SYSTEMS OF IGNITION AND COMBUSTION STABILIZATION FOR WATER-COAL FUEL

by

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The paper presents the review of researches of the ignition and combustion stabilization of the water-coal fuel. Working models of plants are described, the results of their tests in laboratory and industrial conditions are given. Two schemes of the water-coal fuel ignition are presented – one with burners with hydrocarbon (solar) fuel, and the other with the system of plasma ignition. Advantages of these two systems are described. The promising future of the systems of plasma ignition application in industrial conditions is demonstrated.

Key words: *water-coal fuel, ignition and combustion stabilization, burners, plasma ignition system, plasmatorch, flow mixing, preparation of water-coal fuel, environmental index*

Introduction

For more than 30 years the systems of plasma ignition (SPI) of coal-dust fuel for boilers have been developed and utilized in Russia and abroad. There are industrial systems for power plant boilers of high, medium, and low power used, in particular, in heating systems [1].

In recent years, the works related with the ignition and combustion stabilization of water-coal fuel (WCF) arouse interest, especially in the regions with big quantity of coal hydrolicking sludge. WCF is attractive because it combines the properties of liquid and dusty fuels, can be prepared and stored on site, or be transported via pipeline.

The WCF presents a disperse system consisting of fine-milled coal, water, and plastifying reactant:

- coal – class 0-200 (500) μm 50-70%,
- water 29-49%,
- plastifying reactant <1%,
- ignition temperature 450-650 °C,
- combustion temperature 950-1050 °C,
- lower heating value 1,500-4,000 kcal/kg.

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The distinctive property of WCF from other kinds of liquid fuel are its high density (1.2-1.3 g/cm^3), high viscosity (about 1,000 mPa·s), modest heating value (2,000-4,000 kcal/kg), absence of light inflammable fractions, high content of water (35-50%).

Peculiarities of water-coal fuel ignition and combustion

Today, both in Russia and abroad, specific requirements to the technology of WCF combustion and applied design elements and equipment have come out from the researching and design activities as well as from the experience of the industrial operation of boilers with the WCF [2, 3].

As was mentioned above, the ignition and combustion stabilization of the WCF torch is an important challenge.

Fine spraying of WCF is carried out with pneumatic-mechanical sprayers designed in JSC Research and Practice Enterprise "Sibekotekhnika". To ignite the sprayed WCF torch, it is necessary to provide the needed ignition temperature ~450-650 °C (for the coals with increased volatile content), and up to 650-750 °C for the WCF from anthracite coals.

When developing burners for WCF, designers must also take into account that during WCF spraying and combustion, a long torch occurs, and the high-temperature core shifts to the torch "tail".

The following methods of torch stabilization are applied in order to provide the stable combustion of WCF in the burner:

- a burner tunnel,
- fuel and air jets collide at a certain angle,
- fuel and air jets are swirled,
- air and fuel are heated,
- recirculation of combustion products over the torch periphery and axis,
- early supply of air to the fuel jet base,
- back radiation of the heated refractory onto the torch (ignition belt),
- torch division into several jets,
- cyclone (swirling-type) furnaces,
- an auxiliary black-oil or gas torch, and
- a plasmatorch to generate air plasma.

To realize the listed conditions in high-power boilers, the following engineering solutions are utilized:

- high-effective pneumo-mechanical and other sprayers,
- high-reactive kinds of fuel (liquid, gaseous), or low-temperature plasma, and
- heated blow air (up to 400 °C) supplied to the torch base.

The preferable model of spraying is shown schematically in fig. 1. It provides the maximum possible heat application to the sprayer torch base, both by periphery jets of hot gases and by the circulation flows inside a hole cone of the sprayed fuel [4, 5].

Without thoroughgoing modification of boilers and boiler cells in available boiler-houses with standard steam and water-heating boilers with thermal power up to 25 MW, because of their small size and, often, absence of free room for air heaters and other auxiliary equipment, the above engineering solutions can hardly be realized. The best decision would apparently be the development of new boilers especially designed for WCF combustion.

For the independent stable combustion of WCF, the combustion chamber in the boiler furnace must be heated up to the needed temperature, *i. e.* the boiler must be ignited. Normally, to ignite boilers, the heat of additive fuel, such as coal, wood, black oil, gas, *etc*., and this fuel is combusted directly in the furnace (engineering design of researching center, Production Enterprise "Bijskenergomash", Barnaul). However, the application of such a system of ignition is not always realizable and effective.

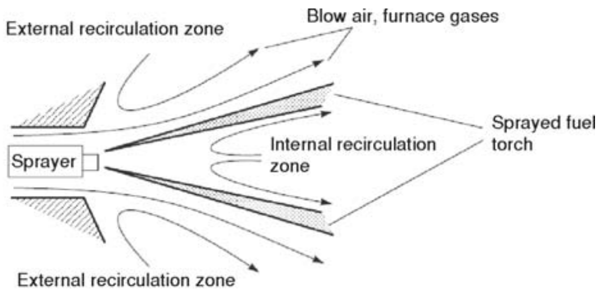

Figure 1. Schematic of flow mixing during WCF spraying

The other method of WCF combustion is the ignition of it in a burner with the aid of a solar burner like WSO or plasmatorch. These systems are purposed for the complete or partial replacement of the additive fuel. The basic elements are:
– the burner with a furnace chamber and primary furnace of different diameters, with the refractory of fireproof brick and connected to the boiler furnace,
– the WCF sprayer with the system of air mixture feeding and regulation in the burner,
– a plasmatorch – a device which generates the flow of air plasma in the burner, the flow temperature is of 2,000-4,500 °C, utilized as a lighting torch, and
– a power supply for the plasmatorch.

Schematic image in fig. 1 enables to realize two versions of the plasma ignition location for the water-coal burner ignition [1, 2, 4-6]. In the first case, the primary furnace forms the flow, and the plasmatorch is inserted through the primary furnace wall. The plasma jet intersects the flow of sprayed WCF at the angle in the high-concentration region. The flow temperature reaches 4,000-5,000 K. At a certain ratio of parameters the plasma jet ignites WCF. In the second version, the plasmatorch is located in the central hole of the sprayer. The plasma jet is directed to the base of the sprayed fuel torch in the internal recirculation zone, heats and ignites the WCF.

Thus the effective combustion of WCF with high content of humidity and increased ash content is reached without additive high-reactive fuel or blow air.

Development of equipment for WCF combustion

In 1997, the method of ignition and combustion stabilization of the sprayed water-coal fuel with the aid of plasma-ignition systems was approved in the bench-scale unit of LLC "Santekhnik Ltd." (Kemerovo) [1]. The water-coal burner with the sprayer, combustion chamber, and systems of WCF feeding was developed by Federal State Unitary Enterprise SPC "Ekotekhnika", the system of plasma ignition was designed in ITAM SB RAS. The first version of the SPI location in the burner was used, *i. e.* the plasma jet intersected the torch base. The water-coal suspension used in the experiments was anything but of the best quality: solid phase content was 53-57%, ash content was up to 20%. Nevertheless, we managed to ignite the burner and achieved the stable combustion of the WCF, including the case with the SPI being off. Positive results of the early experiments enabled to adjust the basic units of the burner and SPI. A demonstration plant for WCF combustion with SPI was manufactured and tested inside the territory of the Siberian State Industrial University (Novokuznetzk).

The plant contained all main units needed for an industrial bench: systems of storage and controlled feeding of WCF, water- and gas-supply systems, a burner with the sprayer, SPI, furnace (heat boiler), *i. e.* everything but blow air heating. The engineering characteristics of the plasmatorch included in the SPI, and sprayers for WCF spraying are presented in tabs. 1 and 2.

Table 1. Engineering characteristics of the plasmatorch EDP-324

Parameter	Value
Air flow rate, [gs^{-1}][nm^3h^{-1}]	3-6 (9-18)
Arc current, [A]	100-200
Arc voltage, [V]	Up to 270
Power, [kW]	Up to 45
Thermal efficiency	0.7

Table 2. Engineering characteristics of the sprayer FM 3.00

Parameter	Value
32WCF flow rate, [lh^{-1}]	150-250
WCF pressure, [MPa]	0.2-0.4
Compressed air pressure, [MPa]	0.3-0.5

The process of ignition of the WCF torch followed the order:
– the plasmatorch was switched on, and the muffle (heat boiler) was heated up to 600-650 °C,
– as the required temperature was reached, the WCF was fed into the sprayer in quantity of 50-120 l/h, and
– upon the sprayed jet of WCF ignition and temperature rise up to 700-750 °C, the plasmatorch was switched off, and further combustion of the WCF was independent; the temperature in the burner and muffle furnace was above 850 °C.

The plasmatorch worked steadily both in the ignition mode and in the mode of WCF combustion stabilization. The average values of the plant parameters at the stable mode of WCF combustion are presented in tab. 3.

Table 3. Results of experiments of WCF combustion

Parameter	Numerical value (averaged)	
	Concentrating mill “Abashevskaya”	“Tyrganskaya“ mine
WCF pressure, [MPa]	0.1	0.1
WCF flow rate, [m^3h^{-1}]	0.23	0.24
Compressed air pressure, [MPa]	0.44	0.45
Temperature in the burner, [°C]	840	815
Temperature in the muffle furnace, [°C]	830	800
Arc current, [A]	130	130
Arc voltage, [V]	210	220
Power, [kW]	27.4	29

Figures 2 and 3 show the photos of the plasma jet from the working SPI in the muffle (heat boiler) and steadily working WCF torch.

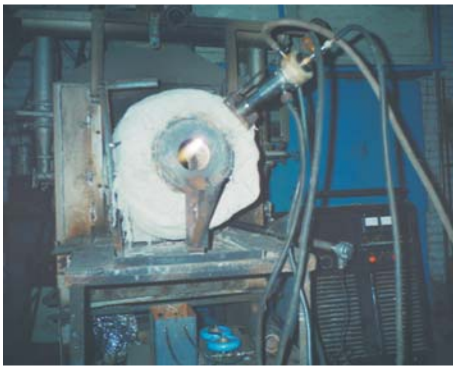

Figure 2. Working plasmatorch in the burner furnace

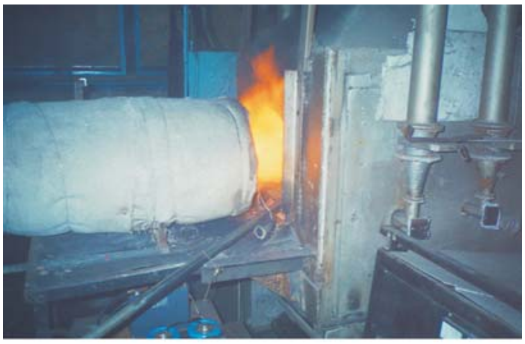

Figure 3. Steadily burning WCF torch

Then, the demonstration plant was utilized to optimize the processes of ignition and combustion stabilization, to obtain the quantitative results of the study of these processes.

The results of the tests in the demonstration bench enabled to give recommendations to install the systems of WCF ignition and combustion in a standard water boiler E1-9, JSC "Kommunenergo" (Kemerovo).

Pilot plant tests

Technological scheme of the pilot plant tests includes an accumulating tank of 30 m^3, a hose pump NP-25 with the inverter J-100, a filter, damper, small and big contours of WCF feeding with locking and regulating devices, boiler E1-9 with the burner with a pre-chamber and sprayers for WCF ignition with a liquid fuel (black oil) or with a plasma jet. To supply the compressed air for WCF spraying and plasmatorch, a movable compressor was used.

During the tests, two technologies of boiler ignition and transition on WCF combustion were approved:
– with the aid of a black-oil burner VM-202 with the power of 162-255 kW, and
– with the aid of plasmatorch EDP-324 with the power about 30 kW.

The ignition of the boiler and its transition on the WCF combustion was carried out as follows. The black-oil burner was ignited in accordance with the actual rules. As the temperature in the furnace reached 550-600 °C, the WCF sprayed was initiated, the fuel flow rate was 50-70 l/h. With the temperature increase to 700-750 °C, the WCF flow rate was increased up to 100-120 l/h. At 850 °C, the black-oil burner was switched off, and at the same time the WCF flow rate was increased to 130-150 l/h.

The SPI method of boiler ignition and transition on the WCF was the following. The plasmatorch was switched on in a standard way. As the temperature in the boiler furnace reached 200-220 °C, the WCF sprayers were initiated, the fuel flow rate was 40-60 l/h. As the temperature increased to 600-650 °C, the WCF flow rate was risen to 80-100 l/h. The WCF flow rate was gradually increased until the furnace temperature reached 850 °C. Then, the plasmatorch was switched off, the WCF flow rate was increased to 130-150 l/h.

As the WCF flow rate was 130-150 l/h, in both cases the stable combustion of the fuel was reached, the boiler worked steadily, its heat productivity corresponded to the standard and made up to about 0.5 Gcal/h. The temperature in the boiler furnace lied within the range of

930-990 °C, the off-gases temperature was 220-240 °C. The total time of operation of the boiler with the WCF in first tests was more than 10 hours, the maximum continuous working period of 3 hours. During the process, 1.5 m^3 of WCF was consumed.

Tests with WCF of brown coals

There are a number of papers with the study of the possibility to apply the SPI in the process of combustion coal-dust fuel, water-coal suspensions (WCS) from stone coals and sludge of hydrolicking of these coals [2, 3, 5]. Plasma-assisted ignition and combustion of brown-coal water suspensions can hardly be found in references.

The purpose of this chapter is the study in the laboratory and industrial scale of the possibility of production and combustion of WCS from brown coals [7].

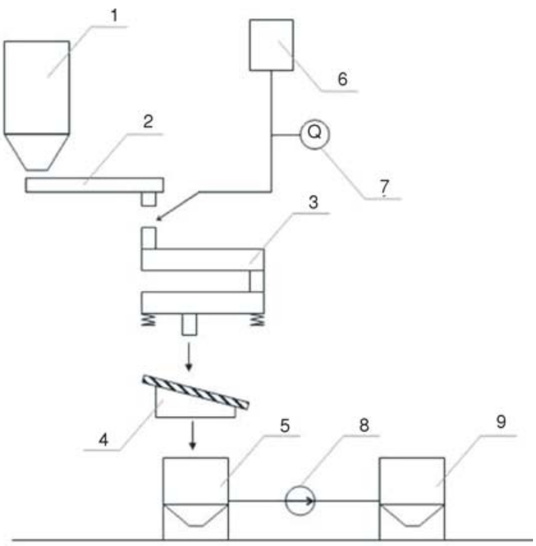

Figure 4. Schematic of the demonstration experimental-industrial plant for WCF preparation
1 – tank, 2 – screw conveyer feeder, 3 – vibration mill of VM-60, 4 – sieve to catch coal particles above 3 mm from the ready product,5 – sunk a capacity for ready WCF receipt from the mill, 6 – capacity tank of aqueous dilution of the reactant, 7 – pipeline for the metered supply of the reactant with the flow-meter MR-400, 8 – rotor-oscillatory device (pump-activator), 9 – tank for the ready product

Experimental batches of WCF were prepared in the demonstration test and industrial bench of JSC SPC "Sibeko-tekhnika" (fig. 4).

Initial coal was fed into the tank and carried out the metered feeding into the vibration mill VM-60 with a screw conveyer feeder. At the same time, the aqueous dilution of the plastifying reactant came into the mill; its total flow rate was controlled by the flow-meter MR-400 and by a valve. The produced suspension passed through the rotor-oscillatory device to improve its rheological characteristics and stability of the ready WCF. The operation principle of the disperser is based on the hydro-mechano-acoustic effect. After the rotor-oscillatory device, the WCF was sent into the ready-product tank.

During the experiments, two batches of WCF were prepared with the aid of the vibration mill VM-60: from Mongolian coals, from Baganuur coal from (coal rank B3) with the reactant DShch, and from the coal of Shivee-Ovoos field (B1) with the reactant S-1 (tab. 4).

This fuel was utilized for the study of the ignition and stable combustion processes in the demonstration test and industrial bench (fig. 5).

From the tank (1) via pipeline system, the fuel was supplied with a peristaltic pump NP-16 (2) in a special combustion chamber with the sprayer (3) and burner (4) and system of gas evacuation. For spray, the compressed air was fed into the sprayer with the compressor (5).

The fed volume was controlled with the aid of inverter "Hitachi" J 100m by means of variation of the rotation frequency in the pump NP-16 engine.

Table 4. Physical and chemical characteristics of the produced WCF

Index	Baganuur coal	Shivee-Ovoos coal
Particle size γ, [μm]	0-350	0-350
Mass share of solid phase S_s [%]	44.0-46.0	32.0-35.0
Effective viscosity at the shift rate of 81 s^{-1}, η [mPa·s]	Up to 1,000	
Ash content for dry state of fuel A^d, [%]	Up to 17.5	
Statistical stability, [days]	At least 10.0	

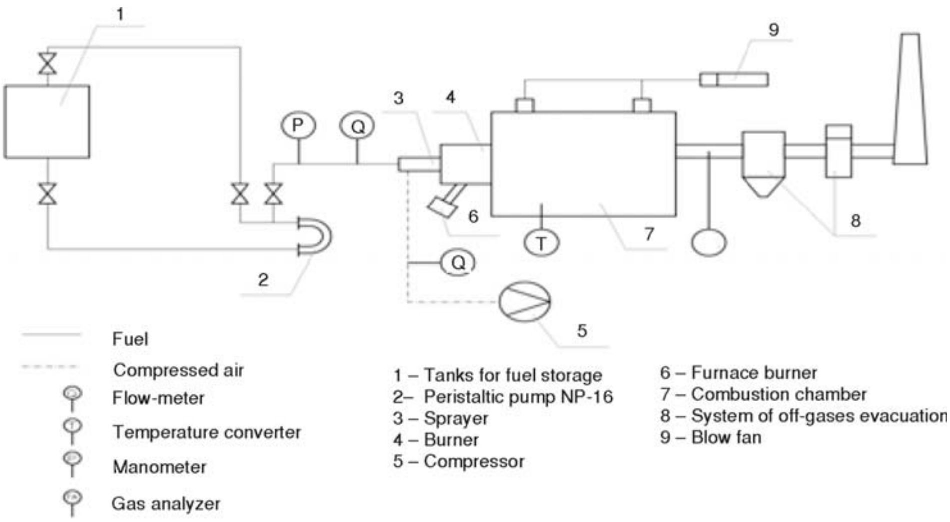

Figure 5. Schematic of the test and industrial plant for WCF combustion

The temperature in the combustion chamber was controlled in a temperature converter: the pressure of the composite fuel and compressed air was controlled with pressure gages and a manometer; flow-meters were used to control the fuel and compressed air flow rates. All pressure and temperature indications were registered with technological meters. A solar burner WSO-12H (6) was used for the ignition.

The combustion chamber (7) was pre-heated with the solar burner within 40 minutes up to 600 °C. Then the fuel was supplied into the chamber via the sprayer. The combustion products were released from the combustion region via the system of off-gas evacuation (8) with the gas analyzer. Blow fan (9) provided the oxidizer transportation into the combustion chamber.

The WCF was combusted together with the diesel fuel until the temperature in the chamber was 888 °C. Then, the diesel fuel was cut off, the WCF burnt independently without assistance. The transit from the WCF from Shivee-Ovoos coal was realized after a short pause at the furnace temperature of 646 °C, with no pre-heating of the furnace with the diesel fuel.

Table 5. Results of WCF combustion

Test duration minutes	Temperature in furnace [°C]	P_{WCF}, [MPa]	Q_{WCF}, [Lh^{-1}]	$P_{\text{compr.air}}$ [MPa]	$Q_{\text{ccompr.air}}$ [m^{3}h^{-1}]	P_{raref}, 10^{-5} [MPa]	Content [mgm^{-3}]		
							CO	NO_x	SO_2
Baganuur coal									
–	888	0.130	130	0.12	98	3	451	182	98
12	855	0.120	130	0.12	100	3	390	196	60
47	885.6	0.150	130	0.15	100	3	272	220	51
63	929.6	0.135	140	0.13	100	5	248	252	47
Coal from Shivee-Ovoos field									
–	750	0.155	200	0.15	90	5	507	184	101
20	816.1	0.150	150	0.15	85	4	411	199	89
40	838.4	0.165	200	0.16	90	7	323	218	74
50	840.7	0.160	200	0.16	90	5	266	239	62
55	856	0.165	200	0.16	90	4	246	252	52

Table 5 presents the results of WCF combustion. Note that the rated content of the controlled components (in accordance with Construction Norms & Regulations) is the off-gases is: CO – 375; NO_x – 750; SO_2 – 375 mg/m^3.

The data presented in tab. 5 show that the combustion of coals in the form of WCF, the content of hazardous components (carbon, nitrogen, and sulfur oxides) in the off-gas is much lower than the rated standard.

During the work, a laboratory plant for WCS combustion equipped with the SPI was developed, assembled, and tested. The plant included all basic units needed to provide the process of ignition and maintenance of the stable combustion of the WCS; there were the system of storage and controlled feeding of the WCS, systems of water and gas supply, burners with sprayers, and a SPI.

The plasmatorch of 30 kW power ignited the WCF and stabilized the flame combustion. It is a one-arc plasmatorch with two coaxial cylindrical electrodes and swirl stabilization of the arc. Such a scheme of the plasma ignition of the WCF was applied when the plasmatorch was located in the central hole of the sprayer. The plasma jet is advanced to the torch base in the internal recirculation zone, it heats up and ignites the brown-coal WCF.

About 20 kg of WCF was combusted during the experiment.

The values of WCF combustion parameters:

- WCS flow rate, [m^{3}h^{-1}] 0.8,
- WCS pressure, [MPa] 0.2,
- compressed air pressure, [MPa] 0.4,
- temperature in the burner, [°C] 780,
- arc current, [A] 125,
- arc voltage, [V] 220.

The plasmatorch worked steadily at every stage of the technological cycle.

The performed tests demonstrated that the WCF suspensions can be produced from the brown coals of Shivee-Ovoos and Baganuur fields, Mongolia; these suspensions are suitable for heat power engineering. This is a pioneering result for the brown coals of Mongolia obtained in the pilot plant for WCF in the industrial scales. It is also demonstrated that effective ignition and stable combustion of the WCF from the brown Mongolian coals is realizable also by the SPI, which enables to provide the ignition and combustion stabilization of WCF within the minimum time.

Tests results and discussion

The experiments performed in demonstration plants and real industrial furnaces and boilers gave the results somehow different from the common knowledge about the properties and peculiarities of the water-coal fuel combustion.

In accordance with the theory developed by Delyagin and his team [8], the temperature of WCF ignition and its reactivity weakly depend on the mass share of the solid phase and volatile content in the initial coal [3]. However, the results of experimental investigations and practical experience with boiler operation on the WCF show that both the humidity content (25-50% weight per cent) and volatile content in the WCF (metamorphism stage) of the initial coal significantly affect the reactivity and steadiness of the fuel combustion. Primarily it was established that the processes of heat and mass exchange occurring at the liquid phase (water) evaporation, extend the time needed for the heating and thermal decomposition of the coal particles which are presented in each element of the sprayed fuel. On the other hand, the following must be taken into account. Available modes of WCF spraying with the compressed air, or overheated steam, or other reactants, permit to provide the fuel drop size up to 50-60 mm. The size of a certain part of coal particles (up to 30% and more) in the WCF exceeds this size. The high-speed flow of the fuel and spraying reactant mixture from sprayer nozzles (above 300 m/s) provides the effective separation of the liquid phase and smaller coal particles from the big particles surface. As a result, as the WCF is sprayed, there are WCF drops in the boiler furnace, which contain from several units to several dozens and hundreds of fine coal particles (up to 70 weight per cent), and also individual "pure" coal particles of 50-100 μm and more.

Taking the above said into account, we suppose that the processes of combustion must be considered as consisting of two basic and mutually related components.

The first component of the above mentioned processes is caused by the present of up to 30 weight % of "pure" coal particles above 50-60 μm, their ignition and combustion follow the laws of powdered coal combustion. It is known the from the powdered coal combustion theory that the volatile content in the coal significantly influences the ignition and combustion of a solid fuel.

The second component is relayed with the presence of the sprayed WCF drops which contain from several units to several dozens and hundreds of fine coal particles; their ignition and combustion take place in the presence of a big quantity of liquid phase, and a certain part of it imposes the significant catalytic action on carbon oxidation reactions. As was mentioned, the theory of these processes was developed in [8].

Hence, the reactive properties and steadiness of combustion of the WCF are caused and highly depend both on particle size and volatile content in the initial coal, and on the quantity of the liquid phase in the WCF.

Conclusions

The problems of production, transportation, storage, and utilization of the WCF have been being solved in Russia and abroad for more than 40 years. The most serious progress seems to be reached in the power engineering in respect to WCF combustion in high-power boilers. In the heat-power engineering, in medium- and low-power boilers, calcinations kilns, *etc*., the challenge of ignition and combustion stabilization for the WCF is topical. The application of the SPI is a promising solution.

The performed experiments and calculations of the engineering, economical, and environmental indices of the WCF combustion with various methods of ignition have demonstrated that the SPI permits to exclude completely the utilization of black oil or any other high-reactive fuel for the WCF ignition and combustion stabilization in the medium- and low-power boilers. The power of the plasma system consumed during the ignition is much lower than the power of black-oil or other burners. Thus, the operation consumptions and consumptions for boiler modification decrease. The application of the SPI in the combustion mode provides the reduction of the mechanical and chemical underburnt, reduces the yield of nitrogen oxides in the off-gases.

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