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Plasma-Assisted Stimulation of the Coal-Water Fuel Ignition

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Abstract: This paper considers an efficient approach to the combustion of water-coal fuel with minimal environmental impact. Today, a plasma system can provide high-quality ignition of water-coal fuel and accompany its combustion. The purpose of this paper is to study the plasma stimulation of carbon burn-up in coal-water fuel. To study the features of the interaction of a water-coal suspension with plasma, an electric arc plasma torch of a linear scheme with copper electrodes, operating in the air as a plasma-forming gas, was chosen. To analyze the influence of an external magnetic field on the control of the plasma jet parameters, a series of experiments were carried out using an electric arc plasma torch on a 15 kW plasma laboratory setup. It has been established that the use of an external transverse magnetic field makes it possible to intensify the process of heating water-coal fuel and burning out carbon in fuel particles. The observed intensification of the fuel gasification process is the result of the harmonization of the relative position of the plasma flow and the material being processed due to the spatial displacement of the high-temperature zone of the plasma flow towards the fuel supply. Experimental studies have been carried out on the temperature distribution along the axis of a dusty jet and the degree of mass-average carbon burnout. The averaged dependences of the particle temperature on the flow rate of the plasma-forming gas and the polarity of the magnetic field within the initial section of the jet are obtained. In a plasma-coal burner, the problem of sufficiently rapid mixing of the transversely supplied raw material and heat carrier in the minimum volume of the reaction zone has been solved. The optimization of the mixer was reduced to the choice of such a geometry (diameter and opening angle of the plasma torch nozzle channel, diameter and angles of the holes for supplying water-coal fuel with respect to the axis of the plasma torch channel), which ensures uniform distribution of the atomized fuel in the channel. The patterns obtained can be used for constructive and technological design in the creation and development of installations for the combustion of coal-water fuel.

Keywords: Coal-Water Fuel, Electric Arc Plasma Torch, Plasma Stimulation, Temperature Profile, Active Particles, Gasification

1. Introduction

There are two opposing trends in the energy sector. When investing in fossil fuels, the decarbonization process and the energy transition to renewable energy sources suffer due to the energy crisis. It is hard to believe that any measures to improve energy efficiency and introduce renewable energy and green hydrogen can prioritize compressed natural gas and coal at the same time as green energy. The ongoing energy crisis and the economic fallout from the war in Ukraine are likely to exacerbate skyrocketing inflation, sapping the potential for energy investment.

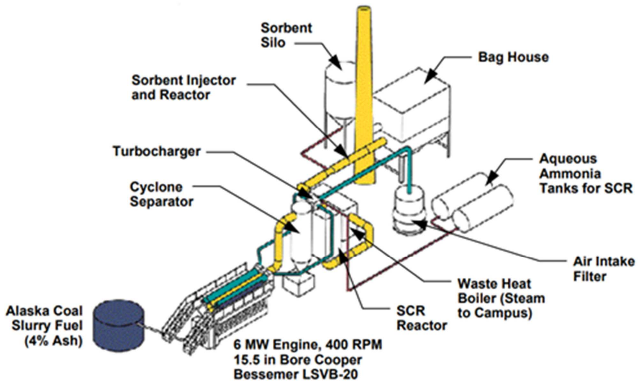
There is a widespread belief that coal must be phased out in order to achieve zero emissions. For many countries, mainly most of Asia, phasing out the use of coal in the coming decades is not possible, as it remains the dominant source of energy due to its low cost and availability [1]. Thus, an increase in the capacity of renewable energy sources (RES) reduces the production of coal-fired power plants but does not necessarily mean their closure.

Coal-fired power plants do not compete with RES. Instead, they can help expand the penetration of renewable energy into the electricity grid by maintaining a stable grid and producing low-emission power when needed. However, as investments and energy sector transformation policies focus on renewables, inefficient coal-fired power plants continue to operate, rather than being replaced with clean coal technologies. This is exacerbated by the exodus of international financial services and technology providers from the coal sector. One of the difficulties in financing clean coal technologies by the World Bank is the need for project sponsors to demonstrate the economic and financial viability of the project [2]. Many countries can move closer to net zero emissions (NZE) starting with the introduction of low-emission coal technologies. Emissions from coal-fired power plants can be reduced through the introduction of innovative technologies, including coal-water fuel (CWF) [3].

The use of water-coal slurry, i.e. mixtures of fine coal and water seem to be an irrational solution, contrary to engineering practice due to "thermodynamic aspects" (mainly the need to evaporate the water introduced with the fuel into the combustion chamber). However, if this technology, as an alternative to traditional fuels, is used for a specific purpose, the number of measurable benefits that can be demonstrated in the overall balance sheet calculation outweigh the disadvantages [4]. Coal-water slurry is a mixture of coal dust and water with or without additives of surfactants, which has the properties of a fluid medium capable of moving through pipelines using pumps. Such a mixture is sprayed into droplets in furnaces and burns with the formation of a torch similar to fuel oil, diesel fuel, and other fuel liquids.

This is the current trend. Small, inefficient and constantly running coal-fired power plants should be closed. Improving the efficiency of existing power plants can significantly reduce emissions of CO_2 and other pollutants [5]. There are several alternative high-efficiency pathways that offer the potential additional opportunities and benefits of fuel flexibility to produce valuable products. Co-combustion of coal in the form of CWF with the disposal of animal waste allows for solving the problems of increasing the efficiency of thermal energy production, resource-saving (replacing high-quality fuel with coal enrichment waste), rational environmental management (reducing emissions of harmful substances into the biosphere) and can offer a cheaper option to achieve NZE [1, 6].

The agro-industrial complex today is faced with the problem of waste disposal. On the other hand, it needs energy resources, namely, heat and electricity. Composite quasi-liquid fuels from various wastes have become increasingly popular and more attractive to scientists in recent years. Due to the high moisture content of manure (90 - 95% water and 5 - 10% dry organic residue burned), its direct combustion in liquid form in furnaces is almost impossible. However, if a mixture is prepared from liquid manure and oil refinery waste, it becomes possible to use the resulting composite fuel for the needs of an agricultural enterprise. An example here is the use of CWF. It is believed that the co-firing of biomass and waste with coal will be a key factor in allowing coal technology in most countries to approach NZE while maintaining economic growth [1]. Investments in advanced coal technologies are an important part of global action to reduce emissions and achieve the intended results of the 2015 Conference of the Parties Paris Agreement on Climate Change - the United Nations Framework Convention on Climate Change (COP21) [7]. This study aims to accelerate the transition.



(a)

(b)

Figure 1. *Coal Fueled Diesel Power Plant (6 MW): a - A typical Coal Diesel System with a single 6 MW engine, b - Test Engine Area [8].*

It should be noted one more topical application of CWF. The level of political support and today's high oil prices allow coal to be slurried to gain public acceptance and become commercially viable. This is a challenge to find a new source of fuel as a competition for crude oil and allows you to get a new engine fueling technology. The main advantages are cheaper fuel and the relatively high calorific value of coal compared to gaseous fuel or alcohol. Many countries in the world depend on oil for the energy sector and in order to be independent in the event of a crude oil crisis, a lot of work has been done on high-power coal-water slurry diesel engines. In particular, to demonstrate the new "Clean Coal" technology, the "Clean Coal Diesel" project was undertaken by Wilson [8] and a group for the US Department of Energy. This innovative technology enables the use of pre-treated clean coal fuel (CFC) in powerful medium-speed diesel engines. These are in many respects conventional modern engines, except that they are specially equipped with hardened parts to be compatible with traces of abrasive ash in coal fuel. The aim of the project was industrial and utility applications for power generation in the power range from 10 to 100 megawatts. Today, there are hundreds of these reciprocating power plants running on natural gas and/or fuel oil all over the world (Figure 1).

As a result of numerous studies, it was concluded that suitable coals for the preparation of CWF for a diesel engine using physical cleaning methods can be found in almost every state. Even in the early stages of development [8], it was noted that the main technical problem areas in the design of a coal-fired diesel engine are: 1) fuel combustion, 2) engine wear. The main areas subject to wear are found in fuel injection systems, rings, and liners. It should be noted that ring and liner wear will still be a problem if unburned coal gets into the wear pair, even if the ash has been completely removed from the coal. In general, tungsten carbide hard coatings have been proven to provide acceptable wear characteristics. Regarding fuel combustion, coal combustion is an area that has undergone much research. An important condition for complete combustion after ignition of a water-coal suspension in a diesel engine is to ensure that the initial gas temperature is above 850 K. At lower temperatures, the combustion quality deteriorates sharply. The burnout percentage drops very rapidly as the initial temperature approaches 850–900 K [9]. The slurry properties must be adapted to meet the atomization and combustion requirements imposed by the time available and the thermodynamic conditions of the engine. The compression and temperature must be as high as possible to achieve ignition and an acceptable burning rate. The most important parameter is the time required for the complete combustion of a coal particle of a given radius. The faster the coal burns, the higher the permissible engine speed.

The operating experience of the developed engines with a system of direct injection of water-coal fuel gives certain conclusions. The main thing is that they provide more efficient operation than a diesel engine. Combustion of CWF in diesel is more efficient and economical, environmental friendliness is higher than that of other thermal power engines (steam and gas turbine). In the era of the fuel crisis, replacing diesel fuel with coal fuel is a promising solution due to the presence of large coal deposits in the world and taking into account the reduction of CO_2 emissions [10].

There are few scientific works devoted to the problem of combustion of water-coal fuel in reciprocating engines, however, many experimental tests have been carried out in the world. The most important problem is to find dependencies between the fuel-air mixture, pressure, and temperature changes during the combustion process. At the moment, it seems that the best ignition control method is a pilot injection of a small amount of diesel fuel [11] (Figure 2). Pilot quantities are equivalent to 5 to 6 percent of the energy input over the entire load range to achieve stable operation.

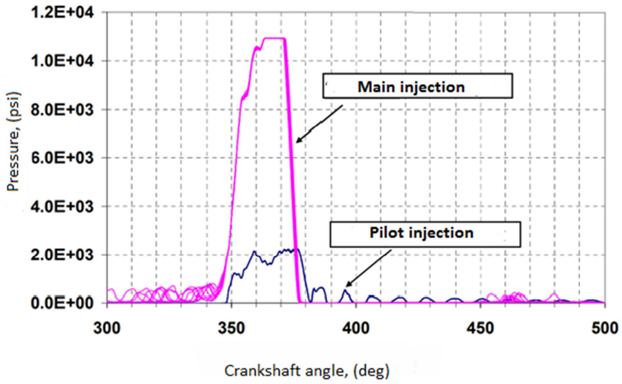


Figure 2. *Discharge pressure curve for a CWF engine (Figure 1 b) during testing.*

The idea of burning coal-water slurry has been intensively developed since the 1980s. Despite several decades of history, numerous studies continue to improve the quality of such fuels, as well as improve the combustion process.

The main problem when using CWF is its low reactivity after spraying at the initial stage of combustion. Since the active ignition of the fuel determines its further combustion, this problem hinders the development of technology. The main efforts of developers to solve the problem of stable and reliable combustion of water-coal fuel are directed primarily to the intensification of fuel ignition at the "root" of the flame. There are several approaches to solving this problem [12, 13]. Basically, this is some construction made of refractory ceramics, which plays the role of a high-temperature heat accumulator and the organization of intensive recirculation flows of combustion products. In all the methods accepted for use, the boiler is started on starting fuel - fuel oil, sometimes on solar oil, and only when the operating temperature is reached ~ 900... 1000°C, it is switched to the main fuel. This is a big drawback, which is inherent in all coal-fired power boilers. In all considered cases, two fuel supply systems are required, which is inconvenient and difficult to operate. To date, according to the authors, the best system for ignition and fuel combustion support would be a plasma system [14]. It should be noted that Iegorov R. I. et al. [13] at the stage of research in 2011–2013 unfortunately, could not use plasma technologies for the ignition of CWF, but they received a firm conviction that this direction is promising. An analysis of the considered methods shows the superiority of plasma technology as simpler and more convenient than ignition using pilot fuel. The reality of using plasma ignition and accompanying the combustion process of CWF both in diesel engines and various furnaces is based on successfully completed studies [14].

Carbon Water Market Analysis Report, Global Overview (USA, Canada, UK, Germany, France, Italy, Spain, Netherlands, Russia, China, India, Japan, Australia, South Korea, Malaysia, Brazil, Mexico, Argentina, Gulf States, South Africa), industrial segment, market estimates, trends and forecasts for 2020-2028 are presented in the work [15]. The main conclusion is that in the coming period, the "Coal-water sludge market" industry will grow as quickly as possible, since the scale and scope of its application are growing significantly around the world. It can be used to power boilers, gas turbines, diesel engines, and thermal power plants. In 2016, global revenue from coal-water slurry was almost US$ 1,600 million; the actual production is about 37 million tons. The average global price for water-coal sludge is on the rise: from USD 37.9 per tonne in 2012 to USD 43.5 per tonne in 2016. According to this study, over the next five years, the water-coal sludge market will demonstrate a CAGR of 14.7%, and the global market will reach US$ 4,090 million by 2024, up from US$ 1,800 million in 2019.

The increase in the volume of coal burned is exacerbated by the problem of reducing their quality, which requires an increase in fuel oil consumption at existing pulverized coal stations for kindling and lighting the pulverized coal torch. The use of CWF with plasma activation will make it possible to exclude fuel oil from the fuel balance.

2. Methods

The low reactivity of CWF after spraying at the initial stage of combustion requires the intensification of fuel ignition processes. The promise of plasma technology is associated with a number of processes occurring in plasma. It is known that the concentration of radicals in arc plasma is 50–100 times higher than that of ions; therefore, it can be expected that chemical reactions under plasma conditions develop according to a scheme in which intermediate radicals are involved. In other words, the reactions of radicals with molecules and radicals with ions are extremely important. The mechanism of coal gasification under plasma conditions is very complex and may contain parallel chain and network reactions. In [16], a mechanism was proposed that explains the gasification of coal in air and water vapor under conditions of atmospheric pressure electric arc plasma, which includes 24 reactions. During the gasification of coal in the air with water vapor under conditions of atmospheric pressure electric arc plasma, all processes can be divided into four stages. The first stage - the air in the plasma reactor partially dissociates and ionizes, forming active particles N^{+2}, O^{+2}, O^{+}, N^{+}, O, N, and NO molecules after arc plasma excitation. Water molecules dissociate into OH radicals and H atoms due to collision with electrons. Some radicals can quickly react with other active species, forming new species such as NH radicals and excited O atoms. At the second stage, under plasma conditions, coal undergoes rapid decomposition and dissociation reactions with the release of volatile substances and coke residue, which, upon further decomposition, form a large number of active particles, including CmHn hydrocarbons, excited C and H atoms, etc. In the third stage, various gases CO, H_2, and CO_2 are formed due to a complex set of parallel chain reactions. The fourth stage covers the reactions of CO ionization, particle conversion, and gas dissociation on the one hand and the formation of CN radicals, on the other hand, CN radicals can also be converted into C atoms and N_2 molecules. Most importantly, gases such as CO_2 and H_2 are converted or converted to CO with the release of many active species such as OH, H radicals, and electrons, which take part in the reactions in the recycling scheme.

The purpose of this article is to study the plasma stimulation of carbon burn-up in coal-water fuel.

3. Key Features of Our Approach

To study the features of the interaction of a water-coal suspension with plasma, an electric arc plasma torch of a linear scheme with copper electrodes was adopted, operating in the air as a plasma-forming gas [14]. Adopted slurry plasma sputtering is an innovative process in which a suspension of submicron-sized coal particles is injected into a DC plasma jet. The liquid jet is quickly atomized by a high-speed plasma jet, forming suspension droplets, which, in turn, are heated by the plasma, releasing suspended particles, which are then heated, gasified and sent to the combustion chamber. A preliminary analysis of the possible consequences of the interaction of an electric arc in the arc channel of the output electrode of an indirect plasma torch with an external magnetic field proves that it is promising to use transverse (with respect to the direction of the current in the arc column) fields to influence the process of plasma flow formation. A constant transverse magnetic field (CMF) is created by a magnetic system, which consists of a DC electromagnet 2 and its power supply circuit (Figure 3) [17].

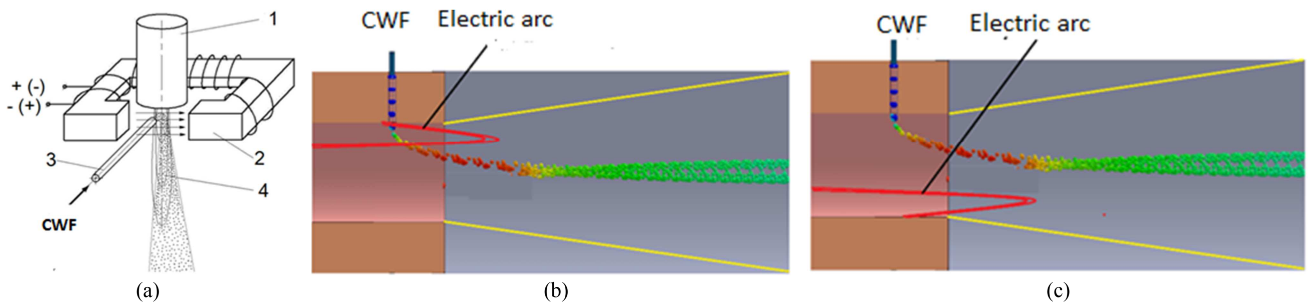


Figure 3. *Scheme of plasma initiation of ignition of the CWF under the action of a transverse magnetic field: a - the relative position of the electromagnetic coil and the output nozzle of the plasma torch: 1 - plasma torch, 2 – the core of the magnetic circuit, 3 - CW feed channel, 4 - plasma jet; b – deflection of the electric arc at initial polarity, c – deflection of the electric arc at reverse polarity.*

The electromagnet is fixed relative to the nozzle system of the plasma torch 1 in such a way that part of the arc column, its section with the attachment spot to the electrode, the initial section of the plasma jet 4, and the nozzle part of the arc channel are located between the poles of the electromagnet, in the zone of the magnetic field. When interacting with an external magnetic field, the arc binding zone is forcibly displaced in a certain direction and fixed in a rather limited section of the arc channel. The direction of movement of the arc binding zone is determined by the direction of the magnetic induction of the external field in the interaction region, the direction of the current in the arc sections that interact with the external magnetic field, the direction of the initial swirl, and the flow rate of the plasma-forming gas. The result of the purposeful orientation of the part of the column and the end section of the arc is the rearrangement of the temperature and velocity profile of the plasma jet, which is formed in the nozzle part of the arc channel. In turn, such a restructuring leads to the deviation of the plasma jet flowing from the arc channel of the plasma torch at a certain angle relative to the longitudinal axis of the channel 5-6° in one direction in the studied range of parameters of interacting objects. The deflection angle of the plasma jet depends on the flow rate of the plasma-forming gas, the magnitude of the arc current, and the value of the magnetic field induction in the interaction region. Controlling the spatial position of the arc column relative to the injection point of the CWF makes it possible to directly influence the intensity of its activation and ignition. It is known that, in the general case, the transfer channels of the gas and solid phases in two-phase flows do not coincide [18, 19]. This leads to the entry of part of the material being processed into the region of relatively low temperatures and speeds of the working medium. In turn, the difference in the conditions of heating and acceleration of the particles results in different rates of carbon burnout. Correction of the mutual position of the phases of a two-phase flow will improve this process efficiency indicator to a certain extent. The study of the influence of the magnetic field on the process of ignition and burnout of coal particles was carried out by measuring the temperature of the dusty jet and the degree of carbon burnout. A plasma torch with CWF ignition in operation is shown in Figure 4.

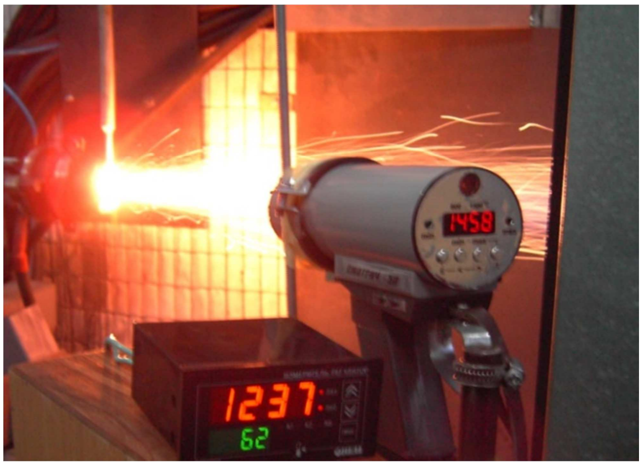


Figure 4. *Plasmatron with CWF ignition in operation.*

CWF was prepared according to the technology [14] from a dispersed material (coal dust with a particle size of Figure 5).

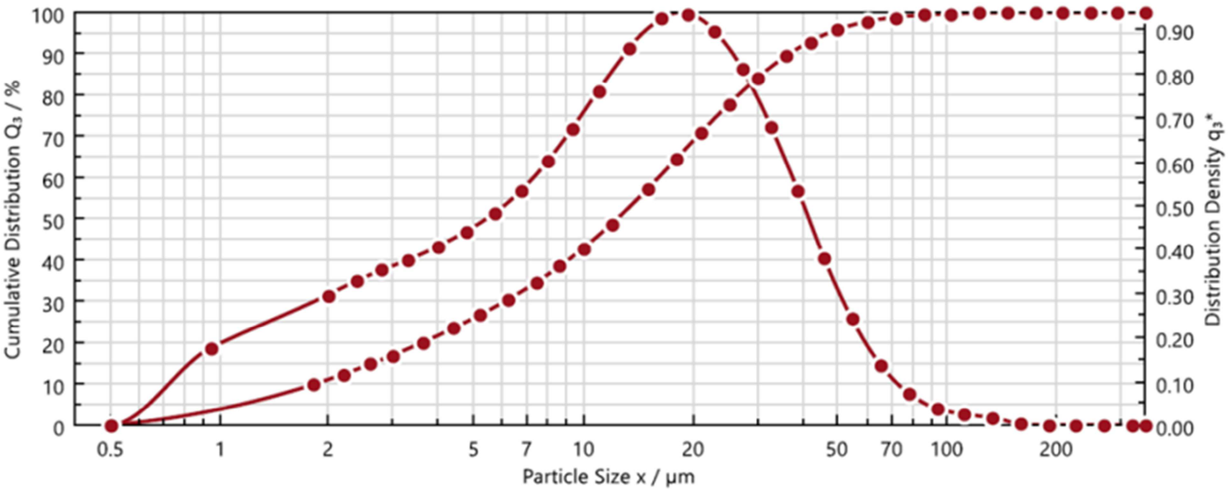


Figure 5. *Particle size of initial coal dust.*

The slurry properties must be adapted to meet the atomization and combustion requirements imposed by the available time and thermodynamic conditions. The average particle size of the coal in the slurry is likely to be within 10-micron load on the order of 50 percent by weight and 95% of particles smaller than 30 microns. Larger particles burn too long at 1000 rpm. engine and much smaller particles are too expensive to manufacture [8].

The plasma jet, brought to the root of the torch, heated up and ignited the CWF. Figure 4 shows the plasma jet when CWF is fed. In a plasma-coal burner, the problem of sufficiently rapid mixing of the transversely supplied raw material and heat carrier in the minimum volume of the reaction zone has been solved. The interaction of the hot arc plasma flow with the sprayed cold CWF begins in the area of the near-anode part of the electric arc column (Figures 3 b, c). The optimization of the mixer was reduced to the choice of such a geometry (diameter and opening angle of the plasma torch nozzle channel, diameter and angles of the holes for CWF supply with respect to the axis of the plasma torch channel), which ensures uniform distribution of the sprayed CWF in the channel. The number of transverse jets is 1 - 4. It should be noted that in order to ensure the required range, it was necessary to maintain the value of hydrodynamic parameters with high accuracy - small changes in flow rates or temperature lead to very significant range fluctuations. All this must be taken into account when designing a mixer. The combustion process of CWF in a fuel-plasma burner (Figure 4) must be carried out in the "complete burnout" mode with "gasification". The operation of the plasma torch was recorded with the following parameters: anode nozzle diameter - 10 mm; consumption of plasma-forming air G = 7 nm^3/h, arc current I = 60 A, arc voltage U = 300 V, electrical power N = 18 kW, length of the initial section of the plasma jet - 15 cm. Productivity – 20 - 50 kg/h.

Basic experimental studies were carried out on a bench with plasma torches (Figures 3, 4) on the distribution of temperature along the axis of a dusty jet and the degree of mass-average carbon burnout. Dust sampling was carried out by a water-cooled probe along the jet axis. Figure 6 shows the average dependences of the temperature of the particles on the flow rate of the plasma-forming gas and the polarity of the magnetic field within the initial section of the jet.

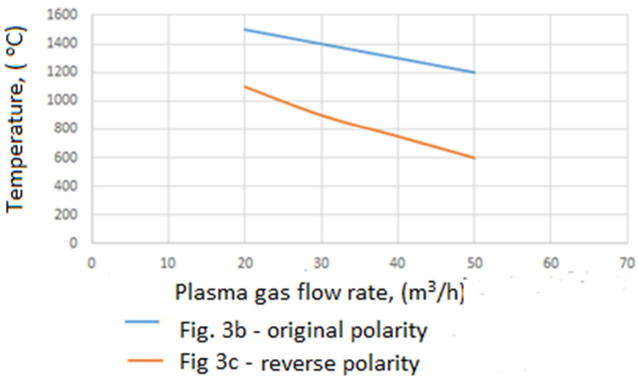


Figure 6. *Particle temperature dependences on the plasma gas flow rate.*

Fast and complete carbon burnout is important, especially for diesel engines - in one stroke of the piston. Figure 7 shows the dependence of the burnup of carbon in particles as they move away from the point of injection of CWF into the plasma jet. It has been established that the application of an external transverse magnetic field leads to heating intensification and carbon burnout in CWF particles. The processes of degassing and oxidation of coal occur very quickly. The observed intensification of the CWF gasification process is the result of the harmonization of the relative position of the plasma flow and the processed material due to the spatial displacement of the high-temperature zone of the plasma flow towards the CWF supply.

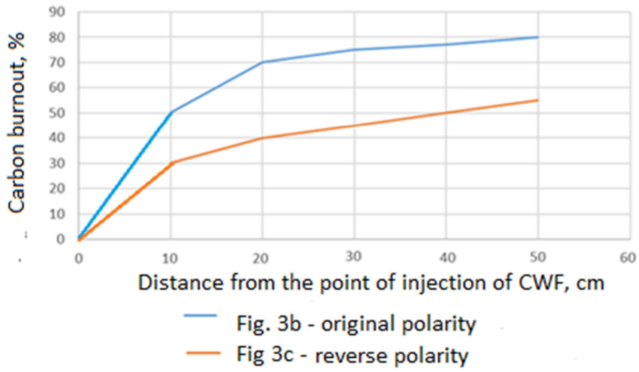


Figure 7. *Dependences of carbon burnout in particles with distance from the point of injection of CWF into the plasma jet.*

Under these conditions, most of the CWF falls into the region of higher temperatures and plasma flow rates. An increase in temperature and intensification of carbon burnout, in this case, is explained by an increase in the level, high stability of the heating conditions of the processed material, and the presence of active particles. The fundamental point of this study is the fact of more efficient heating of the dispersed phase (Figure 6) and intensification of carbon gasification when CWF is supplied to the zone of the anode section of the electric arc. The higher rate of carbon burnout in the initial section of the plasma jet (Figure 7) is apparently associated with the release of volatile substances. Gasification of the solid phase is a slower process, although the overall rate remains high beyond the plasma jet. The passage of dispersed particles at a distance of 0.5 m under conditions of plasma spraying is carried out within a few hundredths of a second. During this time, the degree of carbon burnout reaches 80%. Ensuring fast complete carbon burnout is a matter of process optimization.

4. Recommendations for the Follow-up Work on This Topic

Limiting factors in the use of coal in the energy sector are always were extremely dirty technology and the low efficiency of its combustion. Micro-grinding coal with plasma ignition changes its kinetic characteristics, approaching in properties to oil and gas. Among the fundamental problems of chemical kinetics it is absolutely necessary to understand many phenomena and to create a theory of processes of gasification of solid carbon-containing particles under conditions of atmospheric pressure plasma to take into account the influence of radicals on the speed and regularities of chemical reactions and transfer processes. The important task from the point of view of chemical kinetics is of applied character: at carrying out of corresponding calculations it is necessary enough complete quantitative information on kinetics of chemical reactions. There is no general theory of reactions of steam plasma gasification in nonequilibrium conditions, and in many cases there is no even approach to it. The available experimental material is scattered and very few. Here one can expect the most unexpected manifestations.

5. Conclusion

1) Ease of implementation, high operational reliability, and efficiency of the technology of plasma stimulated combustion of WCS, allow us to conclude that a solution has been found that provides kindling (heating) without the use of additional expensive fuel.
2) The fact of the intensification of the process of gasification of CWF carbon when it is supplied to the zone of the electric arc of the indirect plasma torch has been established.
3) The experimentally established fact of the intensification of plasma stimulation of ignition and subsequent gasification of CWF carbon due to magnetic correction of the process of formation of a dispersed flow in arc plasma.
4) Plasma technology presents an opportunity to expand the market for the consumption of water-coal fuel, primarily in small and medium-sized thermal power plants, and eliminate typical administrative and technical difficulties: it speeds up implementation, and reduces capital costs for implementation and operating costs associated with environmental protection.

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