International Journal on "Technical and Physical Problems of Engineering" (IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

December 2023	Issue 57	Volume 15	Number 4	Pages 351-361

ENHANCING AERODYNAMIC EFFICIENCY IN SOLID FUEL PLASMA PREPARATION FOR POWER PLANTS

A.G. Batukhtin E.A. Makhov M.S. Bass S.G. Batukhtin

Department of Energy, Transbaikal State University, Chita, Russia
batukhtin.1982@mail.ru, egor_makhov@bk.ru, maxim.bass@inbox.ru, batukhtin_1988@mail.ru

Abstract- This study aims to explore the most crucial aspects of thermophysical and aerodynamic processes in units for plasma thermochemical fuel preparation.This research delves into the procedure for generating thermochemical substances in a plasma state using solid fuel as a starting point., which can be effectively used for combustion in pulverized coal boilers within thermal power plants, eliminating the need for oil. The authors present the combination ofresults of reviewingdomestic and foreign literature, mathematical modeling results of plasma processes to determine the core components of aerodynamic operations during the coal combustion of Okino-Klyuchevskoe deposit, as well as experimental findings. The research results provided insights into the knowledge ofthe processes occurring during the plasma treatment of solid fuels and are applicable in the design of units for plasma thermochemical fuel preparation, expanding the possibility of their introduction at thermal power plants.

Keywords: Aerodynamic Process, Burner, Plasma, Solid Fuel, Thermal Power Plants.

1. INTRODUCTION

Modern-era global heat power engineering enhances the use of solid fuels and limits the usage of liquid fuel, a valuable raw material for the industry of oil refining. In the recent decade, considerable attention has been paid to improving the efficiency and environmental safety of solid fuel combustion processes at pulverized coal-burned thermic power plants (TPPs), which produce 40.6% of electric and 24% of thermal energy [1]. Meanwhile, the global decrease in thermal coal quality leads to the use of non-designed fuels and the corresponding deterioration of boilers' technical, economic, and environmental performance. Therefore, the creation and application of new technologies for the efficient combustion of solid fuels, regardless of their quality, is of particular relevance.

Coking coals used for metallurgical coke production have a maximum ash content of 10%, moisture content of 9%, and calorific value of about 7000 kcal/kg. While coking coal deposits deplete everywhere, the world production of metals using coke is constantly increasing, which leads to a shortage of expensive metallurgical coke (costing more than $400 per ton) [1]. Therefore, its replacement with new efficient reducing agents is an urgent task. High-quality synthesis gas from low-grade coal and municipal waste is an environmentally friendly fuel for combined cycle plants, a promising raw material for methanol production, and what is essential in the context of this study, it is possible to feed it to the furnace of a pulverized coal-fired power boiler. One of the prominent technologies to solve these problems is thermochemical fuel preparation (TCFP) which utilizes the plasma fuel systems (PFS) [2].

This kind of technology has the ability to make it possible to increase the efficiency in, the environmental performance of TPPs, and further, abolish the fuel oil usage, generally utilized for boiler startups and stabilization of pulverized coal flare combustion. Implementing the latest plasma technologies of solid fuel processing depends on the level of development of calculation methods for the processes under study and plasma devices for their performance [2]. Developing calculation methods needs calculation-theoretical and experimental studies of thermophysical processes of motion and heating of coal particles and thermochemical processes of their transformations in electric arc devices. The intricate and interconnected nature of the processes involved under examination of both solid fuel and gases with multiple components will need a mathematical model.The combination of computational and theoretical approaches as well as empirical research involves determining thermos-physical constants.

2. LITERATURE REVIEW

In 1978, P.R. Blackburn (USA)secured the world's first patent for a device with electric arc ignition of pulverized coal stream and tested backlighting of pulverized coal flare using a unit with a capacity of 800 MW [3]. Starting from the early 1800s, one of the initiatives taken by the State Committee for Science and Technology, the Institute of Thermo-physics of the Russian Academy of Sciences, the Kazakh Research Institute of Power Engineering, and G.M. Khrzhizhanovsky Power Engineering Institute have launched conducting research on the development and investigation related to plasma technology for the combustion of pulverized fuel. This research area was led by scientists such as M.F. Zhukov, V.S. Peregudov, V.E. Messerle, Sh.S. Ibrayev, S.L. Buyantuyev, and T.M. Seitimov.

In 1991, with the participation ofthe Institute of Thermo-physics, one of the Siberian branches of the Russian Academy of Sciences and the Kazakh Research Organization of Power Engineering, the laboratory of plasma-energy processes was established on the basis of Gusinoozerskaya SDPP. At the end of 1994 and the beginning of 1995, an interdepartmental commission consisting the Institute of Thermo-physics of the Russian Academy of Sciences, Kazakh Research Institute of Power Engineering, the Russian Joint-Stock firm"United Energy-System of Russia"), Novosibirsk Branch of the Institute "Teploelektroproekt," and others, after a thorough analysis and operational experience, recommended the plasma ignition system for use at TPPs when operating on highly reactive coals [4].

Later, by modernizing the PFS of the first generation, a Chinese company named Yantai LongyuanElectric-Power Technology Co. Ltd. introduced a new way of implementing plasma ignition systems in more than 500 boilers [5]. Since the early 2000s, in Russia, a group of scientists, including E.I. Karpenko, G.B. Zonkhoev, A.S. Askarov, A.B. Ustimenko, I.V. Loktinova, I.V. Starinsky, S.Y. Shishulkin, A.E. Urbach, A.M. Shilyaev, V.V. Drobchik, T.A. Pichugina, V.S. Peregudov, A.V. Messerle and others have been actively researching the modernization and enhancing the plasma burners and optimization of combustion processes of steam coals in various boiler units. They developed some mathematical models describing the dynamics, heating, and physio-chemical thermal fuel preparation processes. In addition to this, they have created many programs for numerical simulation of the thermochemical fuel preparation (TCFP) processes known as "Plasma-coal" and "Plasma-muffle" [6-7]. Moreover, these researchers have also patented many methods of plasma ignition and stabilization of pulverized coal flare combustion, installations, and diverse burner designs, plasma igniters, two- and three-stage methods of plasma TCFP, and a technique to clean gas emissions during plasma ignition.

A.E. Urbakh [8] investigated the mechanism of anode erosion and determined the criterion when fulfilling which provides its maximum service life (1000h and more), developed and implemented the system of plasma ignition of air mixture and coal in KBTK-100-150 heating the boiler. In the beginning, the plasma ignition system, a pulverized coal concentrator was used to reduce energy consumption for igniting the coal-air mixture. A.M. Shilyaev, et al. gave the results of studying the ignition processes of low-grade fuels such as wood waste, peat, and sludge with a low content of combustibles and their mixtures using electric arc plasmatrons [9].

V.V. Drobchik [10] investigated the ignition of pulverized solid fuel by a remote plasma arc and determined the excess air ratio, providing efficient ignition of coal-air mixture. The plasma combustion of a coal and wood waste mixture was studied with the numerically modeled heat exchange of the muffler stabilizer designed to sustain the coal and air mixture combustion. The boundary line of stable combustion area of electric arc discharge under the influence of the coal and air mixture stream and the dependence of airflow rate on plasmatron power were determined. By thermo-physical experiments on industrial boilers, V.S. Peregudov demonstrated the feasibility of igniting a wider range of steam coals in boilers equipped with an intermediate bin and with direct injection of coal dust [11]. For the first time, the start-up of boilerswith direct coal dust injection and stabilization of liquid slag output based on plasma-coal TCFP was realized. A plasmatron of a two-chamber scheme with an arc partially carried out in the coal-air mixture stream and an efficiency close to 90% and the methodology of research on energy consumption of plasmatron at plasma TCFP were developed.

The work by A.V. Messerle [12] totallyreflects the methodology of numerical modeling of the ignition and TCFP processes and, for the first time, introduced empirical characteristics of the plasma source flare and features of its interaction with the coal-air mixture stream, considering multi-fractionality and the nature of the interaction of the pulverized coal and air mixture with the internal plasma source. The mathematical model represents the program "Plasma-muffle". In [13], V.S. Peregudov gave schemes of PFS with low coal concentration, considered the influence of oxygen concentration in the coal and air mixture, and also provided an equation to determine energy consumption for plasma ignition through coal depending on the importanttechnological criterion process:

$$Q = Q_0 \left(0.79 + 0.21V\right)_{\mu}^{-0.6} d_s^{0.4} \left(1.4 - 0.4T_g\right) L^{-0.4} \quad (1)$$

where, Q is energy consumption for ignition (kWh/t), Q_0 is specific energy consumption for ignition (kWh/t); V is the velocity of the coal and air mixture (m/s); μ is concentration of the coal in coal and air mixture (kg/kg); d_s is particle size (m); T_g is temperature of primary air (K), and L is length of TCFP chamber (m).

In 2012, the Laboratory of Plasma-Energy Processes and Technologies was opened in the structure of the Institute of Physical Materials Science, Ulan-Ude with Dr. E.I. Karpenko appointed as the head of the laboratory later elected by competition. Since 2012, scientists E.I. Karpenko, A.B. Ustimenko, K.S. Sharonov, E.B. Butakov, L.S. Buyantuev, E.E. Boyko, and others have continued to improve physical and mathematical models and calculation methods. They have developed the method of step-by-step calculation of PFS for electric TCFP, the method of complex calculation of furnaces of boiler units equipped with PFS, and proved that PFS reduces mechanical underburning of fuel by 18% and the concentration of nitrogen oxides by 25%, increasing the environmental and economic efficiency of solid fuel combustion. A package experimental electroplasma unit for environmentally friendly and waste-free processing and utilization of organic waste with the production of high-calorie synthesis gas has been developed, manufactured and tested. A kinetic model of pyrolysis, ignition and combustion of fine-dispersed coal-water slurry has been developed considering the main chemical reactions [14]. Burner devices, methods and devices for plasma gasification and synthesis gas production are being modernized and patented.

Mukhaeva, et al. [15] considered the issues of plasma processing of brown coals from the Okino-Klyuchevskoye and Adun-Chulunskoye deposits, presented the results of experiments on their gasification, and also considered the issue of synthetic liquid fuel production.

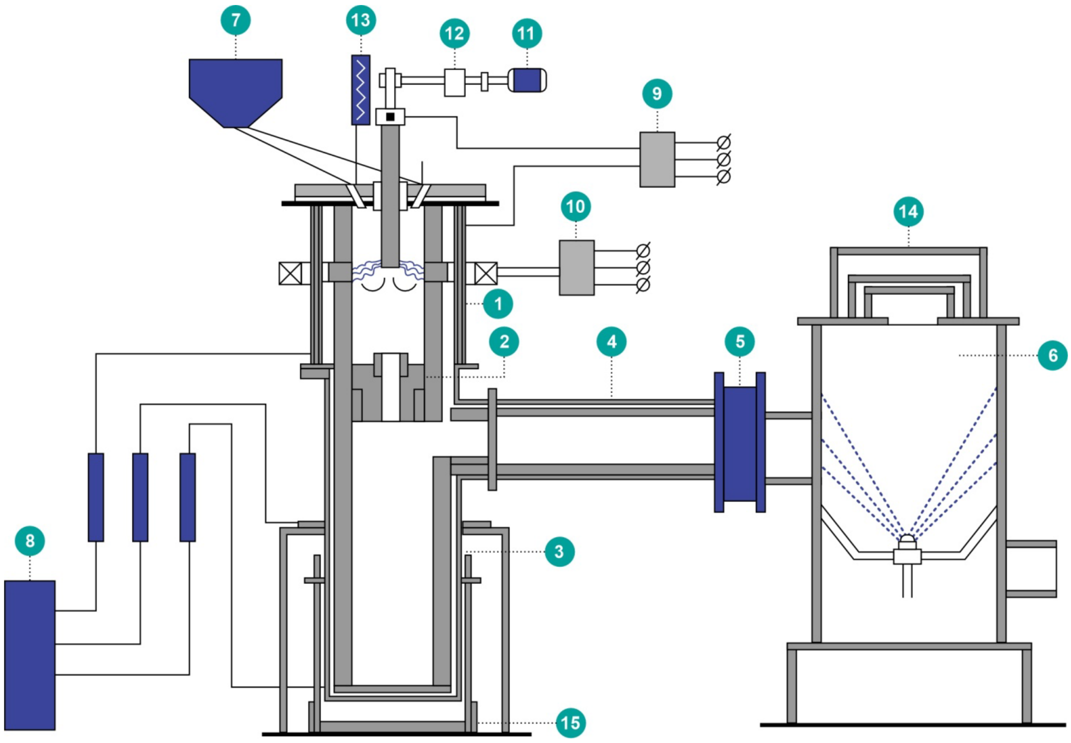


Figure 1. Plant layout for plasma chemical fuel processing: 1. plasma-chemical reactor; 2. diaphragm, chamber of gas and slag separation; 3. slag collector; 4. oxidation chamber; 5. diaphragm; 6. water scrubber; 7. solid fuel supply; 8. water cooling system; 9, 10. power supply system; 11, 12. central electrode supply system; 13. steam generator; 14. safety valve; 15. slag collector elevator [16]

Messerle, et al. [17] carried out an investigation where they analyzed the burning process of Ekibastuz high ash coal in a PK-39 furnace boiler. Karpenko and Ustimenko's research as outlined in their work [16] presented a wide range of findings on various processes such as hydrogenation, plasma chemical pyrolysis, and thermochemical preparation for combustion. Their findings also include gasification, and complex processing of solid fuels as well as uranium production from coal, cracking of hydrocarbon gases, and the plant for implementing these processes (Figure 1). The researchby Ydrys and Messerle [18] describes the model of plasma thermochemical composing for pulverized coal combustion implemented in the form of the PlasmaKinTherm program.

Messerle, et al. [19] described the kinetic model of pyrolysis, ignition, and combustion of fine-dispersed coal-water slurry considering the main chemical reactions and developed a method of engineering design of cyclone burner. Afterward, in 2019, the task was experimented to increase the efficiency and service life of plasma ignition system at Gusinoozerskaya SDPP [20]. Foreign works are represented by the studies conducted by Chinese scientists and (mainly), Kazakhstan, Ukraine, Germany, Korea, and others [21] reflects modeling of the processes of pulverized coal boiler starting up and backlighting, fuel gasification, and reduction of harmful emissions into the atmosphere. Messerle, et al. [22] describes the study of microwave radiation's influence on pulverized coal streams. Kazantsev, et al. [23] presents the commissioning system of plasma ignition of the DG-1910/25.4-II 600 MW boiler operating at supercritical parameters. Pan et al. [24] reflect a hybrid structure combining waste gasification and subsequent supply of synthesis gas to the furnace of a pulverized coal-fired power boiler.

For further improvement of calculations of installations of plasma oil-free initiating combustion of coals, it is necessary to continue developing specific methods of calculation of burner devices, allowing with the required accuracy to preliminarily estimate the core criterion in the processes arisingin the volume of the burner equipped with a plasmatron, to calculate aerodynamic parameters, temperature, and composition of the fuel mixture at the furnace inlet. It is also necessary to further develop and implement the methods of calculating the working process of boilers equipped with burners and extended furnaces with plasmatrons and TCFP chambers.

3. RESEARCH METHODS

The research methodology used in this study aimed to enhance the efficiency of aerodynamic processes involved in the plasma thermochemical preparation of solid fuel for combustion at thermal power plants. This complex methodology incorporates experimental, theoretical, and computational techniques to ensure the accuracy and reliability of the findings. A crucial element of this research involves conducting intricate thermo-physical experiments. These experiments are conducted in laboratory conditions, pilot test benches, and full-scale power boilers. This multi-tiered approach ensures that the results are derived from various settings, each with unique challenges and conditions. This diversity in experimental setups enhances the robustness and reliability of the data obtained. In the laboratory setting, controlled experiments allow researchers to isolate specific variables and closely monitor the fuel processing under controlled conditions. These experiments are invaluable for establishing fundamental principles and gaining insight into the underlying physical and chemical processes.

Pilot test benches provide a bridge between laboratory-scale experiments and real-world applications. These tests help researchers evaluate the scalability of the technology and assess how it performs under conditions that closely mimic those in actual thermal power plants.Utilizing power boilers for experimentation brings the research closer to practical implementation. It enables the investigation of the technology's real-world viability and challenges. This phase offers valuable insights into how the proposed improvements will function when integrated into the existing power plant infrastructure.Theoretical analysis forms another critical facet of this research methodology. Researchers employ a range of theoretical techniques, primarily based on the fundamental laws of thermophysics, heat engineering, thermodynamics, plasma chemistry, and kinetics of thermochemical transformations of fuels.

Thermophysical principles help describe the behavior of matter and energy in the studied processes. This includes heat transfer, phase changes, and the behavior of materials at different temperatures and pressures, all of which are essential for understanding the thermodynamic aspects of fuel preparation.Thermodynamics plays a pivotal role in assessing energy conversion and efficiency. Researchers use thermodynamic models to predict the behavior of the fuel, plasma, and overall system. This theoretical framework enables them to assess the thermodynamic feasibility of their proposed improvements and optimize the process accordingly. Moreover, Plasma chemistry and kinetics are essential for understanding the complex reactions occurring during plasma thermochemical preparation. Theoretical modeling of these reactions helps design more efficient processes and predict reaction pathways, which are crucial for achieving better fuel combustion.

The research methodology also relies on computer programs and program complexes to model and simulate various aspects of the fuel preparation process. These simulations are based on the theoretical principles and thermophysical laws mentioned earlier. They help optimize the process, make predictions, and explore different scenarios. A rigorous validation approach is followed to ensure the reliability of the research findings. The calculations and simulations are subjected to internal scrutiny, ensuring that material and heat balance equations converge, and that solution methods are robust and consistent. This internal validation process helps maintain the integrity of the research.Moreover, the results obtained from the theoretical models are compared with the outcomes of the experiments conducted at different scales, including laboratory, pilot test benches, and power boilers. This step validates the theoretical predictions' accuracy and aligns them with practical observations.Finally, the research methodology emphasizes the results of Plasma Fuel Systems (PFS) industrial tests. The outcomes of these tests, conducted under real-world conditions, provide valuable insights into the feasibility and performance of the proposed improvements in an industrial context.

A noteworthy aspect of this research is the emphasis on quality control. The research was conducted within the framework of state programs and assignments, which implies stringent oversight and accountability. R&D efforts were subject to quality control by the state customer, ensuring that the research adhered to established standards and met the defined objectives.Additionally, international experts were involved in the evaluation process. This external oversight validates the research findings and aligns them with global standards and best practices in the field. Hence, the research methodology employed in this study is a robust and dynamic approach that combines experimental, theoretical, and computational techniques to improve the efficiency of aerodynamic processes in plasma thermochemical preparation of solid fuel for thermal power plants. This method ensures the reliability and completeness of information while stringent quality control and international expert evaluation add an extra layer of credibility to the research.

4. RESULTS

Coal playsa pivotal role in the production of heat and electricity worldwide. Contemporary, thecoal-fired power plants provide up to 31% of the world's electricity (Figure 2), while proven coal reserves amount to 1.06 trillion tons. Coal reserves at the current production rates will last for about 132 years. The giant reserves are in the USA, Russia, China, India and Australia [25]. Data from the international energy agency "Enerdata" show that if the current "EnerBase" trend continues, coal will still produce 24% of the world's electricity in 2050 (Figure 3), maintaining its position as one of the largest energy sources in the world [26].

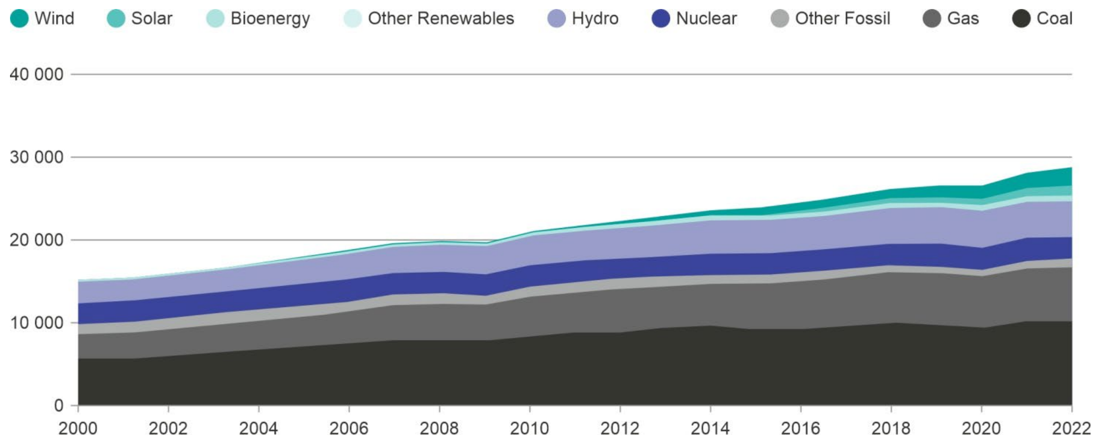


Figure 2. Change of energy balance in the world electricity production (in Terawatt-hours) [25]

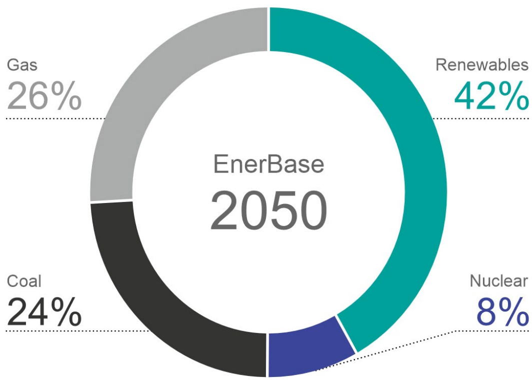


Figure 3. Forecast of the world energy balance for 2050 [26]

According to the data provided by the Ministry of Energy, Russian Federation for 2022 [27], the important types of boiler fuel of thermal power plants (TPPs) across Russia, considering heat supply enterprises, industrial enterprises, housing, and utility enterprises consists of gas and coal as illustrated in Figure 4. Gas fuel includes natural gas (as the primary type of gas fuel), associated, and synthetic gas. Coal fuel includes coal from all deposits used at TPPs in Russia. The main Russian coals are Kansk-Achinsk and Kuznetsk coals; TPPs in the Urals and Omsk also use imported Kazakhstani coals. Oil fuel in Russia's thermal power plants includes diesel fuel and various others with heating oil considered as one of the primary sources. In Russia, these oil fuels are primarily included as auxiliary fuels with the purpose of flare backlighting, operating boilers at low loads, start-up of boilers, as well as backup, and emergency fuel options [27].

In recent years, there has been a steady trend towards deterioration of the quality of coal supplied to TPPs, increase in ash and moisture content, and decrease in volatile yield and heat of combustion due to the depletion of high-quality coal deposits mined by the shaft method and the transition to developing high coal deposits by open pit mining. Deterioration in the quality of solid fuels contributes to increased consumption of oil at pulverized coal-fired TPPs. This increased consumption of oil initiates the start-up modes of boilers, backlighting, and stabilization of flare combustion, as well as in the operation of boilers not only at low parameters but even at nominal loads. Continuing the simultaneous combustions of coal and heating oil leads to some outcomes such as a decrease in boiler efficiency due to increasing heat loss with mechanical under-burning of fuel, boosting the output of nitrogen oxides and vanadium pentoxide having carcinogenic and mutagenic properties. Furthermore, collaborative combustion increases high temperaturesin corrosion of heating surfaces and sulfur dioxide emission because the initial sulfur content in heating oil, as a rule, exceeds by several times the content in coal.

Among all the technical solutions to the issues pertaining to starting up and combustion backlighting in pulverized coal boilers, thermochemical methods of solid fuel processing that are utilized in plasma-fuel systems (PFS, Figure 5) seems to be the most advanced. These methods convert electricity into plasma energy through the electric arc as shown in Figure 6, and microwave plasmatrons to heat and undergo thermochemical transformations of organic and mineral components of coals [28]. Today, testing at several TPPs in Russia, China, Korea, Mongolia, Kazakhstan, Ukraine, and Slovakia confirmed the efficiency of plasma technology application in power engineering (Table 1).

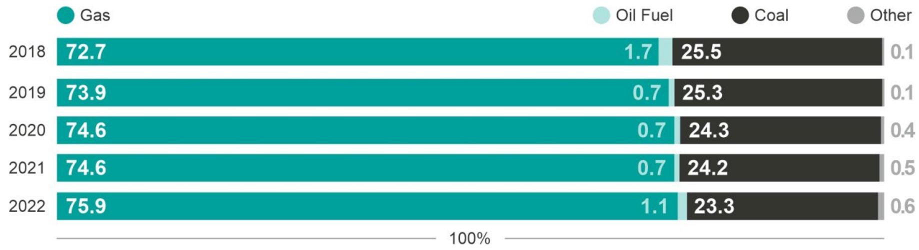


Figure 4. Structure of fuel consumption at TPPs in Russia from 2018 to 2022 [27]

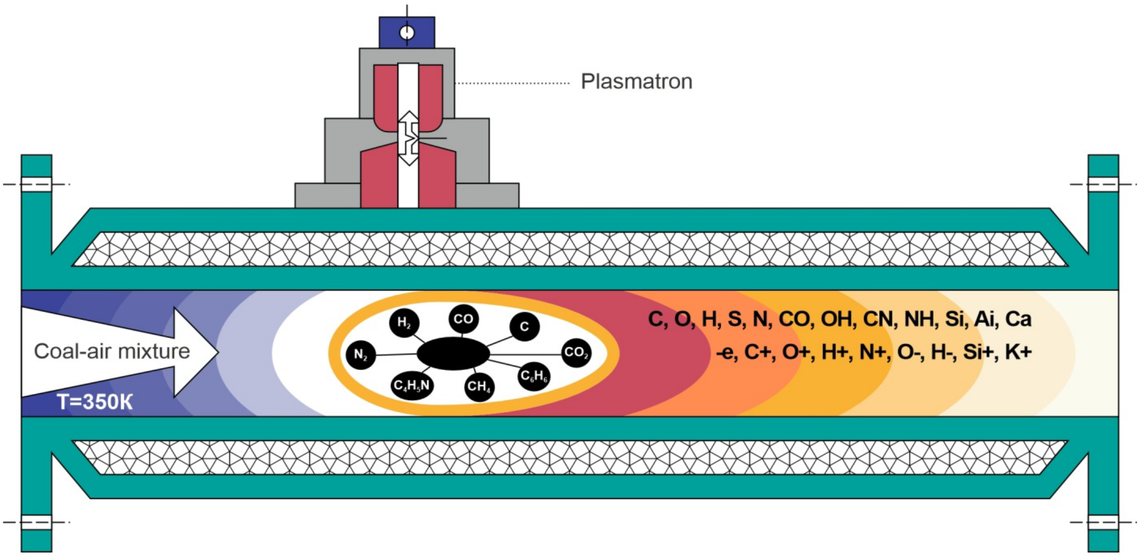


Figure 5. Features of the interaction of arc plasma with pulverized coal stream [29]

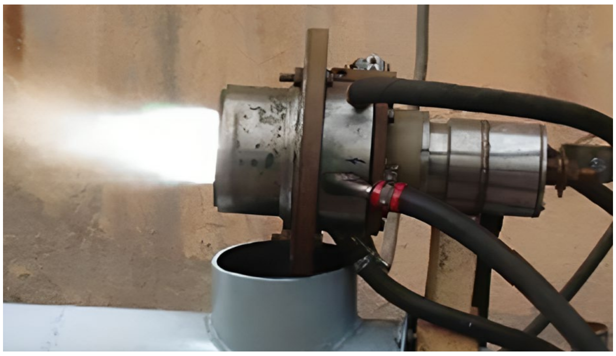


Figure 6. Electric arc plasmatron [30]

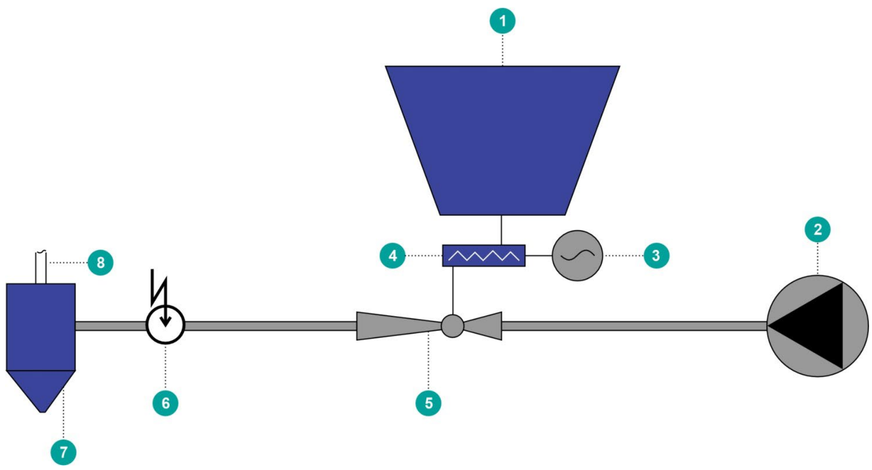


Figure 7. Experimental plant layout of plasma TCFP: 1. coal dust bin; 2. blowing fan; 3. electric motor with frequency regulator; 4. coal dust feeder; 5. dust mixer; 6. plasmatron; 7. cyclone; 8. flue gas outlet [30]

Table 1. Plasma fuel systems at Eurasian TPPs [30]

Location of TPP	Type and number of boilers with PFS	Boiler steam capacity, t/h or hot water boiler capacity, MW	The number of PFS, pcs.
Russia			
Gusinoozerskaya State district power plant (SDPP) (Gusinoozersk, 1994-1995)	TPE-215 × 2 BKZ-640 × 2	670 640	8 7
Cherepetskaya SDPP (Suvorov, 1997)	TP-240 ×1	240	4
Neryungrinskaya SDPP (Neryungri, 1997)	KVTK-100 ×1	116 MW	2
Partizanskaya SDPP (Partizansk, 1998)	TP-170 ×1	170	2
Ulan-Ude Central Heating and Power Plant (CHPP)-2 (Ulan-Ude, 1997)	TPE-185 ×1	160	2
Khabarovsk CHPP-3 (Khabarovsk, 1998)	TPE-216 ×1	670	4
Ukraine			
Kurakhovskaya TPP (Kurakhovo, 1998-1999)	TP-109 ×1	670	4
Mironovskaya SDPP (Mironovka, 1989)	TP-230 ×1	230	2
Kazakhstan			
Almatinskaya SDPP (Almaty, 1996)	BKZ-160 ×1	160	2
Ust-Kamenogorsk CHPP (Ust-Kamenogorsk, 1989)	CKTI-75 × 2	75	4
Almatinskaya CHPP-2 (Almaty, 2011)	BKZ-420 ×1	420	6
Mongolia			
Ulaanbaatar CHPP-4 (Ulaanbaatar, 1994)	BKZ-420 ×8	420	16
Erdenet CHPP (Erdenet, 1995)	BKZ-75 ×1	75	1
China			
Baodia TPP (Baodi, 1995)	Ch-200 ×1	200	3
Shaoguan TPP (Shaoguan, 1999-2001)	F-220/100-W × 1 K-75 ×1	230 75	4 1
TPP “Golden Mountain” (Shenyang, 2007)	BG-75/39-M ×1	75	2
TPP "Gangshun" (Shanxi, 2009)	BG-950/150 ×1	950	4
North Korea			
East Pyongyang TPP (Pyongyang, 1993)	E-210 ×1	210	3
Slovakia			
TPP "Wojany" (WielkieKapusany, 2000)	TAVICI ×1	350	2
Serbia			
Belgrade TPP "Nikola Tesla" (Obrenovac, 2007)	TP-210 ×1	650	16

The authors conducted an in-depth analysis of domestic and foreign literature with thorough examinations of achievements by prominent scientists in the research field. They have studied specialized computer programs like TERRA, Plasma-coal, and Plasma-muffle, which made it feasible and allowed them to implement the model of plasma ignition and start-up of pulverized coal boilers. Figure 7 shows a laboratory bench developed to conduct experimental studies of plasma ignition. The coal dust from supply bin 1 using feeder 4 enters dust mixer 5 for ejection and mixing of coal dust with air supplied by blowing fan 2, then the pulverized coal stream goes to the TCFP chamber with plasmatron 6. In cyclone 7, fuel combustion occurs, discharging flue gases into the atmosphere through chimney 8.

Preliminary during the experimental studies, the dependence of fuel supply by the dust feeder on the electric motor speed was determined, adjusting the airflow rate based on the calculated values with subsequent measurements of airflow rates and aerodynamic resistance of all units of the plant during air purging without plasmatron operation. A further step was to investigate the regime of stable combustion of pulverized coal stream in low-temperature plasma. The studies were conducted for Okino-Klyuchevsk coal with the main characteristics shown in Table 2.

The computer simulation yielded the composition of plasma gasification products and the temperature dependences of gas and coal particles of different fractions along the length of PFS (Figure 8).

Table 2. The main characteristics of the studied coal

Characteristics	Unit	Value
Moisture of primary fuel (Wtr)	%	21.3
Ash per dry weight of raw coal (Ad)	%	22.3
Volatiles per combustible mass (Vdaf)	%	42.3
Lower heating value of as-fired coal (Qir)	MJ/kg	16.7
Deformation temperature of ash (ta)	°C	1327
Ash softening temperature (tb)	°C	1350
Melting temperature (tc)	°C	1373

The results of this research provide an essential insight into the significance of coal in global energy production. As of now, coal-fired power plants continue to play a vital role in generating up to 31% of the world’s electricity. It is important to note that proven coal reserves stand at a staggering 1.06 trillion tons, which are estimated to last for approximately 132 years, given current production rates. The largest coal reserves are found in countries such as the USA, Russia, China, India, and Australia [25]. This data underscores the enduring importance of coal in the energy landscape.

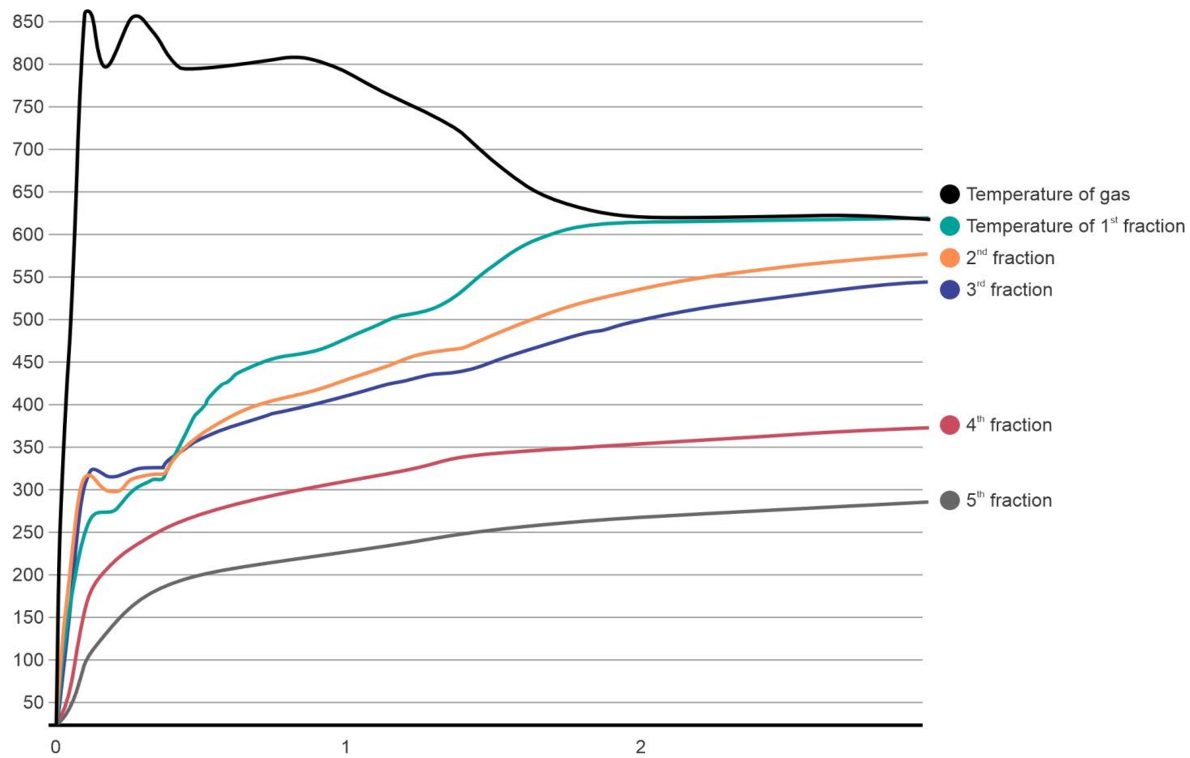


Figure 8. Simulation results of gas temperature and coal particles (concentration 0.2) along the length of PFS [30]

In the context of the study's findings, projections from the international energy agency "Enerdata" indicate that coal is expected to continue generating a significant portion of the world's electricity, with an estimated 24% share by 2050. This reflects coal's resilience as one of the most substantial energy sources on a global scale [26]. Examining the Russian energy landscape, data from the Ministry of Energy for 2022 reveals that the key types of fuel for thermal power plants in Russia comprise gas and coal, as well as oil as an auxiliary option. Gas fuel encompasses natural gas as the primary type and associated and synthetic gas, while coal fuel includes coal from various deposits. Notably, coal degradation, characterized by increased ash and moisture content and reduced volatile yield and heat of combustion, has resulted from the depletion of high-quality coal deposits mined traditionally and a shift towards open pit mining methods. This degradation has increased oil consumption in pulverized coal-fired thermal power plants, especially during startup and backlighting modes. The consequences of simultaneous coal and heating oil combustion include decreased boiler efficiency, elevated nitrogen oxide and vanadium pentoxide emissions, higher corrosion of heating surfaces, and sulfur dioxide emission due to the higher sulfur content in heating oil [27].

To address these challenges, thermochemical methods, particularly those implemented through plasma-fuel systems, have emerged as an advanced solution. These methods involve the conversion of electricity into plasma energy via electric arcs and microwave plasmatrons for heating and thermochemical transformations of coal's organic and mineral components [28]. Furthermore, a review of testing across several countries, including Russia, China, Korea, Mongolia, Kazakhstan, Ukraine, and Slovakia, confirms the efficiency of plasma technology in power engineering (Table 1). This test data underscores plasma technology's global applicability and effectiveness in diverse energy contexts.

The study's robust analysis of existing literature and advanced computer programs, such as TERRA, Plasma-coal, and Plasma-muffle, played a crucial role in modeling the plasma ignition and startup of pulverized coal boilers. A laboratory setup was developed to conduct experimental studies on plasma ignition, involving the ejection and mixing of coal dust with air, followed by combustion in a low-temperature plasma chamber. During experimental studies, the research team explored the influence of the electric motor speed on fuel supply via the dust feeder, adjusting airflow rates and assessing the aerodynamic resistance of various plant components during air purging without plasmatron operation. Subsequent investigations focused on achieving stable combustion of the pulverized coal stream in low-temperature plasma. The research incorporated a case study using Okino-Klyuchevsk coal, and computer simulations yielded valuable insights into the composition of plasma gasification products and temperature dependencies along the PFS length. These results provided critical data on the behavior of coal particles and the products of their thermochemical transformations, adding depth to the understanding of the plasma-fuel system's operation and potential benefits.

Comparing various methods for improving coal combustion and analyzing their advantages and disadvantages is a crucial aspect of this study. One of the primary technologies under scrutiny is the Plasma-Fuel System (PFS), a method that aims to optimize coal combustion efficiency and reduce emissions. PFS boasts several significant advantages. Firstly, it demonstrates remarkable combustion efficiency by converting electricity into high-energy plasma through electric arcs and microwave plasmatrons, creating an ideal environment for thermochemical transformations of coal. This, in turn, results in a reduction in energy loss during the combustion process. Secondly, PFS is known to lower emissions, particularly of pollutants like nitrogen oxides (NOx) and vanadium pentoxide. The precise control of temperature and conditions within PFS allows for cleaner combustion, with minimal harmful emissions. Furthermore, the research highlights that PFS has been successfully tested across various countries and power plants, signifying its adaptability in different contexts.

Nevertheless, there are notable disadvantages associated with PFS. Firstly, the technology is capital-intensive, requiring significant investment for installation and operation. The initial cost can be a barrier for some power plants considering its adoption. Secondly, the operation of PFS is complex and requires advanced technical knowledge, along with specialized equipment. Managing such intricacies can be challenging for some power plants, further influencing the adoption rate.

In comparison to PFS, alternative methods for enhancing coal combustion and reducing emissions exist, each with its own set of advantages and disadvantages. Traditional combustion, for instance, remains a cost-effective and widely adopted approach but often leads to higher emissions and reduced efficiency compared to advanced methods such as PFS. Fluidized bed combustion, another alternative, involves suspending coal particles in an upward flow of air or other gases. While it offers greater fuel flexibility and lower emissions than traditional combustion, it may not match the efficiency levels achievable with PFS. On the other hand, Integrated Gasification Combined Cycle (IGCC) is a technology that converts coal into synthetic gas for combustion, delivering high efficiency and lower emissions. However, it also comes with a substantial capital investment, similar to PFS.

A comparative analysis shows that PFS and IGCC offer superior combustion efficiency and emissions reduction when juxtaposed with traditional combustion and fluidized bed combustion. With its ability to create a high-energy plasma environment, PFS stands out in terms of efficiency. In emissions reduction, PFS and IGCC perform well, reducing pollutants like NOx and sulfur dioxide (SO2), which are of significant concern for environmental and health reasons. However, PFS and IGCC also carry higher capital costs and are more complex to operate compared to the simpler traditional combustion methods. The choice of technology depends on multiple factors, including regulatory requirements, the specific objectives of the power plant, and available resources. As demonstrated in this study, PFS presents a compelling solution for enhancing coal combustion efficiency, particularly when emissions reduction is a priority.

5. CONCLUSION AND PROPOSALS FOR PRACTICAL USE

The experimental investigations have revealed that during the thermochemical preparation of coal combustion in PFS, the heat loss from mechanical under-burning with slag was less than 1%. In addition to this, the heat loss due to incomplete entrainment was negligible. These traits show that synthetic fuel which is produced after thermos-chemical treatment of $CO+H_2$ and coke residue at 970 ℃ burns out completely, thus, providing high combustion temperature. Table 3 presents the experimental results. Among all the technical solutions to the problem of starting up and backlighting boiler combustion, the most progressive seems to be thermochemical methods of solid fuel processing realized in plasma-fuel systems (PFS). Studying the processes occurring in the interaction of solid fuel with plasma sources will accelerate the introduction of oil-free combustion technology in the power industry.

Table 3. Results of the PFS experimental study

	Characteristics	Unit	Value
1	Dust mass flow rate	t/h	0.0375
2	PFS outlet temperature	℃	971
3	Combustion air temperature	℃	100
4	Air flow rate	m3/h	138.9
5	Temperature in the chamber	℃	>1500
6	Excess air ratio	-	0.8
7	Blower fan discharge pressure	kPa	10.3
8	Coal-air mixture pressure after the dust mixer	kPa	4
9	Head loss in TCFP chamber	Pa	247.12

However, to achieve wider implementation, further research is required in this field. Moreover, the issues of development and implementation of calculation methods in working process of boilers equipped with burners and extended furnaces with plasmatron are still unsolved issues today. The results of modeling and experimental studies can be used to determine the local aerodynamic drag coefficient of the TCFP chamber, which will further make it possible to estimate the aerodynamic drag of the plant at the design stage.

ACKNOWLEDGEMENTS

This work was performed under the State Assignment from Ministry of Science and Higher Education, Russia (Topic No. 123102000012-2 Complex research of aerodynamic characteristics of thermal-chemical fuel preparateion plasma systems, agreement No. 075-03-2023-028/1 from October 5th 2023).

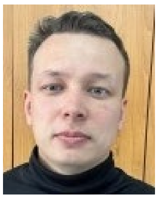
REFERENCES

[1] D.Y. Bektasov, "Innovative Technologies for Efficient Combustion of Solid Fuels in Kazakhstan", E²nergy, 27 August 2021.
[2] V.R. Okorokov, R. V. Okorokov, "Open Seminar Economic Problems of the Energy Complex", Forecast for the Development of Global Energy until 2050: Goals and Technical Capabilities for their Implementation, Institute of National Economic Forecasting RAS, Moscow, Russia, 2009.

[3] A.M. Hashimov, E.E. Novruzova, "New Technologies in Energy Sector and Automated Energy Accounting Systems and their Main Factors of Influence on Ecology", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 42, Vol. 12, No. 1, pp. 53-57, March 2020.
[4] E.I. Karpenko, V.E. Messerle, "Introduction to Plasma-Energy Technologies of Solid Fuels Utilization", Novosibirsk, Nauka, Russia, 1997.
[5] Longyuan Ltd. Yantai Electromechanical Company, "Plasma Technology of Ignition and Maintenance of Combustion in Pulverized Coal Boilers", Electric Power Plants, No. 2, 2008.
[6] I.V. Starinsky, "Sorption Properties and Structure of Coals Processed in Low-Temperature Plasma", Ph.D. Thesis, East Siberia State University of Technology and Management, Ulan-Ude, Russia, 2007.
[7] S.Yu. Shishulkin, "Plasma-Thermal Preparation of Solid Fuels for Combustion Based on a Modular Twin Unit", Ph.D. Thesis, East Siberia State University of Technology and Management, Ulan-Ude, Russia, 2009.
[8] A.E. Urbakh, "Development and Research of Electric arc Plasmatrons with Long Service Life for Electric Technologies of Plasma Ignition of COAL, cutting and Welding of Metals", Ph.D. Thesis, Novosibirsk State Technical University, Novosibirsk, Russia, 2003.
[9] A.M. Shilyaev, V.V. Drobchik, V.A. Klimenov, G.G. Volokitin, A.A. Mandrik, "Investigation of the Process of Firing of Low-Grade Fuels in a Plasma Module by an Open Electric Arc", Polzunov Bulletin, No. 1, 2004.
[10] V.V. Drobchik, "Development of Technology of Ignition and Stabilization of Combustion of Powdered Solid Fuels Based on a Device with a Remote Plasma Arc", Ph.D. Thesis, Tomsk State University of Architecture and Building, Tomsk, Russia, 2004.
[11] V.S. Peregudov, "Plasma Thermochemical Preparation of Coals and Development of Equipment for its Implementation", Doctoral Thesis, Khristianovich Institute of Theoretical and Applied Mechanics of SB RAS, Novosibirsk, Russia, 2006.
[12] A.V. Messerle, "Mathematical Modeling of Processes of Thermochemical Preparation of Pulverized coal fuel using electric arc plasmatrons", Industry Center for Plasma Energy Technologies of RAO UES of Russia at JSC Gusinoozerskaya State District Power Plant, Moscow, Russia, 2006.
[13] V.S. Peregudov, "Optimization of the Process of Plasma Ignition of Coal", High Temperature, Vol. 47, No. 2, pp. 181-186, 2009.
[14] K.S. Sharonov, "Thermophysical Parameters of the Process of Plasma Processing of Coals", Ph.D. Thesis, East Siberia State University of Technology and Management, Ulan-Ude, Russia, 2012.
[15] D.V. Mukhaeva, E.I. Karpenko, A.P. Rinchinov, "Plasmatron with a High-Resource Cathode", Buryat State University Bulletin, No. 2-3, pp. 20-26, 2019.
[16] E.I. Karpenko, A.B. Ustimenko, "Plasma Methods for Efficiency of Solid Fuel Utilization Improvement", Recent Contributions to Physics, Vol. 75, No. 4, pp. 72-85, 2020.
[17] V. Messerle, K. Umbetkaliev, A. Ustimenko, "3D-Calculation of Plasma Assisted Ecibastuz Coal Combustion at Reftinsk PK- 39-II Furnace Boiler", Combustion and Plasma Chemistry, Vol. 18, No. 3, pp. 111-126. 2020.
[18] U.Y. Ydrys, V.E. Messerle, "Research on Synthesis Gas Obtained by Pyrolysis from Solid Household Waste", Universum: Technical Sciences: Electronic Scientific Journal, Vol. 4, No. 85, pp. 18-23, 2021.
[19] V. Messerle, K. Umbetkaliev, A. Ustimenko, "Plasma Gasification of Coal in Various Media", Combustion and Plasma Chemistry, Vol. 20, No. 3, pp. 219-227, 2022.
[20] A.A. Khalimov, M.R. Sanatullin, I.O. Storozhev, I.M. Safarov, D.S. Krekhov, "The Prospect of Using Automated Process Control Systems with Plasma Coal Burning in the Far North", Engineering Journal of Don, No. 5, pp. 1-18, 2022.
[21] V.M. Shipilov, V.L. Artemenko, S.G. Nikolsky, B.C. Meskhi, "Steam-Plasma Burner Device with Integrated Gasification of Fuel", RU Patent 205967, No. 1, August 2021.
[22] A.V. Messerle, V.E. Messerle, A.B. Ustimenko, "Plasma Thermochemical Preparation for Combustion of Pulverized Coal", High Temperature, Vol. 55, No. 3, pp. 352-360, 2017.
[23] V.I. Kazantsev, D.M. Vavriv, P.M. Canilo, N.I. Rasyuk, K. Schuneman, S.V. Gritsayenko, A.V. Tymchik, AV. Messerle, "Investigation of Microwave Plasma Technology for Combustion of Low-Grade Coals", Thermal Engineering, No. 12, pp. 39-44, 2022.
[24] P. Pan, W. Peng, J. Li, H. Chen, G. Xu, T. Liu, "Design and Evaluation of a Conceptual Waste-to-Energy Approach Integrating Plasma Waste Gasification with Coal-Fired Power Generation", Energy, Vol. 238, p. 121947, 2022.
[25] I.H. Teke, M.S. Mamis, "An Investigation of Installation and Operational Difficulties in Lignite Coal Power Plants and Environmental Impacts", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 33, Vol. 9, No. 4, pp. 78-83, December 2017.
[26] EnerData, "Global Energy and Climate Outlook 2050 Website", 2023.
[27] Ministry of Energy of the Russian Federation, "Fuel and Energy Complex of Russia 2022: Functioning and Development", Moscow, Russia, 2023.
[28] E.I. Karpenko, V.E. Messerle, "Mathematical Modeling of Plasma Processes", Lectures, Ulan-Ude, East Siberian State University of Technology and Management, Russia, 2010.
[29] V.E. Messerle, M.N. Orynbasar, "Ecological Efficiency of Utilization Solid fuel Plasma Technology", Combustion and Plasma Chemistry, Vol. 19, No. 4, pp. 289-298, December 2021.
[30] D.V. Sosnin, A.V. Shtegman, I.A. Ryzhiy, E.A. Fomenko, S.D. Bor, C.O. Tsyrenov, A.V. Yakovenko, "Increasing the Efficiency and Increasing the Resource of the Plasma-Ignition System by its Modernization at Gusinoozerskaya TPP", Thermal Engineering, Vol. 68, No. 4, pp. 302-309, 2021.

BIOGRAPHIES

Name: **Andrey**
Middle Name:**Gennadievich**
Surname:**Baturkhtin**
Birthday: 01.03.1980
Birthplace: Chita, Russia
Specialist: Thermal Power Plants Department, Faculty of Energy, Chita State Technical University, Chita, Russia, 2002
Doctorate: Energy Systems and Complexes, Melentiev Energy Systems Institute, Siberian Branch, Russian Academy of Sciences, Irkutsk, Russia, 2022
The Last Scientific Position: Assoc. Prof., Department of Energy, Faculty of Energy, Transbaikal State University, Chita, Russia, Since 2002
Research Interests: Energy, Informatics, Economy
Scientific Publications: 59 Papers, 11 Books, 30 Patents, 58 Theses



Name: **Egor**
Middle Name: **Alexandrovich**
Surname: **Makhov**
Birthday: 16.05.1995
Birthplace: Chita, Russia
Bachelor: Thermal Power Plants Department, Faculty of Energy, Transbaikal State University, Chita, Russia, 2016
Master: Thermal Power Plants Department, Faculty of Energy, Transbaikal State University, Chita, Russia, 2018
Research Interests: Energy, Informatics, Economy
Scientific Publications: 5 Papers

Name: **Maxim**
Middle Name: **Stanislavovich**
Surname: **Bass**
Birthday: 08.07.1977
Birthplace: Vinnytsia, Ukraine
Specialist: Thermal Power Plants Department, Faculty of Energy, Chita State Technical University, Chita, Russia, 2000
Doctorate: Thermal Power Plants, their Power Systems and Aggregates, East Siberia State University of Technology and Management, Ulan-Ude, Russia, 2005
The Last Scientific Position: Assoc. Prof., Department of Energy, Faculty of Energy, Transbaikal State University, Chita, Russia, Since 2000
Research Interests: Energy, Informatics, Economy
Scientific Publications: 29 Papers, 4 Books, 10 Patents, 18 Theses

Name: **Sergey**
Middle Name: **Gennadievich**
Surname: **Batukhtin**
Birthday: 01.04.1988
Birthplace: Chita, Russia
Specialist: Thermal Power Plants Department, Faculty of Energy, Chita State University, Chita, Russia, 2010
Doctorate: Energy Systems and Complexes, Melentiev Energy Systems Institute Siberian Branch, Russian Academy of Sciences, Irkutsk, Russia, 2018
The Last Scientific Position: Assoc. Prof., Department of Energy, Faculty of Energy, Transbaikal State University, Chita, Russia, Since 2019
Research Interests: Energy, Informatics, Economy
Scientific Publications: 31 Papers, 6 Books, 8 Patents, 3 Projects, 10 Theses