different approach by optimizing the level of centralization and focusing on decentralized heating systems. In this process, heat generation equipment was improved, increasing the efficiency (thermal performance), safety, and automation levels, as well as environmental, ergonomic, sanitary, and hygienic indicators, among others. Alternative sources of thermal energy were introduced.

According to the obtained data, the actual efficiency (thermal performance) of small-capacity water heating boilers with layer combustion chambers using low-quality coals ranged from 30-60%, compared to the normative 75-80%. The main reasons for the low efficiency (energy, economic, and environmental) of low-capacity boilers are: technical imperfection, low level of operation, which depends on the ergonomics for the operating personnel, and the low quality of fuel.

However, there is a need to continue such research in the context of small-scale energy.

In this regard, **the aim of the dissertation** is to improve heat transfer efficiency and reduce harmful emissions into the environment during the combustion of solid fuel in a fixed bed in low-capacity industrial heating boilers by enhancing the design of the combustion chamber to control air supply to the fuel combustion zone.

To achieve the stated objective, the following tasks were undertaken:

- To analyze the current state and development trends of boiler-furnace equipment and layered combustion technologies of organic fuel in low-capacity boilers;
- To theoretically justify the main parameters and operating modes of low-capacity boilers during solid fuel combustion in a fixed bed through numerical modeling;
- To conduct a multifactor experiment to justify the geometric parameters of the air nozzle and air supply line under laboratory conditions;
- To carry out industrial tests of the developed combustion scheme for coal in a fixed bed in low-capacity boilers and to obtain data on the emission parameters of harmful substances into the atmosphere;
- To assess the techno-economic efficiency of fixed-bed coal combustion using the proposed scheme in comparison with the classical scheme.

Object of study: The combustion chamber of low-capacity boilers for burning coal in a fixed bed.

Subject of study: Characteristics of coal combustion in a layer-type furnace without a grate, with horizontal supply of oxidizer (air) to the fixed bed.

Research methods: The research methods include theoretical and experimental studies using standard and specialized techniques:

- Theoretical studies are based on the application of the laws of mechanics, thermodynamics, and numerical modeling.
- Experimental studies involved conducting laboratory research using mathematical statistics, experimental design theory, and chemical analysis. It also included laboratory experiments using an experimental sample.

Scientific novelty of the dissertation lies in the improvement of the combustion chamber design of a low-capacity heating boiler for solid fuel combustion in a fixed bed, ensuring complete combustion and increasing the efficiency of the boiler by eliminating the loss of fine fuel particles with flue gases and through the grate. It also includes the determination of gas velocity and temperature profiles above the fixed coal bed after ignition via numerical modeling; obtaining air flow parameters for the fixed coal layer during forced horizontal air supply; and the theoretical and experimental justification of the operating modes of the new coal combustion scheme in low-capacity boilers.

The novelty of the proposed technological and technical solutions is confirmed by **patents** for inventions of the Republic of Kazakhstan:

- №35521 dated 18.02.2022, Bulletin №7 – "Industrial low-capacity water heating boiler";
- №37168 dated 31.01.2025, Bulletin №5 – "Grate-tray".

The practical significance of the work is as follows:

1. The design of the boiler combustion chamber has been improved, and an innovative solid fuel combustion technology has been proposed.
2. Research and development of a new boiler design for efficient solid fuel combustion have been conducted.

3. A methodology for designing a combustion chamber of a new design for low-capacity boilers intended for the layered combustion process of solid fuel has been developed.

4. The effectiveness of applying the proposed boiler combustion chamber design for solid fuel combustion in a fixed bed, reducing harmful emissions, decreasing chemical incomplete combustion, and minimizing mechanical losses of small coal particles (industrial testing).

The study of the parameters and operating modes of the experimental combustion chamber blocks included: determining the dependence of the length, width, and height of the air flow in the fixed coal bed on the hole diameter, air flow in the air supply duct, and the granulometric composition of the coal. The conducted multifactorial (three-factor) experiment was carried out on a specially developed device, which includes: an air supply unit (fan with an electric motor); a frequency converter for adjusting the fan motor speed; a sealed pipeline with side holes (of different diameters); parallelly installed glass surfaces for loading the coal mass. The heat output of the modified boiler was calculated computationally.

An experimental design for the combustion chamber of small capacity coal boilers for conducting laboratory tests was developed. This design includes a standard grate and blind plate, as well as a chimney with the ability to sample gases for analysis. The grate and blind plate are made with identical dimensions and can be replaced for comparison of parameters when burning coal using the classical method and the proposed method.

Theses to be defended:

- Parameters of the improved combustion chamber design for small capacity industrial heating boilers for burning coal in a fixed bed;
- Key technological parameters and operating modes of the proposed coal combustion scheme for small capacity boilers;
- Results of experimental studies.

The author's specific personal involvement in achieving the scientific results includes:

- Formulation of research tasks and methods for their implementation;
- Development and manufacturing of the experimental model;
- Conducting experimental studies.

The validity and reliability of the scientific propositions, conclusions, and recommendations are confirmed by the results of conducted laboratory and industrial experiments, the application of standard measurement methods, and precise measuring equipment. The reliability is further confirmed by the presented results of the comparison between numerical methods and experimental studies.

The approbation of the dissertation work includes:

- Participation in the Republican contest "100 ideas for Kazakhstan" as a young energy researcher with a poster presentation at the Sustainable Energy Days 2023 (February 28 - March 3, 2023) in Wels, Austria, in the Republican Student Innovation Project Competition 2021 in honor of the 25th anniversary of the L.N. Gumilyov Eurasian National University, in the "Best Scientific Project 2021" competition, and in the "Jas Galym" competition.

- Publication in conference proceedings of the III International Scientific Forum on Computer and Energy Sciences (WFCES 2022) on May 20-21, 2022, in the 3rd International Conference on Innovations in Energy Management and Renewable Resources (IMRE 2023) on February 16-18, 2023, in the 44th International Scientific and Practical Conference "Advances in Science and Technology" in Moscow, in the XXXI International Conference of the EUROPEAN ACADEMY OF SCIENCES AND RESEARCH. Section: Engineering on June 15, 2022 (Hamburg, Germany), in the International Scientific and Practical Conference "Global Challenges of the 21st Century and the Environment", in the electronic scientific journal "Central Asian Scientific Journal", in the international conference "GLOBAL SCIENCE AND INNOVATIONS: CENTRAL ASIA", Enlit Asia 2022, Bangkok, AIP Publishing (USA); publication in the proceedings of the World Sustainable Energy Days (Wels, Austria); publication in the proceedings of the International Scientific and Practical Conference "Current Problems and Development Paths of Technical Service in the Agro-Industrial Complex" on June 5-6, 2024.

Publications

Within the framework of the dissertation research, 14 scientific works have been published, including 2 articles in journals indexed in the Scopus and Web of Science databases, 2 patents, 1 article in a journal recommended by the Committee for Quality Assurance in the Sphere of Education and Science of the Republic of Kazakhstan (KOKSNVO), and 9 publications in the proceedings of international scientific conferences.

Scopus, Web of Science indexed journals:

1. “Efficient Combustion of the Fixed Coal Layer in an Advanced Combustion Chamber Design for Low-Power Boilers”, Transactions of Tianjin University. Advanced Energy Chemistry and Materials. – China, 2024 (Scopus, Web of Science, Q1, 93rd percentile).

2. “Reduction of Harmful Emissions in Water Heating Solid Fuel Boilers of Low Power KVTS-0.2”, AIP Conference Proceedings – USA, 2023.

Patents:

1. “Industrial Low-Capacity Water Heating Boiler”, Patent of the Republic of Kazakhstan №35521 dated 18.02.2022, Bulletin №7.

2. “Grate-Tray”, Patent of the Republic of Kazakhstan №37168 dated 31.01.2025, Bulletin № 5.

Structure and volume of the dissertation:

The dissertation consists of an introduction, five chapters, a conclusion, a list of references, and appendices.

- Chapter 1 presents an analysis of the current state of the problem of improving the efficiency of solid fuel combustion in small-capacity boilers, focusing on the reduction of air pollution. It discusses the main sources of pollutants and methods for minimizing them during combustion.

- Chapter 2 introduces a new boiler design for solid fuel combustion, proposed by the author, as well as a laboratory model of the boiler. It provides a theoretical justification for the main parameters and operating modes of small-capacity boilers,

including the specifics of burning solid fuel in a stationary layer through numerical modeling.

- Chapter 3 presents experimental studies on the improvement of small-capacity boiler designs based on the proposed scheme and discusses the results of the experiments.

- Chapter 4 provides the results of industrial trials to improve the design of the combustion chamber in small-capacity boilers for burning coal in a stationary layer.

- Chapter 5 evaluates the economic effect of implementing the new boiler design for solid fuel combustion.

In the conclusion, the main conclusions of the work are drawn based on the presented and discussed developments and research.

The appendices contain information about the experimental trials and the practical application of the results.

The work is presented on 151 pages of computer text, includes 45 figures, 14 tables, and 48 pages of appendices. A total of 106 scientific sources were used for the preparation of this work.