ABSTRACT

for the dissertation submitted to qualify for
the degree of Doctor of Philosophy (PhD) in the educational program
«8D07106 – Thermal Power Engineering»

MAGZHAN ORYNBASAR

ENERGY AND ECOLOGICAL EFFICIENCY OF PLASMA-COAL BURNERS: NUMERICAL SIMULATION AND EXPERIMENT

General characteristics of the work

The dissertation is devoted to the study and optimization of a plasma-coal burner for ignition and combustion stabilization of low-grade coal. For numerical studies, software packages for thermodynamic and kinetic calculations were used: TERRA and PlasmaKinTerm, respectively. Experimental studies were carried out on a plasma-coal burner and the results obtained were compared with the results of numerical studies.

Relevance of the research work

At present, pulverized coal thermal power plants in Kazakhstan and Commonwealth of Independent States (CIS) nations predominantly utilize low-grade, high-ash coal, which is primarily obtained through open-pit mining methods. Such coals have a high ash content and a low yield of volatile substances. The direct combustion of these low-grade fuels in conventional firing systems poses considerable challenges, including poor ignition and incomplete burnout, as well as elevated emissions of harmful particulates and gases such as ash, nitrogen oxides (NO_x), and sulfur oxides (SO_x) into the atmosphere.

There are various traditional methods for improving the ignition and combustion stabilization of low-grade thermal coals in thermal power engineering. One of the widely used technologies for many thermal power plants in the world is fuel oil kindling of boilers and combustion stabilization of a pulverized coal flare, which is ineffective from an environmental, energy and economic point of view. This technology requires substantial amounts of scarce fuel oil (approximately 25 million tons annually across the CIS) and is associated with the release of environmentally hazardous gases. When fuel oil is burned, harmful gases are released – nitrogen and sulfur oxides, the use of which is restricted by the world community. Existing technologies for heating boilers and stabilizing the combustion of a pulverized coal torch worsen the energy and environmental safety of countries.

Coal is an attractive option for energy producers because it is relatively cheap and widely available. In addition to being a major energy resource, coal plays a significant role in multiple industrial sectors. It is utilized in metallurgy, the production of phosphate-based fertilizers, and the manufacturing of cement. Moreover, byproducts derived from coal contribute to the creation of various advanced materials, including activated carbon for filtration systems,

carbon fiber for aerospace and automotive applications, metallic silicon used in lubricants, and rare earth elements extracted through chemical processing. These examples highlight coal's continued relevance, as it remains a fundamental component of the global energy mix and cannot be entirely phased out as a fuel source. Addressing today’s global challenges requires a multifaceted approach that combines various energy sources and technological innovations. Despite shifts toward alternative energy, coal remains a vital part of the global energy mix (owing not only to its widespread availability, but also to its essential role in supporting numerous strategic industrial domains). Furthermore, coal contributes to the development and stabilization of infrastructure essential for the deployment and reliable operation of renewable energy systems. Therefore, research should be focused on finding new technological advances in the efficient use of coal.

A promising technology in the field of thermal power engineering is plasma ignition and combustion stabilization of pulverized coal using plasma-coal burner (PCB). The PCB eliminates the need for additional highly reactive fuels (such as natural gas or fuel oil) during boiler startup and for maintaining stable ignition and combustion of pulverized coal. This technology is based on the concept of electrothermochemical fuel preparation for combustion (ETCPF), which involves the use of an electric arc plasma to heat the air–coal mixture to temperatures that trigger the release of volatile compounds and partially gasify the remaining coke. Through this process, the PCB transforms the original solid coal into a highly reactive, dual-component fuel (HRDF), consisting of combustible gases and solid carbon residue. Upon exiting the PCB, the HRDF undergoes rapid ignition due to its effective mixing with air in the furnace chamber.

A substantial body of research on plasma-assisted ignition and stabilization of pulverized coal combustion has been published globally. Notably, the most extensive implementation of this technology is observed in China, where approximately 45% of coal-fired boilers are equipped with PCBs. Experimental investigations into the ignition and combustion behavior of low-grade coal with ash content as high as 45% have demonstrated that such high-ash fuels can be effectively ignited and sustained using PCB technology.

Connection of the thesis topic with the plan of scientific projects

The dissertation work was completed in accordance with the approved research plan of the Ministry of Science and Higher Education of the Republic of Kazakhstan, as well as within the framework of grant funding for scientific research on the topics: «Obtaining energy gas and neutral inorganic material by plasma gasification of carbon-containing waste, including polyethylene terephthalate» (AP19674754, 2023-2025); «Development and testing of technologies for new functional materials using plasma-chemical, mechanochemical and self-propagating high-temperature synthesis processes» (BR18574084, 2023-2025); «Ecological and energy efficiency of plasma technology: numerical modeling and experiment» (AP22687016, 2024-2026).

The aim of the dissertation is to assess the environmental and energy efficiency of using a plasma-coal burner at pulverized coal thermal power plants.

To achieve these goals, it was necessary to solve the following **tasks:**

1 To perform thermodynamic and kinetic modeling of the products formed during the electrothermochemical preparation of low-rank, high-ash fuel for combustion, using the TERRA and PlasmaKinTherm software packages, in order to obtain a highly reactive dual-component fuel at the outlet of the plasma-coal burner;

2 To conduct experimental studies of plasma ignition and combustion stabilization (PICS) processes within the burner volume;

3 To determine the optimal parameters ensuring the efficient progress of plasma ignition and partial gasification processes of pulverized coal fuel within the volume of the plasma-coal burner.

The object of the study is plasma-coal burners.

The subject of the research is a process of electrothermochemical preparation for combustion of Ekibastuz coal in a plasma-coal burner.

Research methods

Numerical analyses were performed using the TERRA and PlasmaKinTerm software packages, which are designed for thermodynamic and kinetic calculations, respectively. To analyze the results, experimental studies were conducted using a plasma-coal burner and compared with the numerical results.

The scientific novelty of the work is reflected in the following original findings:

1 Numerical simulation was performed for the first time, confirming the possibility of producing highly reactive dual-component fuel from high-ash, low-grade energy coal using a plasma-coal burner;

2 Experimental data were obtained for the first time, confirming the formation of synthesis gas ($CO + H_2$) with a total concentration of 37.1% during the plasma ignition and partial gasification of high-ash Ekibastuz coal in the plasma-coal burner chamber;

3 Optimization of plasma ignition and partial gasification processes of high-ash Ekibastuz coal in the volume of burner was carried out and optimal parameters were determined.

Statements for defence

1 Electrothermochemical preparation of pulverized low-grade Ekibastuz coal for combustion enables the production of a highly reactive dual-component fuel (comprising combustible gases and coke residue) with elevated concentrations of CO (26.5%) and H_2 (15.2%), ensuring rapid ignition at the outlet of the plasma-coal burner;

2 The highly reactive dual-component fuel obtained at the outlet of the experimental setup, with a specific calorific value of 12,550 kJ/kg, ensures stable and intensive ignition when mixed with secondary air;

3 The optimal parameters of the plasma-coal burner are an average mass temperature of 1880 K, pressure of 0.1 MPa, plasmatron power of 60 kW with its length of 3 m and diameter of 0.15 m.

Theoretical significance of the research

The identified general patterns of the distribution of temperatures, velocities, and concentrations of products in the electro-thermochemical preparation for coal combustion along a plasma-coal burner allow for the improvement of the efficiency and stability of such systems. The obtained results can be used to develop new methods for enhancing the energy efficiency of coal combustion, optimizing combustion processes, and reducing the environmental impact.

Practical significance of the research

The optimal parameters of plasma ignition for high-ash Ekibastuz coal have been experimentally confirmed, ensuring increased efficiency and reliability of plasma-coal burners in pulverized coal-fired thermal power plants and boiler systems. The developed approach was applied on the TPE-215 boiler at the Gusinoozersk State District Power Station, in collaboration with the Industry Center for Plasma Energy Technologies of RAO "UES of Russia." This confirms the applicability, efficiency, and industrial relevance of the technology for improving the ignition and combustion stability of low-grade, high-ash coal in thermal power generation.

The personal contribution of the author consists in independently solving the tasks and performing numerical calculations of the plasma ignition and combustion stabilization processes. The author took an active part in the bench experimental studies of the plasma-coal burner for plasma ignition and combustion stabilization processes of solid fuel. The formulation of research tasks, the choice of methods and the discussion of the results were carried out jointly with the scientific supervisors.

Reliability and validity of the obtained results

The dissertation uses widely known and verified thermodynamic and kinetic mathematical models TERRA and PlasmaKinTherm. The reliability and validity of the research findings are supported by a consistent correlation between the results of numerical modeling and experimental studies. Additionally, the scientific credibility of the work is confirmed through its dissemination in peer-reviewed international journals with a non-zero impact factor, in publications recommended by the Committee for Quality Assurance in the Sphere of Science and Higher Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan, as well as in the proceedings of international scientific conferences held both in neighboring and distant countries.

Approbation of the dissertation work and publications

The main results of the dissertation research were published in 14 scientific printed works, including: 1 article in a journal indexed by Scopus and Web of Science, 7 articles in publications recommended by the Committee for Quality Assurance in the Sphere of Science and Higher Education of the

Ministry of Science and Higher Education of the Republic of Kazakhstan, 1 publication in a collective monograph recommended by the Academic Council of the Institute of Combustion Problems of the National Academy of Sciences of the Republic of Kazakhstan, and 5 papers in the proceedings of international scientific conferences.

Scope and structure of the dissertation:

The dissertation work consists of an introduction, three chapters, a conclusion and a list of references. The work includes 26 figures, 9 tables, 153 sources in the bibliography, 108 pages and 3 appendices.