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Ecological efficiency of utilization solid fuel plasma technology

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ABSTRACT

Coal is the main fuel of thermal power plants (TPP), which provides more than 40% of electricity generation and about 25% of thermal energy in the world. Unlike renewable energy sources, thermal power plants supply consumers with energy around the clock and without interruption, regardless of the time of year. Expensive highly reactive fuel (fuel oil or natural gas) is burned to kindle pulverized coal boilers of thermal power plants. The burning of heating oil leads to an increase in harmful emissions into the atmosphere and initiates the search for alternative solutions for fuel-free kindling of pulverized coal boilers of thermal power plants. The most effective solution to this problem is the use of innovative plasma technology for fuel-free boiler kindling. Currently, much attention is paid to the fight against global warming and related environmental problems that lead to a negative impact on people, animals, and plants. The installation of plasma-coal burners in the furnaces of power boilers, providing their fuel-free kindling and illumination of the pulverized coal torch, significantly improves the environmental and economic indicators of thermal power plants. Currently, one of the priority tasks is to optimize the design of plasma-coal burners at existing thermal power plants.

Keywords: thermal power plant, pulverized coal fuel, combustion, plastron, plasma-coal burner.

1. Introduction

Renewable energy sources are becoming increasingly necessary due to concerns about the impact of anthropogenic emissions on the climate. Different types of renewable energy sources can be associated with different effects and different term-ecological costs on energy supply systems [1-8]. Active research has begun on the efficient and clean use of energy resources due to limited resource reserves and air pollution due to greenhouse gas emissions. The most widely used and affordable type of fuel worldwide is coal. Therefore, an important role is played by the environmentally and energy-efficient use of this common fuel [9].

The main source of energy is coal, which accounts for about 30% of the total energy consumption. In recent years, many studies have been conducted aimed at reducing the harmful effects of coal-burning in connection with global warming. Many coal-fired thermal power plants have significant problems with performance or operability due to aging. Accordingly, work is underway to renew thermal power plants, which is of great importance to compensate for the growing demand for energy [10].

The main air pollution due to coal-fired power plants running on fuel oil leads to serious consequences for human and animal health and the ecology of the region. People living in these regions have problems with asthma, cancer, heart and lung, neurological diseases, and the environment is polluted by acid rain, global warming for the environment [11].

When coal is burned in many quantities in thermal power plants, oxygen reacts with emissions of both sulfur, carbon, and nitrogen and forms the corresponding oxides: carbon monoxide (CO) and carbon dioxide (CO_2), sulfur

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dioxide (SO_2), and sulfur trioxide (SO_3), as well as nitrogen oxide (NO) and nitrogen dioxide (NO_2), respectively. Emissions of these gases are indirectly or directly associated with many health problems, including diseases of the cardiovascular system, skin, brain, blood, and lungs, as well as various types of cancer.

During the process of combustion of coal, energy is released when the carbon atoms are torn apart. However, various chemical reactions transfer heavy metals and toxic pollutants to the environment.

On average, coal-fired power plants generate the following amounts of pollutants per year (Fig. 1):

1. CO_2 (carbon dioxide) pollution from power plants causes global warming and climate change. Estimated 3.7 million tons.

2. The toxic heavy metal that pollutes the air, water, and earth is mercury. It can damage the nervous, digestive, and immune systems and poses a serious threat to the development of the child (170 pounds).

3. When the sulfur in the coal reacts with oxygen, SO_2 (Sulfur dioxide) is formed. It combines with other molecules in the atmosphere to form small acidic particles. These small particles can penetrate and cause various diseases such as bronchitis, asthma. Also, pollute with acid rain and smog (10,000 tons).

4. NO_x (nitrogen oxides) are visible in the form of smog and irritate the lung tissue, making people more susceptible to chronic respiratory diseases and worsening asthma (10,200 tons).

5. Particulate matter is linked with aggravated asthma, chronic bronchitis, cardiovascular effects (500 tons).

6. Lead, cadmium, and other toxic heavy metals (114 pounds).

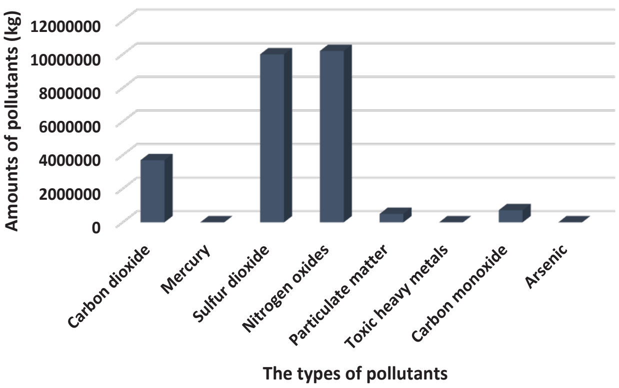

Fig. 1. Amounts of pollutants generated by coal-fired power plants in kg per year.

7. Carbon monoxide causes headaches and other heart diseases (720 t).

8. Arsenic causes cancer in one out of 100 people who drink water containing 50 parts per billion (225 pounds) [12].

Reducing carbon dioxide emissions from coal combustion at traditional thermal power plants can only be achieved by increasing efficiency. For example, increasing the efficiency of thermal power plants from 30 to 40% could reduce CO_2 emissions by about 25%.

Of particular relevance is the study of heat and mass transfer processes occurring in the combustion chambers of pulverized coal thermal power plants (TPP). Mainly, the start-up of the boiler is carried out using auxiliary heavy oil burners. This start-up method is expensive due to the still rising and high crude oil prices. The method is also harmful to the environment due to high emissions of soot and heavy hydrocarbons. Moreover, heavy oil installation is technologically complex and requires high investments and maintenance costs. As well as, large energy losses for heating liquid fuel [13].

When using coals, there are characteristic problems such as the high sensitivity of the combustion process to the properties and the need to burn a huge amount of additional auxiliary fuel to stabilize the combustion of a pulverized coal torch and kindling boilers.

2. Ecological efficiency of plasma-coal burner (PCB)

In the conditions of strict standards for crude oil, it seems rational to find another way to start up as pulverized coal boilers without using liquid fuel. From an environmental, economic, and energy point of view, it would be cost-effective to start up a boiler using pulverized coal as fuel. However, it is not easy to keep the necessary stable operation and ignition of the pulverized coal burner in the furnace of a cold boiler. Accordingly, an additional high-power ignition source is required, sufficient to cover energy losses in a cold environment. Efficient fuel use is the thermochemical preparation of coals for combustion, including plasma technologies characterized by high productivity, environmental cleanliness, and relatively low cost of equipment. To solve this problem, necessary such a source of ignition as plasma generators (plasma torches), which allow reducing the cost of operation and investment, as well as reducing the negative impact of starting the boiler on the environment.

They work on electric energy, installed directly on pulverized coal burners (Fig. 2) [14].

The use of electric arc plasma in many cases is energetically and environmentally more efficient than the use of traditional firing methods, since plasma with a high concentration of energy, characterized by the presence of a large number of chemically active atoms, radicals, ions, and electrons in it, contributes to the multiple accelerations of thermal and chemical transformations of coal and oxidizer, hence, the complete burnout of the torch.

In plasma reactors of the combined type, the electric arc zone and the zone of thermochemical transformations of coal are combined in one working volume, which increases the efficiency of the process, and the heating of raw materials is carried out directly by an arc containing active centers.

The use of electric arc plasma with a high energy concentration (200-300 MW/m^3) of chemically active ions (O^{2-}, H^{2-}, OH^-, C^+, H^+), atoms (O, H, C), radicals (OH, CH, HO_2), and electron gas contributes to the multiple accelerations of thermochemical transformations of fuel and oxidizer. Figure 3 shows the physical scheme of the fuel-free ignition of the air mixture (coal dust + air) in the plasma-coal burner.

The tightening in the future of the sale of fuel with a sulfur content of more than 0.5% and an increase in the price of liquid fuels (fuel oil) leads to finding an alternative to fuel-free ignition. Kazakh scientists have developed a plasma ignition technology that has been widely used in the world. This technology was presented by Professor Vladimir Messerle at the world exhibition EXPO-2017 (Astana). In China, for example, at pulverized coal thermal power plants, this technology accounts for 40% of the total installed capacity of the country (about 1000 boilers are equipped), it is used to heat and ignite part of the fuel mixture and further ignite and stabilize the burning of the main torch.

Comparatively, the plasma activation of coal particles works more efficiently for ignition and combustion stabilization than fuel oil burners. Plasma combustion systems can be used to promote early ignition and improved flame stabilization of pulverized coal. In addition, igniting coal with plasma reduces harmful emissions and

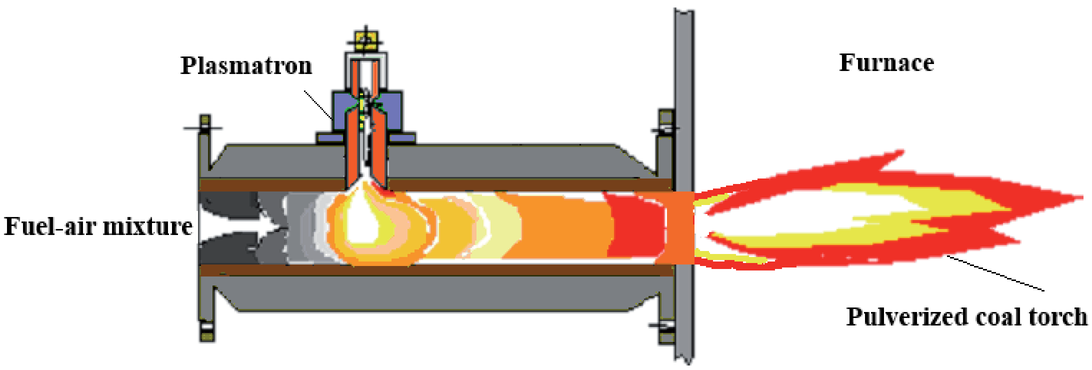

Fig. 2. Working principle of the plasma-coal burner (PCB).

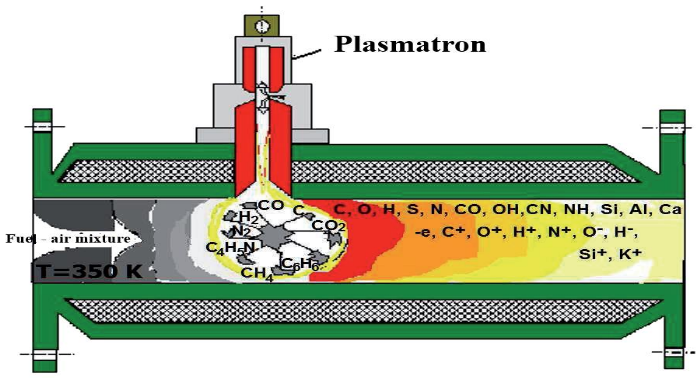

Fig. 3. The scheme of interaction of an air mixture with a plasma torch.

requires less energy to start and stabilize the flame in thermal power plants. Consistently, in the process, the oxidation of chemical reactions is accelerated and free radicals are formed. This is due to the additional crushing of coal particles by plasma. Kanilo et al. reported that the use of microwave plasma torches instead of fuel oil burners reduces the energy consumption almost maximum at startup. During plasma activation, coal gasification and partial carbon oxidation are obtained by supplying a coal/air mixture to the plasma torch, where the plasma flame contains more energy. The carbon is mainly oxidized to carbon monoxide at the furnace inlet, which is highly flammable [15-20].

Known advantages of plasma processes:

- Environmental cleanliness;
- High concentration of energy;
- High selectivity;
- Slight inertia;
- The possibility of full automation;
- The possibility of processing various types of fuel;
- Dramatic acceleration of chemical reactions;
- Small dimensions of the main equipment.

Among the methods of coal processing, the processes of its full and partial gasification have received significant development. Methods of partial gasification of low-grade coals are based on the use of combustible gas obtained during gasification as more highly reactive than the original coal. After separating the solid residue, the combustible gas can be burned in furnaces or used to illuminate a pulverized coal torch. In our case, partial gasification occurs due to an external source of the plasmatron, an allothermic type of energy supply to the process.

During the thermochemical preparation of coal, its molecular structure is destroyed or rebuilt to one degree or another. The thermal transformation affects only the organic mass of coals, practically without affecting their mineral part. The methods of thermal preparation include heating of the entire air mixture before mixing with secondary air and heat treatment of a smaller part of the pulverized coal stream with its last mixing with the rest of the dust and secondary air.

The essence of the thermal preparation of solid fuel is to heat the flow of the pulverized coal mixture in a special chamber to a temperature exceeding the temperature of self-ignition of coal when there is a shortage of oxygen. At the same time, there is an almost complete release of volatile and partial combustion and/or gasification of coal carbon is possible. As a result, at the exit from the thermochemical fuel preparation chamber into the furnace, the resulting highly reactive two-component fuel (coke residue + gas) or fuel mixture ignites when mixed with secondary air and burns steadily without using another fuel (for example, fuel oil or gas) to stabilize the flame.

The whole process of plasma thermochemical preparation of solid fuel for combustion is carried out in a plasma fuel system. And the plasmatron in it is installed on the lined channel of the air mixture of the burner. The air mixture entering the burner interacts with the plasma jet flowing from the nozzle-anode of the plasmatron. The average temperature of the plasma jet is 3000-5000 ^{o}C, depending on the electric power of the plasma torch and the flow of plasma-forming air. The basic principle of plasma thermochemical preparation of fuel for combustion is the stepwise nature of the effect of a plasma source on pulverized coal fuel: first, the plasma jet (electric arc plasma) interacts with a small part of the air mixture, as a result of heating, volatile coal is released, and partial gasification of the coke residue is carried out with the formation of a highly reactive two-component fuel (coke residue + combustible gas). Then the highly reactive two-component fuel itself, oxidizing in the primary air of the air mixture, heats the rest of the air mixture, which is not in direct contact with the activator and the allothermic source - the plasmatron. Thus, it gradually activates the main flow of the air mixture. As a result, all the fuel passing through the plasma fuel mixture is subjected to plasma thermochemical preparation. When entering the combustion chamber and mixing with secondary air, it ignites intensively and burns steadily, in turn, stabilizing the combustion process of pulverized coal flares not subjected to plasma thermochemical fuel preparation.

The cold air mixture enters the plasma fuel mixture, where it is exposed in the plasma flare zone, forming a highly reactive two-component fuel from low-grade coal.

In the case of low-reactivity coals (Vr <30%), the flow of the air mixture in front of the plasma-fuel system is divided into two unequal parts. The smaller of them enter the chamber with a plasma source. The heating of most of the air mixture occurs as a result of oxidation of a smaller part of the fuel that has undergone plasma thermochemical preparation. In the case of high reactivity (Vr >30%), there is no need to separate the air mixture beforehand. Nevertheless, 3–5% of the air mixture is in direct contact with the plasma torch, which is predetermined by the natural thermophysical boundaries of a compact plasma torch burning in the volume of the plasma-fuel system.

Plasma-fuel systems tested and developed in industrial conditions provide ignition and increase the efficiency of coal combustion while reducing harmful emissions from pulverized coal thermal power plants. The economic effect of the introduction of a plasma fuel system depends on the ratio of prices for fuel oil, gas, coal, depending on which the payback period varies from 1 year to 2 years.

For efficient fuel combustion, the residence time of reagents (carbon particles + oxidizer) in the plasma fuel system is affected, for high temperatures (3000-5000 K) – 0.001-0.1 s, low temperatures (1000-2000 K) – 0.15-0.3 s.

Advantages of the plasma fuel system compared to traditional technologies, including fluidized bed and circulating fluidized bed combustion:

– the refinement of coal of any quality occurs before its combustion due to thermochemical preparation of the fuel, which results in an increase in reactivity and recombination of atomic nitrogen of the fuel, which comes out together with volatile, into molecular nitrogen. For this reason, the formation of nitrogen oxides from molecular nitrogen is possible mainly at furnace temperatures above 1700 ^{o}C (thermal nitrogen oxides);

– low costs for plasma equipment due to its small dimensions and the high energy concentration in electric arc plasma torches (about 200-250 MW/m^3);

– small values of the relative electrical power of plasma torches for thermochemical fuel preparation (0.5-1.5%) of the thermal power of the pulverized coal burners on which they are installed. For comparison, the cost of electricity for the own needs of conventional pulverized coal boilers is 8-10%;

– the use of plasma-energy technologies at thermal power plants makes it possible to expand the range of coals burned in the same boiler and, ultimately, reduce the sensitivity of pulverized coal boilers to fuel quality;

– low inertia of plasma ignition systems, which makes it possible to use them in the "pick-up" mode of the torch;

– the rapid payback and low cost of the introduction of plasma energy technologies while reducing emissions of nitrogen oxides, sulfur, and vanadium pentoxide and mechanical combustion of fuel with plasma illumination of a pulverized coal torch makes them practically the only real means for today to increase the ecological and economic efficiency of using solid fuels and replacing scarce and expensive fuel oil and natural gas in the fuel balance of thermal power plants in the required volumes.

Plasma technologies provide significant savings in liquid and gaseous hydrocarbon fuels, traditionally used for boiler kindling and stabilization of combustion low-grade coals. However, the development of plasma-energy technologies is largely hindered due to the lack of adequate mathematical models that allow calculating with the necessary accuracy the processes occurring inside the heat treatment chamber.

In contrast to traditional methods of thermochemical preparation of fuel (TCPF), certain features are inherent in the burning of plasma technology:

– the plasma jet flows into the stream at a speed of ~ 200 m/s with a huge temperature gradient between the jet and the stream, i.e. the intensity of turbulent heat transfer into the flow of the air mixture (coal dust mixture with air) is very high, which contributes to its rapid heating and ignition;

– it has been experimentally established that coal particles when interacting with a high-temperature plasma jet at a heating rate of 103-104 degrees/c, are subjected to a thermal shock and split into dozens of fragments due to thermal stresses, which leads to a sharp increase in the reaction surface and a corresponding increase in the rate of heat release during combustion, i.e. acceleration of the TCPF. In addition, in the plasma TCPF, a part of coal dust, which is the main fuel, is used as fuel for heating the air mixture. Simplify the technological process as a whole.

3. The comparison of traditional and new technology

The main advantages of using plasma-coal burners (PCB) in comparison with traditional solutions:

– the manufacturability of TCPF using PCB. From the point of view of manufacturability, the fuel oil TPP is more complex: it inevitably requires the presence of a fuel oil farm with well-known, inherent problems. In the case of fuel oil TCPF, the appearance of additional links in the ignition chain makes the possibility of its use in the flare pick-up mode more uncertain. At the same time, due to the almost inertia-free launch of the plasma torch, there are no obstacles to the use of plasma TCPF in this mode;

– arrangement of the PCB with boiler equipment. In the case of fuel oil thermal treatment (for example), the chamber has an internal diameter of 630 mm, which is impossible to reduce several times. It is practically impossible to integrate such a chamber into an existing burner. The most likely solution is to install the camera in an embrasure specially created for it, which is associated with additional costs for re-equipment of the boiler. The newly installed, rather bulky equipment will create certain difficulties in the maintenance of boiler equipment at work sites, where there is already a shortage of available space. Due to the higher energy efficiency of the plasma TCPF, the dimensions of the PCB allow it to be integrated into the main burner of the boiler without changing the defining parameters of the latter;

– environmental aspects. With plasma TCPF, the heating of the flow of the air mixture is carried out mainly as a result of the combustion of a certain part of coal. At the same time, fuel nitrogen, responsible for the formation of «fuel» nitrogen oxides, which make up 90-95% of NO_x emissions, comes out together with volatile coal and forms molecular nitrogen in conditions of oxidant deficiency. Only «thermal» nitrogen oxides can be formed from the latter. Moreover, due to the lack of an oxidizer, the temperature of gases in the PCB is significantly lower than the temperature of the torch in the furnace and «thermal» nitrogen oxides are practically not formed. In the case of fuel oil TCPF, the heat necessary for the thermochemical preparation process is supplied as a result of the combustion of fuel oil (Figs. 4 and 5).

Fuel oil burnout should be complete. At the same time, an excess of oxygen must be provided,

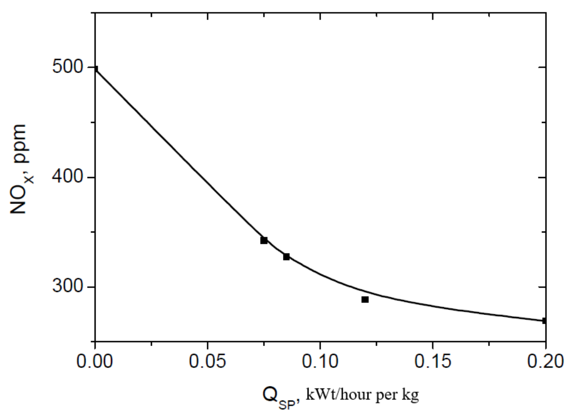

Fig. 4. Reduction of NO_x concentration during plasma stabilization of combustion coal torch depending on specific energy consumption (Q_w) for the process, reduced to 1 kg of coal.

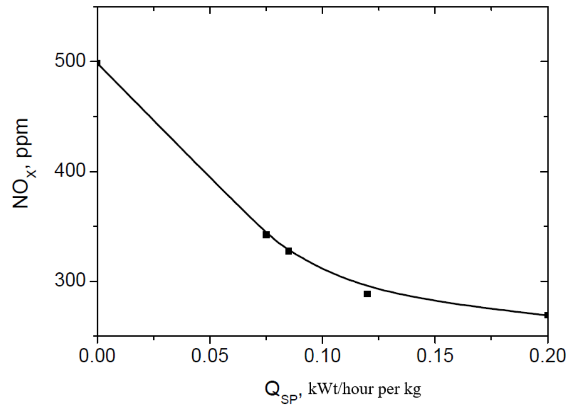

Fig. 5. Reduction of mechanical burn (q4) during plasma stabilization of combustion coal torch depending on the specific energy consumption for the process, reduced to 1 kg of coal.

which is necessary for the thermochemical transformations of coal in the TCPF chamber. Due to the higher reactivity of fuel oil, in comparison with coal, combustion will occur in conditions of increased excess air and at a higher temperature than coal combustion. In this case, conditions for the formation of both "fuel" and "thermal" nitrogen oxides are more likely. As a rule, the sulfur content in fuel oil is higher than in coal, which entails an increase in the emission of sulfur oxides. Vanadium is present in the fuel oil, which forms a carcinogen – vanadium pentoxide. Vanadium is also the cause of high-temperature corrosion of heating surfaces, and it practically does not occur in coal;

– economic indicators. As a rule, the cost of fuel oil is several times higher than the cost of coal in terms of conventional fuel. This makes the use of PCB for the implementation of plasma thermochemical preparation of fuel for combustion quickly recoupable (the previously used heating oil is replaced by coal dust itself). The payback period of the plasma system of oil-free ignition of coals, as a rule, does not exceed 12-24 months.

Studies have shown that where carbon is present in the fuel, carbon monoxide and the main gas formation of NO is mostly concentrated in the zone of the main distribution of the fuel flow from the burners. At the same time, the distribution of curves in this area is ambiguous, indicating a complex process of forming nitrogen oxides in this region and the influence of plasma activation on the formation of NO. With an increase in plasma-activated flows and, accordingly, due to an increase

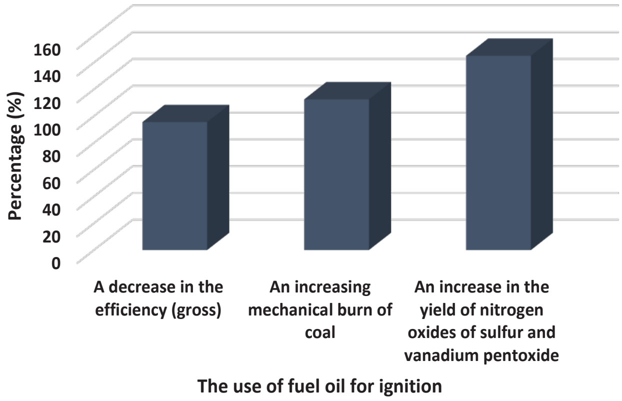

Fig. 6. The use of fuel oil for ignition in thermal power plants.

in the CO content in the incoming highly reactive two-component flow, maximum CO values are observed in the cross-section plane of the burners. It is seen that the use of plasma burners leads to a decrease in the total concentration of NO and CO at the outlet of the furnace space. In particular, to reduce harmful CO_2 emissions is used the re-powering of installed capacity at thermal power plants [21-23].

When burning fuel oil and coal together, several economic, environmental, and technical problems arise. These are the difficulties of using and storing fuel oil in winter conditions; a decrease in the efficiency (gross) (by 4-5%); an increasing mechanical burn of coal (10-15%); an increase in the yield of nitrogen oxides (by 40-50%) of sulfur and vanadium pentoxide (Fig. 6).

Based on the above, we can conclude about the advantages of using plasma technologies in terms of environmental aspects of fuel combustion compared to the use of fuel oil. The use of plasma technologies leads to a decrease in nitrogen oxides by 1.5-2 times and mechanical combustion by 2-3 times. In addition, the exclusion of fuel oil from the technological process of kindling allows reducing vanadium pentoxide emissions by 90-95% (Fig. 7).

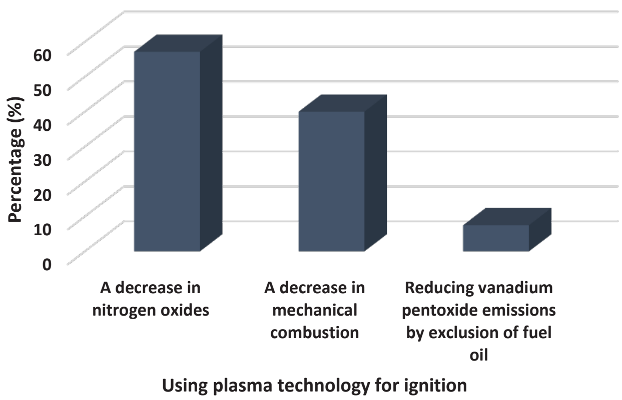

Fig. 7. Using plasma technology for ignition in thermal power plants.

The above figures show comparisons from an environmental point of view of the use of fuel oil and plasma technologies for ignition in thermal power plants [24].

4. Conclusion

It should be noted that the installation of a plasma burner in the combustion chambers of power boilers significantly improves the environmental performance of thermal power plants. Nowadays, optimizing the design of plasmatron to increase its power and efficiency is the priority. Coal-fired power plants are reliable in terms of stability. And the use of new innovative technologies makes it environmentally and economically beneficial for all mankind. This is a very important point to prevent environmental problems, which means the lives of people and animals. As well as plants and global warming in general. New technologies and techniques allow us to stop this process to the maximum and improve the quality of life.

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Экологическая эффективность использования твердотопливной плазменной технологии

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Аннотация

Уголь является основным топливом тепловых электростанций (ТЭС), которые обеспечивают более 40% выработки электроэнергии и около 25% тепловой энергии в мире. В отличие от возобновляемых источников энергии тепловые электростанции круглосуточно и бесперебойно снабжают энергией потребителей независимо от времени года. Для растопки пылеугольных котлов ТЭС сжигается дорогостоящее высокореакционное топливо (мазут или природный газ). Сжигание топочного мазута приводит к увеличению вредных выбросов в атмосферу и инициирует поиск альтернативных решений для безмазутной растопки пылеугольных котлов ТЭС. Наиболее эффективным решением этой проблемы является использование инновационной плазменной технологии безмазутой растопки котлов. В настоящее время большое внимание уделяется борьбе с глобальным потеплением и связанным с ним экологическим проблемам, приводящим к отрицательному воздействию на людей, животный и растительный мир. Установка плазменно-угольных горелок в топках энергетических котлов, обеспечивая их безмазутную растопку и подсветку пылеугольного факела, значительно улучшает эколого-экономические показатели ТЭС. В настоящее время одной из приоритетных задач является оптимизация конструкции плазменно-угольных горелок на действующих ТЭС.

Ключевые слова: тепловая электростанция, пылеугольное топливо, горение, плазмотрон, плазменно-угольная горелка.

Қатты отынның плазмалық технологиясын қолданудың экологиялық тиімділігі

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Аңдатпа

Көмір әлемдегі электр энергиясын өндірудің 40% - дан астамын және жылу энергиясының 25% - ын қамтамасыз ететін жылу электр станцияларының (ЖЭС) негізгі отыны болып табылады. Жаңартылатын энергия көздерінен айырмашылығы, жылу электр станциялары жыл мезгіліне қарамастан тұтынушыларды тәулік бойы және үздіксіз энергиямен қамтамасыз етеді. ЖЭС шаң-көмір қазандықтарын жағу үшін қымбат тұратын жоғары реактивті отын (мазут немесе табиғи газ) жағылады. От жағатын мазутты жағу атмосфераға зиянды шығарындылардың көбеюіне алып келеді және ЖЭС шаң-көмір қазандықтарын мазутсыз жағу үшін балама шешімдерді іздеуді бастайды. Бұл мәселенің ең тиімді шешімі қазандықтарды майлаусыз жағудың инновациялық плазмалық технологиясын пайдалану болып табылады. Қазіргі уақытта адамдарға, жануарлар мен өсімдіктер әлеміне теріс әсер ететін жаһандық жылынумен және онымен байланысты экологиялық мәселелермен күресуге көп көңіл бөлінеді. Энергетикалық қазандықтардың оттықтарында плазмалық-көмір жанарғыларын орнату, олардың мазутсыз жағылуын және тозаң-көмір алауын жарықтандыруын қамтамасыз ете отырып, ЖЭС-тің экологиялық-экономикалық көрсеткіштерін едәуір жақсартады. Қазіргі уақытта басым міндеттердің бірі жұмыс істеп тұрған ЖЭС-те плазмалық-көмір жанарғыларының конструкциясын оңтайландыру болып табылады.

Кілт сөздер: жылу электр станциясы, ұнтақты-көмір отын, жану, плазмотрон, плазма-көмір жанарғы.