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The clean combustion of solid fuel using a plasma-coal burner

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ABSTRACT

Solid fuels have a great chance to take a leading position in the energy market in the future from an environmental and energy point of view. The development of science and technology makes it possible to use coal with minimal harmful emissions. Also, looking at a sufficient supply for the coming years can preserve the energy balance around the world. This type of solid fuel is the primary source of thermal power plants and can maintain a long-term stable price. To burn low-reactive fuels (coal), highly reactive fuels (fuel oil or natural gas) are used, leading to various environmental and economic costs, climate change, and polluting the environment by providing initiatives to find alternatives to clean-burning minimal financial outlay. One of the promising technologies presented at various international exhibitions and widely used in some countries is plasma technology. Burners running on fuel oil or gas are replaced by a plasma-coal burner, which gives low-temperature plasma using a plasma torch. The temperature of the plasma-air torch at the outlet of the plasma torch in conventional plasma burners can reach 5000 K, which allows you to destroy harmful substances in your area.

Keywords: coal, pulverized coal thermal power plants, combustion, plasma-coal burner, plasma torch.

1. Introduction

Coal is the most widespread and vital source of electrical and thermal energy worldwide, currently providing about 40% of the world's energy. Coal-fired thermal power plants provide reliable, affordable, and constant power available on-demand to meet energy consumption needs. Coal continues to play a crucial role in the fight against energy poverty worldwide, as most of the world does not have access to modern and clean energy. Of particular relevance is the development of technology and ways to achieve zero emissions, especially carbon dioxide, which scientists define as a climate change factor (Fig. 1) [1].

Coal is a universal fuel because it can be burned, pyrolyzed, liquefied, gasified, etc. In Western and CIS countries, coal classifications differ depending on the stage of coalification (metamorphism). Carbon, hydrogen, sulfur, and nitrogen are the main chemical elements in coal. Therefore, coal can be represented as carbon (C) + ash content (Ac) + volatile (V) + moisture (W) = 100%. Table 1 shows the types and thermal characteristics of solid fuels.

The world energy industry is currently, and for the foreseeable future, focused on the use of organic fuels, mainly solid fuels. The utilization of coal in the energy sector meets various difficulties, leaving tremendous potential for optimizing and improving the efficiency of its combustion technologies. The following main difficulties in solid fuels are the sensitivity of the combustion process and the need to burn a considerable amount of additional auxiliary fuel to stabilize the combustion of a pulverized coal torch and kindling boilers.

Although the long period of use of coal has a disadvantage caused by the complex structure of coal, it is actively used in the world energy industry due to its many advantages during combustion. The deterioration of coal quality has become a trend worldwide, and the burning of

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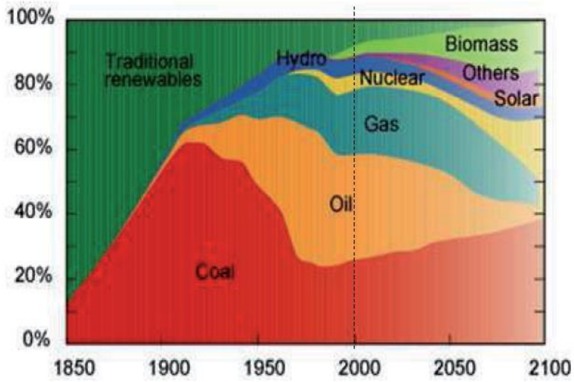

Fig. 1. The share of energy carriers in energy production.

Table 1. Thermal characteristics of solid fuels

Type of coal	W^w	A^d	V^{daf}	Q^l_w
Shale	40-50	75-80	48-50	1600-2000
Lignite	32-40	28-35	23-27	1900-2100
Brown coal	25-35	15-20	35-50	3000-3800
Hard coal	5-12	20-56	15-40	4000-5000
Anthracite	5-8	25-35	4-10	4300-6200
Petrocoke	1-2	2-3	3-4	8800-9700
Coal mixture	10.4	48.5	38.2	3150

Designations: W^w – moisture content per working mass, A^d – ash content per dry mass, V^{daf} – volatile yield per combustible mass, Q_l^w – lowest heat of combustion of coal per working mass.

low-grade energy coals worsens the ecological, economic, and technical indicators of boilers.

From the burning of low-grade coals with high ash content, humidity, sulfur content, and low volatile yield, it is possible to notice an increase in mechanical combustion, deterioration of ignition and fuel burnout, and harmful emissions (greenhouse gases, ash, nitrogen oxides, and sulfur).

There are various methods for improving ignition and stabilizing the combustion of low-grade coals with high ash content and low volatile yield, which mainly consist of thinning the grinding, heating the air mixture and secondary air, supplying high-concentration coal dust with subsequent dilution, and finally, co-combustion with coal of fuel oil and natural gas. The latest co-combustion with liquid fuel has become the most widespread.

More than 50 million tons of fuel oil per year are spent on kindling pulverized coal boilers from the cold and hot states and stabilizing the combustion of the pulverized coal torch. At thermal power plants, boilers are kindled (the kindling time is 3-14 hours) several times a year (up to 25 starts annually for one boiler), and the illumination of the pulverized coal torch is carried out periodically when the torch dims or the load decreases (Table 2).

Table 2. Fuel oil consumption for kindling boilers of various steam capacity

Boiler steam capacity, tons/hour	Fuel oil consumption per 1 kindling
50–75	3–6
160–200	10–25
220–420	30–80
640–670	80–100
950	100–140
1650	150–250
2650	250–350

For the efficient combustion of solid fuels, the use of expensive and environmentally unclean fuel oil and natural gas during the eruption of liquid fuels lose their relevance today. The modern development of energy is characterized by a reduction in the use of low liquid fuel, which is a valuable raw material, and the expansion of solid fuels, the quality of which is steadily declining.

2. Technical characteristics of the plasma-coal burner (PCB)

Instead of a traditional burner, there is the most efficient innovative plasma-coal burner for burning solid fuel. The fuel for this burner is coal dust, which replaces high-level fuels (fuel oil or natural gas). The technological process of a plasma-coal burner (PCB) occurs by heating an air mixture (coal dust + air) with electric arc plasma to the temperature of volatile coal and partial gasification of the coke residue. As a result, the highly active two-component fuel (combustible gas + coke residue) obtained from the source coal ignites and burns steadily in the boiler furnace.

During the gasification of coals, thermal transformations can cover the organic and mineral parts. The target products are obtained from both organic and ash mass of coals.

Electricity is used in the form of low-temperature plasma energy to ignite a pulverized coal torch. The conversion of electricity into electric arc discharge energy allows for a more active effect on the ignition and stabilization of the combustion of solid fuels.

The essence of a PCB consists of heating coal dust in oxygen-vapor plasma at a temperature of 2000–3000 K, with a high concentration of chemically active centers.

Let us consider the features of the interaction of electric arc plasma with an air mixture in a muffled cylindrical channel that provides minimal energy losses. When the flow of the «cold» air mixture ($T_{a.m.}$ = 350–400 K) comes into contact with the plasma flow from the nozzle of the plasma torch, coal particles and air are simultaneously heated. At the same time, only 3–5% of the air mixture initially falls into the interaction zone, which is predetermined by the natural thermophysical boundaries of a compact «plasma torch» burning in the volume of the burner device. And if the air is only heated from a plasma source, then coal particles up to 250 microns in size at 10^3–10^4 grad/s rates undergo heat stroke due to the thermal stresses in their volume, as a result of which coal particles are crushed into 8–10 fragments in a time of 0.01–0.05 s. This phenomenon leads to a sharp increase in the interface area between the gas and solid phases and, consequently, to an increase in the reactivity of the air mixture. Coal volatiles (CO, CO_2, CH_4, C_6H_6, N_2, H_2O) and nitrogen-containing components – pyridine (C_5H_5N) and pyril (C_4H_5N) – come out of these fragments of the initial particles.

Then atomic forms (O, H, N, C, S) are formed in the gas phase, including elements of the mineral part (Si, Al, Ca) and radicals (NH, CH, CN, OH, etc.). In addition, electronic gas (e), positive (C^+, H^+, N^+, CO^+, O^+, Si^+, K^+, etc.), and negative ions (O^-, H^-, N^{+2}) are present in the gas phase. The thermal explosion of pulverized coal particles repeatedly accelerates the release of volatile particles due to a more developed reaction surface and the appearance of tiny particles (less than 5 microns), which heat up to the temperature of explosive release much faster than large (50-100 microns) particles. Plasma interactions with pulverized coal fuel increase the energy efficiency of a PCB by 3-4 times compared with traditional fire processes. Moreover, the high temperature of the plasma torch and the heterogeneity of the temperature field in the PCB require special attention to the behavior of the mineral mass of the fuel.

New plasma technology is carried out by determining the degrees of development of calculation methods of the studied processes and devices related to plasma technologies. The story of calculation methods is closely related to theoretical, computational, and experimental studies of thermophysical and thermochemical processes. As a result, we understand those careful physicochemical calculations are required to improve plasma technology. (Fig. 2) [2].

The use of heavy fuel burners to start the boiler is harmful to the environment due to high emissions of heavy hydrocarbons and soot. It also has an economic character, such as the price of fuel is rising and is comparatively more expensive than other types of fuels. In addition, the installation of fuel oil is technologically complex and requires large investments and maintenance costs. There is also a need for more energy due to the continuous heating of fuel oil to maintain its liquidity [3].

Table 3 shows a comparison of traditional technology (fuel oil) and new technology (plasma-coal burner) for boiler kindling.

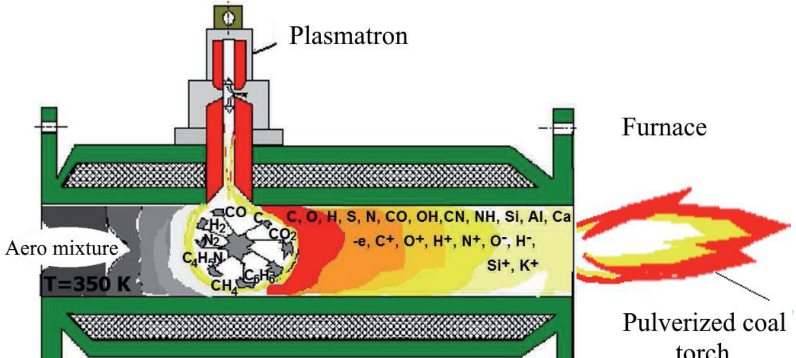

Fig. 2. The share of energy carriers in energy production.

Table 3. Technical characteristics of the plasma torch

Traditional technology (fuel oil)	New technology (plasma-coal burner)
1. Fuel oil consumption at thermal power plants (Russia and Kazakhstan)	
~6.1 million tons per year (the cost is approximately 2.5 billion dollars)	0
2. Capex on thermal power plants	
100%	5%
3. Operating costs	
100%	28-30%
4. Electricity consumption for own needs of thermal power plants	
3-5%	0.5-1.0%

The share of fuel oil in the total amount of heat generated in the boiler furnace can be up to 30%. Burning coal with fuel oil in the above proportions leads to chemical underburning, intense high-temperature corrosion of screens, an increase in the number of emissions of pollutants (compared with coal, fuel oil contains twice as much sulfur), a sharp decrease in the burning of solid fuel particles (its unburned part is emitted together with ash and smoke) and an increase in the frequency of accidents with superheaters.

The processes of ignition and combustion of low-grade coals with the help of plasma technology, which are characterized by environmental safety, high productivity, and relatively low cost of blowing, have received a noticeable promising development. The heating of the air mixture, which is a mixture of coal particles with air in the heat treatment chamber, is carried out by burning with electric arc plasma. The technology ensures reliable operation when using coals of different quality (with different humidity, volatile yield, and ash content). Plasma with a high concentration of energy is characterized by the presence of a large number of chemically active atoms, ions, radicals, and electrons. As a result, a more complete and rapid burnout of the pulverized coal torch is obtained, causing multiple accelerations of the thermochemical transformations of coal and oxidizer.

At the international exhibition EXPO–2017 in Kazakhstan, a promising technology of plasma combustion of solid fuel, that is, fuel-free ignition of boilers was presented [4].

The scheme of the plasma-coal burner of Gusinoozerskaya CDPS, operating on a boiler BKZ-640-140 with a steam capacity of 640 tons per hour, is shown in Fig. 3.

The experiments were carried out on this plasma-coal burner equipped with a plasma torch cylindrical ramjet burner with a diameter of 250 mm and a length of 2350 mm. A plasma torch with

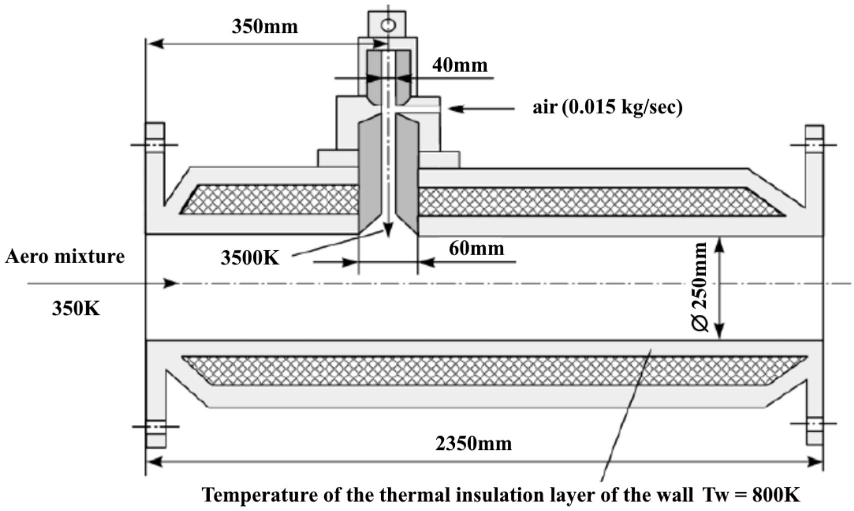

Fig. 3. Diagram of a plasma-coal burner (muffle burner, muffle, with plasmatron).

an electric power of 100 kW was used. At the same time, the average mass temperature of the low-temperature plasma at the outlet of the plasma torch was 4000 K.

In this experiment, Tugnui coal was used with the following characteristics: ash content – 19.4%; humidity – 14%; volatile yield – 45%; lowest heat of combustion – 23000 KJ/kg.

The consumption of air and coal through a plasma-coal burner was 1.75 and 3.5 tons per hour, respectively, and the temperature of the air mixture was 350 K.

According to the results of the study, at the initial section of the plasma-coal burner, 0.75 m from the axis of the plasma torch, the temperature profile is non-symmetrical and has only one maximum. This is a consequence of the aerodynamic disturbance caused by the interaction of the air mixture with a plasma torch propagating perpendicular to the flow of the air mixture. It deviates from its original direction, reacting to the magnitude and direction of the momentum of the flow of the air mixture. And the temperature profile at a distance of 2 m from the axis of the plasma torch has two pronounced maxima in the oppressed region. The maximum value of the wall temperature does not exceed 800 K. At the outlet of the muffle, the composition of the gas phase showed (in volume percentages): H_2 = 8.0; CO_2 = 2.0; H_2 = 8.0; CH_4 = 1.5; N_2 = 59.5; other = 0.5, including NO_x = 50 mg/nm^3 (Fig. 2).

The internal process in a plasma-coal burner consists of a rapid chemical and physical interaction between plasma and pulverized coal, which causes thermal decomposition of coal particles, the release of volatile substances, and their ignition. As a result, is a stable pulverized flame.

The entire process of plasma ignition and combustion of a PCB occurs due to the installed plasmatron. When pulverized coal and air are mixed, there is no shortage of oxygen. As an oxidizer and heat source, electric arc plasma provides a chemically active medium and a high temperature. As a result, there is partial gasification of the carbon residue and a complete release of volatile substances [5].

The use of a PCB in thermal power plants equipped with an arc plasma torch provides the oil-free start of pulverized coal boilers, flame stabilization, and simultaneous reduction of the formation of nitrogen oxides and unburned carbon. The plasma-coal burner (PCB) is based on plasma thermochemical activation of coal for combustion and consists of electric arc plasma heating of the fuel-air mixture to the temperature of coal volatilization and partial gasification of the carbon residue. Due to partial gasification of high or low-quality coal, an air-coal mixture is obtained, which consists of combustible gas and highly reactive coke residue. The use of PCB reduces the number of nitrogen oxides and unburned carbon by half, and carbon dioxide emissions can be reduced by 1–2%.

Due to the special properties of the low-temperature plasma coming out of the plasma torch, it allows obtaining a large amount of energy in a small volume at a high concentration of active atoms, ions, electrons, radicals, which positively affect the rate of chemical and physical reactions and the combustion of coal dust.

The operation of the PCB of the fuel-free boiler kindling is based on heating and ignition of coal dust by low-temperature plasma – a heated ionized gas with a temperature of 3000–5000 °C [6].

Due to the lack of fundamental knowledge of physics, the widespread use of plasma technology in the field of energy is limited. Some of them are related to the interaction between coal particles and plasma or the possible negative impact of plasma systems on the performance of a municipal boiler.

3. Plasma generator (plasmatron)

The most important part of a PCB is the plasma generator. The type and location of the plasma generator depend primarily on the application of the plasma system.

The formation of an electric arc between two electrodes and the injection of high-speed air through the arc formation area creates a plasma discharge. A direct current (DC) power supply is used as an energy source. Due to the high concentration of energy in the arc formation area, the injected air quickly heats up to a high-temperature level, which in this case can reach 10000 K in the arc area. The average temperature of the plasma flame at the outlet of the plasma generator can reach about 5000 K. To prevent overheating of the plasma generator, the entire body and electrodes are cooled with water.

Table 4 shows the technical characteristics of the plasma generator, which was investigated and used at pulverized coal thermal power plants.

The plasmatron is located at the initial site of the pulverized coal burner. An electric arc is formed in it between the electrodes, the anode, and the cathode. The plasma-forming gas (air) is blown between the electrodes and, heating up, forms a

Table 4. Technical characteristics of the plasma generator

Plasmatron power, kWt	50–350
Voltage, V	25–400
Arc current, A	200–900
Mass of the plasmatron, kg	25–35
The resource of the plasma torch electrodes, h	250 (cathode); 500 (anode)
Consumption of plasma-forming gas (air), kg/h	20–80
Plasma torch temperature, K	3000–6000
Weight of the power supply, kg	450

plasma torch. The average mass temperature of the plasma torch is 3500–4000 K. The shape of the air plasma torch and its isotherms are shown in Fig. 2. According to the measurement results, it was obtained that for a free plasma torch, the temperature of which reached 5000 K at the nozzle section of the plasmatron (Fig. 4).

The co-combustion of coal and fuel oil with a higher reactivity worsens the ecological and economic indicators of boilers: the mechanical combustion of fuel increases by 10–15% and the gross efficiency decreases by 2–5%, the rate of high-temperature corrosion of screen surfaces increases, the reliability of boiler blowing operation decreases, the yield of nitrogen oxides and sulfur increases by 30–40% (due to the higher sulfur content in fuel oil), emissions of carcinogenic vanadium pentoxide appear.

Coal particles and air, evenly mixed, enter the plasma-coal burner, which is a flow-through cylindrical channel with a plasma torch. First of all, the electric arc plasma heats the air and, consequently, carbon particles are heated. Coal particles turn into a gas phase when the temperature of the release of volatile substances is reached. The model is based on assumptions about the quasi-stationary flow of the process and its one-dimensionality, coal particles are considered isothermal, and ash (mineral mass) is an inert component. It is also assumed that the particles do not interact with each other. The interaction of the pulverized coal mixed with plasma is considered as heating of the pulverized coal stream with hot gas. The composition of coal is represented in the model by its organic and mineral masses. In the model, the composition of coal is represented as mineral (ash) and organic masses (CH_4, C_6H_6, CO, H_2, H_2O, CO_2, and carbon). The kinetics of heating plays a very important role in the process of separating volatile substances from the organic mass and there is a real dependence. In a plasma-coal burner (PCB), volatile substances are mixed with air and react [7].

At the same time, there is a general decrease in the temperature of coal combustion products at the outlet of the combustion chamber, which is associated with earlier ignition and fuel burnout and indicates an increase in fuel efficiency. A lower oxygen concentration at the outlet of the furnace in the case of using a plasma-coal burner (1%) and a higher (2%) when using fuel oil or natural gas indicates a more complete use of oxygen in the carbon oxidation reaction, which is confirmed by a higher concentration of carbon dioxide at the outlet of the furnace when working with a plasma-coal burner.

The use of a new technology PCB to activate the combustion of solid fuels increases the environmental and economic efficiency of their

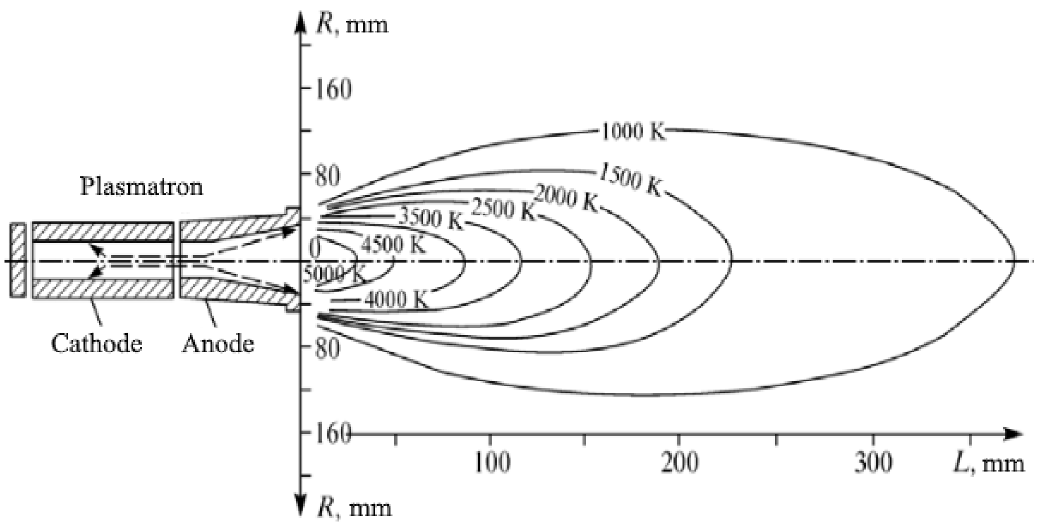

Fig. 4. Isotherms of an air plasma jet.

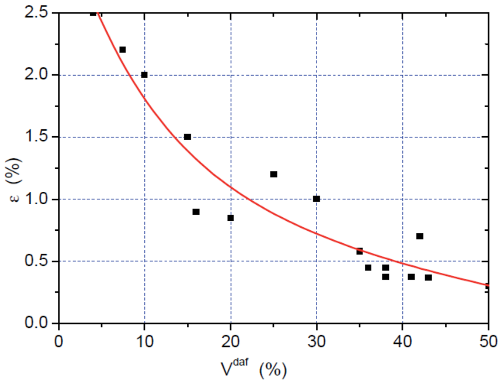

Fig. 5. Generalized experimental dependence of the relative electricity costs for a plasmatron (ε) on the yield of volatile coal (V^{daf}), obtained during tests of PCB at 16 different thermal power plants.

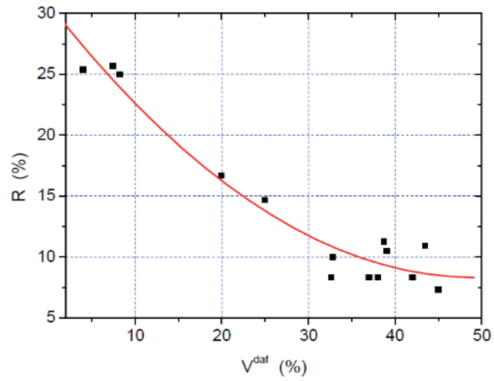

Fig. 6. Generalized experimental dependence of the relative thermal power of the PCB (R) on the yield of volatile coal (V^{daf}), obtained during tests of the PCB at 14 different thermal power plants for the period 1994-2004.

combustion by reducing residual carbon in the ash and emissions of nitrogen oxides against the background of a general decrease in the temperature of the combustion products of coal at the outlet of the furnace due to earlier ignition and fuel burnout.

The problem of emissions of carbon dioxide, methane, etc. causes general warming associated with global climate change on earth, flooding of vast areas of land, desertification, etc. These environmental impacts have developed into a universal problem at this time.

Plasma-coal burners that increase the efficiency of solid fuel combustion while reducing harmful chemical emissions from pulverized coal thermal power plants have been developed, tested, and investigated in industrial conditions. Plasma-coal burners eliminate the need to use expensive gas and fuel oil for combustion boilers and stabilization of the combustion of a pulverized coal torch.

According to the results of the study, we learned that plasma-coal burners provide stable ignition, reduction of mechanical combustion of fuel, and the temperature level in the upper part of the boiler furnace. Thanks to the two-stage mode of fuel combustion (PCB and boiler furnace), NOx emissions are reduced. On the basis of theoretical and experimental studies of plasma fuel-free kindling of pulverized coal boilers, generalized dependences on the yield of volatile coal of the relative cost of electricity per plasmatron and the relative thermal power of PCB are found. With the help of these dependencies, it is possible to determine a priori the required power of the plasma torch and the amount of PCB for kindling a pulverized coal boiler (Figs. 4 and 5) [8].

4. Conclusion

The demand for heat and electricity is growing every year, they directly affect the country's economy. And thermal power plants can provide uninterrupted and stable energy. In addition, the reserves of solid fuel will last for another 50 years. One of the disadvantages is inefficient combustion of solid fuel, which leads to boiler wear, environmental pollution, reduction of energy fuel reserves, various financial costs. This includes the use of fuel oil or natural gas as a highly reactive fuel for burning coal, for reasons of the high cost of liquid fuels and technologically complex blowing, as well as the content of harmful chemical elements, which soon, due to these reasons, a reduction of these liquid fuels was adopted. And a rational alternative solution is the use of a plasma-coal burner (PCB), which ensures cleanliness without the use of additional heavy fuels. The electric arc coming out of the plasma generator interacts with air and ionizes, turning it into a low-temperature plasma with an average temperature of 5000 K and has a high rate of thermochemical transformations. Further development of plasma technology in the energy sector can help to overcome the energy crisis.

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Чистое сжигание твердого топлива с помощью плазменно-угольной горелки

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Аннотация

Твердое топливо имеет большие шансы в будущем занять лидирующие позиции на энергетическом рынке с экологической и энергетической точек зрения. Развитие науки и техники позволяет использовать уголь с минимальными вредными выбросами, а также, глядя на достаточный запас на ближайшие годы, может сохранить энергетический баланс во всем мире. Этот вид твердого топлива является основным источником тепловых электростанций и может сохранить долгосрочно стабильную цену. Для сжигания низкореакционного топлива (угля) используются высокореакционные виды топлива (мазут или природный газ), которые приводят к различным экологическим и экономическим издержкам, изменению климата и загрязняют окружающую среду. Предоставляя инициативы по поиску альтернативы чистому сжиганию и с минимальными финансовыми затратами. Одной из перспективных технологий, которая представлена на различных международных выставках и широко используется в некоторых странах,

является плазменная технология. Горелки, работающие на мазуте или газе, заменяются плазменно-угольной горелкой, которая дает низкотемпературную плазму с помощью плазмотрона. Температура плазменно-воздушного факела на выходе из плазмотрона в обычных плазменных горелках может достигать 5000 К, что позволяет полностью уничтожать вредные вещества в своей области.
Ключевые слова: уголь, пылеугольные теплоэлектростанции, сжигание, плазменно-угольная горелка, плазмотрон.

Плазмалық-көмір оттығын пайдаланып қатты отынның таза жануы

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Аңдатпа

Қатты отынның болашақта энергетикалық нарықта экологиялық және энергетикалық тұрғыдан жетекші орын алуға үлкен мүмкіндігі бар. Ғылым мен техниканың дамуы ең аз зиянды шығарындылары бар көмірді пайдалануға мүмкіндік береді, сондай-ақ алдағы жылдарға жеткілікті қорға қарап, бүкіл әлемде энергетикалық теңгерімді сақтай алады. Қатты отынның бұл түрі Жылу электр станцияларының негізгі көзі болып табылады және ұзақ мерзімді тұрақты бағаны сақтай алады. Төмен реакциялы отынды (көмірді) жағу үшін әр түрлі экологиялық және экономикалық шығындарға, климаттың өзгеруіне әкелетін және қоршаған ортаны ластайтын жоғары реакциялы отын түрлері (мазут немесе табиғи газ) пайдаланылады. Таза күйдірудің баламасын және ең аз қаржылық шығындарды табу бойынша бастамалар ұсыну. Әр түрлі халықаралық көрмелерде ұсынылған және кейбір елдерде кеңінен қолданылатын перспективті технологиялардың бірі-плазмалық технология. Мазутта немесе газда жұмыс істейтін жанарғылар плазмотрон көмегімен төмен-температуралы плазма беретін плазмалық-көмір жанарғысымен ауыстырылады. Кәдімгі плазмалық жанарғылардағы плазмотрон шығысындағы плазмалық-ауа алауының температурасы 5000 К жетуі мүмкін, бұл өз аймағындағы зиянды заттарды толығымен жоюға мүмкіндік береді.
Кілт сөздер: көмір, тозаң-көмір жылу электр станциялары, жағу, плазмалық-көмір жанарғы, плазмотрон.