PLASMA PROCESSING OF LOW-REACTIVE COAL

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Abstract

Coal is one of the main energy source of the 21st century. New plasma-energy technologies are developed to improve efficiency of coal combustion. Today the pulverised-coal heat power stations all over the world generate more than 50 % of the electric and thermal power, the share of coal in fuel balance of heat power stations growing. At the same time, the quality of coals decreases. Traditional methods for decreasing the consumption of fuel oil at heat-electric generation plants (increase in dust milling dispersity, high preheating of the air mixture and secondary air, etc.), used to improve fuel ignition and burning stabilization, have exhausted themselves. Therefore, a radical increase in the efficiency of utilization of fuel can be related only to development and mastering of absolutely new technologies.

The plasma technology seems to hold the highest promise among the alternative technologies available for solving the above problems. This technology provides a substantial increase in cost effectiveness and improvement in environmental indicators of power-generating plants working with solid fuel.

1. Introduction

At heat power stations, in combustion of heavily ballasted coals that cannot burn by themselves, especially under conditions of minimum loads, it is necessary to provide a maximum intensification of the pulverised coal flame with fuel oil. In this case the share of fuel oil in total heat released in a boiler furnace may amount to 30 %. Combustion of coal with fuel oil in the above proportions leads to intensive high-temperature corrosion of screens, dramatic decrease in burnout of particles of a solid fuel (its unburned part is emitted together with ash and fume), chemical underburning, increase in the amount of pollutant emissions (compared with coal, fuel oil contains twice as much sulphur), and increase in the rate of accidents with steam superheaters. As a result, this causes reduction in the efficiency of boilers. High sulphur content of fuel oil leads to formation of sulphides which:

- are emitted into the atmosphere to cause its pollution;
- form sulphurous acid that attacks metal structures of boilers and flues;
- enter into reaction with pulverised slag to form very strong scale on inner parts of boilers and steam superheaters.

For these reasons, boilers of heat power stations have to be subjected to capital repairs once in two years on the average (cost of capital repairs is equal to that of a new boiler). Costs incurred for purchase of fuel oil include costs related to maintenance of fuel oil facilities, which amount to about $ 3/t. The world trend to better refining of oil leads to reduction of the share of fuel oil to 5 %. Considering a high cost of fuel oil, reduction in its supplies, high cost of maintenance of fuel oil facilities, decrease in efficiency and operational reliability of boilers in combined combustion of fuel oil and coal, the technology of fuel oil-free lighting up and intensifying of the pulverised coal mix in boiler furnaces using plasmatrons becomes increasingly topical.

New plasma-fuel systems are developed to raise efficiency of combustion of coal. They are the key element of the plasma-energy technologies. Among them are the pulverised-coal burners equipped with electric-arc plasmatrons and combined plasma gasifiers intended for heat power stations. Plasma-fuel systems provide fuel oil-free lighting up of pulverised-coal boilers, stabilisation of flame and, as a result, simultaneous decrease in mechanical underburning of fuel and formation of nitrogen oxides and sulphides.

The plasma-energy technologies are based on plasma thermochemical treatment of coal to prepare it for combustion. This treatment consists in heating of a fuel-air charge (aeromixture) by the electric-arc plasma to a temperature of formation of volatile coal components and partial gasification of carbon residue. Therefore, independently of the quality of a coal, this provides a highly reactive two-component fuel (combustible gas and coke residue). When this fuel is fed to the furnace, it inflames upon mixing with secondary air and then burns steadily requiring no combustion of extra fuel (fuel oil or natural gas) traditionally used to light up boilers and stabilise flame of low-grade power-generating coals.

The purpose of this study was to investigate the possibility of decreasing the required thermal capacity of a plasma jet to provide stabilised burning of a pulverised-coal mix, and increasing the rate of combustion of low-reactive coals using the technologically significant plasma effects.

2. Basic principles of the plasma-energy technologies

Plasma ignition of coal is based on electro-thermochemical preparation of fuel for combustion, resulting in formation of highly reactive two-component fuel (combustible gas + coke residue). This peculiarity is shown in Figure 1 [1].

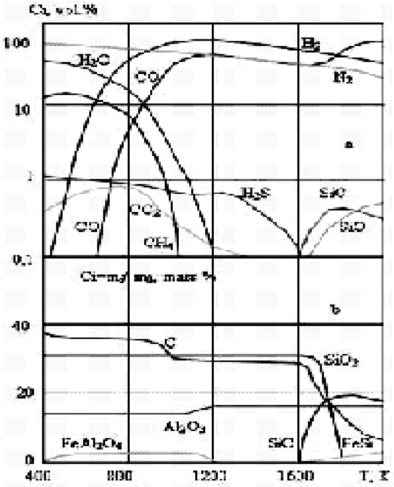


Figure 1. Composition of gaseous (a) and condensed (b) phases of the high-reactive two-component fuel, where m_i is the mass of the i-th component and m_0 is the mass of the fuel-air charge

It follows from Figure 1 that the concentration of combustible components (CO + H_2 + CH_4) grows with increase in a process temperature, reaching 50-70 % of that of the gas phase (T = 900-1200 K). This promotes their intensive self-ignition in mixing with the basic fuel-air charge. The concentration of oxides (H_2O + CO_2 decreases to 0.1 % with growth of temperature. The process of stabilisation of burning of low-reactive coals comprises heating of a small part of the fuel-air charge by the electric-arc plasma to a temperature of full yield of volatile components and partial gasification of coke residue. As a result, a highly reactive two-component fuel, capable of igniting the main flow of the fuel-air charge upon mixing with it and stabilising the flame burning process is produced from a smaller part of the fuel-air charge that passed through the electric-arc discharge zone (independently of the quality of initial fuel). Three plasma-energy technologies, such as fuel oil-free lighting up of pulverised-coal boilers, intensifying the pulverised-coal flame and stabilisation of yield of liquid slag in furnaces with liquid slag removal are based on this principle [2].

Combined plasma steam-air gasification of coals is based on a combination of plasma activation of burning of a small part of fuel (2-3 %) using an external heat source (plasmatron) and subsequent stepwise ignition of the rest of the fuel-air charge using the activated part of coal. The thermal effect of burnout of this fuel-air charge serves for compensation for the endothermic effect of steam gasification of the main part of coal. In this case the latter may constitute 70-80 % of the entire fuel in a combined plasma gasifier.

The main point of the plasma steam gasification is that uses arc plasmatrons to transform an organic mass of coal into a high-calorific synthesis gas ($CO + H_2$), containing no nitrogen and sulphur oxides. In this case the endothermic effect of reactions of steam gasification of coal:

$$H_2O + C = CO + H_2 - Q = 131{,}500\ \text{kJ/mole}, \qquad (1)$$

is fully compensated for by the chemical energy of fuel ignited by the electric-arc plasma.

In comprehensive processing of coals in plasma reactors, the steam-coal mix is heated by plasma to a temperature of complete gasification. This involves transformation of the organic mass of coal into synthesis gas ($CO + H_2$) and simultaneous reduction of oxides of the mineral mass of coal according to the following reactions:

$$M_nO_m + mC = nM + mCO \qquad (2)$$
$$M_nO_m + 2mC = M_nC_m + mCO \qquad (3)$$

Here M is the metal or metalloid contained in the mineral mass of coal, and n and m are the stoichiometric coefficients in equations of reactions (2) and (3).

Reactions (2) and (3) result in formation of valuable components (commercial silicon, carbosilicium, ferrosilicium etc.) in the condensed products of coal processing, in addition to combustible gas (CO) [3].

New plasma-energy technologies for increasing the efficiency of utilisation of coal and decreasing pollutant dust-gas emissions can be developed by combining the above technologies [4].

Figure 2 shows a plasmatron and schematic of its mounting on the pulverised-coal burner. The plasmatron is the basic element of the plasma-fuel system. It generates the low-temperature plasma.

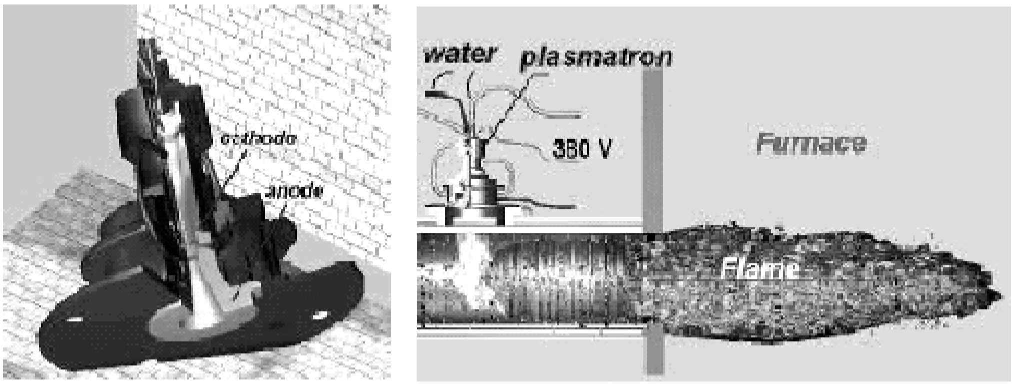


Figure 2. Plasmatron and schematic of its mounting on the straight-flow pulverised-coal burner

This plasmatron comprises water-cooled copper electrodes (cathode and anode). The plasma gas is air blown through the electrodes. The adjustable range of the plasmatron power is 100 to 350 kW. The plasmatron has the following dimensions: height – 0.4-0.5 m and diameter – 0.2-0.25 m. Its weight is 25-30 kg.

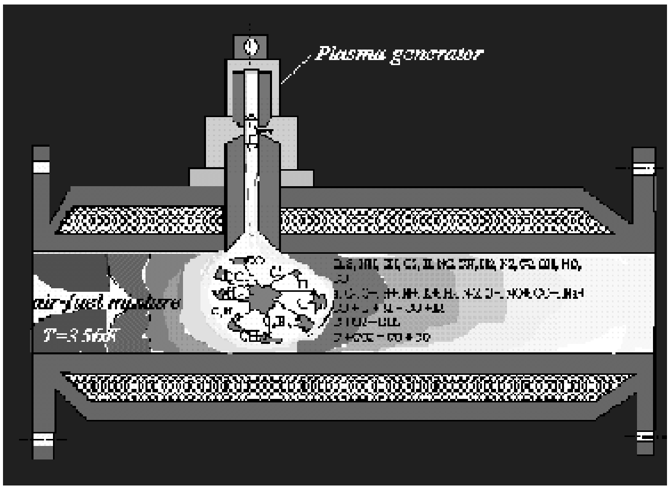


Figure 3. Peculiarities of interaction of arc plasma with fuel-air charge in the plasma-fuel system for coal ignition (muffle with plasmatron)

Figure 3 shows peculiarities of interaction of fuel-air charge with arc plasma in the plasma-fuel system (muffle burner with plasmatron). Coal particles with an initial size of 50-100 μm are subjected in plasma to a thermal shock. As a result, they break into fragments, each being 5-10 μm in size. This leads to an intensive formation of volatile elements (CO, CO_2, H_2, N_2, CH_4, C_6H_6 etc.) and accelerates the process of oxidation of combustible fuel components by a factor of 3 to 4.

Figure 4 shows results of experiments on decreasing the emission of NO_x and mechanical underburning of fuel in plasma ignition of coals.

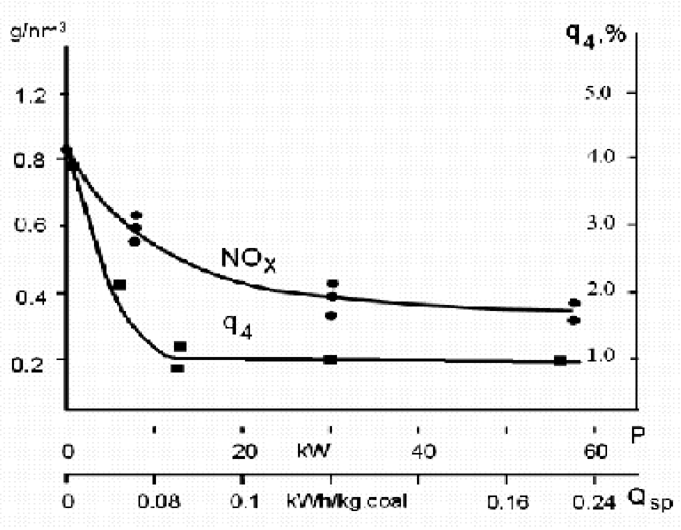


Figure 4. Effect of the plasmatron power (P) and specific power consumption (Q_{SP}) on decrease in formation of NO_x and mechanical underburning of fuel (q_4) during plasma ignition of the pulverised-coal flame

As seen from the Figure, with the plasmatron operating in a mode of plasma stabilisation of flame the emission of NO_x decreases by a factor of 2, and mechanical underburning decreases by a factor of 4. One of the causes of increase in reactivity of fuel ensuring decrease in mechanical underburning is a thermal explosion of coal particles in their interaction with the electric-arc plasma.

Figure 5 shows an experimental relationship between a relative power consumption by the plasmatron and yield of volatile components of ignited coal for different heat power stations.

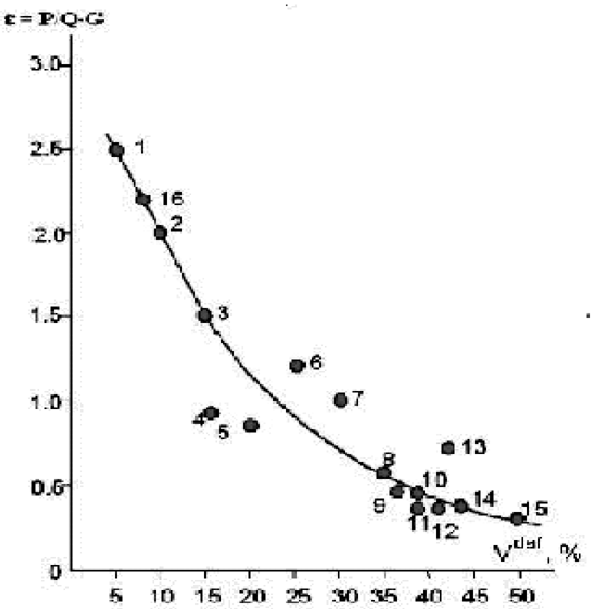


Figure 5. Experimental relationship between relative power of the plasmatron and yield of volatile components of ignited coal for different heat power stations:
1 – Korea; 2, 12 – Ukraine; 3 – China; 4, 5, 8, 10, 11, 15 – Russia; 6 – Kazakhstan; 7 – USA; 13 – Mongolia; 14 – Kirghizia; 15 – Estonia; 16 – Slovakia
P –electric power of plasmatron; Q – heat of combustion of coal; G – consumption of coal in muffle with plasmatron

3. Fundamental problem of commercial application of the plasma-coal technology

The fundamental problem of commercial application of the plasma-coal technology is the need to use high-power (more than 200 kW) plasmatrons. Power of a plasmatron is determined by minimum relative power expenditures equal to the ratio of the required electric power of the plasmatron to thermal power of the burner. It equals 1.5-2.0 % for the ASh grade coal. An actual continuous service life of such plasmatrons is 200-300 h (longer life is declared, but nobody can demonstrate it so far). Today there is no way of substantially extending the life of copper electrodes. Other electrodes capable of providing a substantially longer life, such as a gas-phase self-recovering cathode, tungsten and consumable graphite electrodes, are not considered in terms of application in power generation. The rate of erosion of copper electrodes (cathode and anode) is determined by many factors, and especially by the arc current. Erosion characteristics of the anode and cathode can either fully coincide or exhibit substantial differences, depending upon the dynamics of the near-electrode processes. A critical condition of air atmosphere is the value of the electric current at the excess of which erosion of a material dramatically grows. The cause of formation of the critical condition is the loss of stability of rotation of gas flow in the electrode cavity. One of the main challenges is to ensure a constant level of specific erosion of electrodes during a long-time operation in a range of sub-critical currents. Erosion of a hollow copper cathode in air atmosphere is about $2 \cdot 10^{-0}$ kg/C. The mean level of erosion of anode is lower, it equals approximately $4 \cdot 10^{-11}$ kg/C. After 50 hours of operation, cracking along the grain boundaries initiates in the sub-surface layer of the electrode material. Moreover, in cathode this cracking propagates to a substantial depth: twice as much compared with anode. The anode erosion surface exhibits less oxidation than the cathode one. Therefore, erosion of copper electrodes is determined primarily by density of the heat flux and speed of displacement of the near-electrode regions of the arc. Providing that a stable operation of electrodes is achieved, the guaranteed life of cathodes may currently amount to 200 h, and that of anodes – to 1000 h at a current of 200 A and a material wear depth of $6 \cdot 10^{-3}$ m. Therefore, the realistic application of the plasmatron technology in power generation industry is to decrease power of plasmatrons by an order of magnitude. This must provide the same increase in life of electrodes, i.e. it will extend to thousands of hours. This is the most important advantage. In addition, this will improve economic indices, as heat from electricity is much more expensive than heat generated by coal.

4. New approach to application of the plasma technology for initiation of pulverised-coal flame

R & D Center PLAZER developed a new method for affecting the pulverised-coal fuel to ensure conditions of its burning and provide a continuous service life of plasmatrons acceptable for the power generation industry. The method is characterised by improved technical-and-economic indices of the involved plasma equipment [5, 6, 7]. The purpose of this study was to decrease the required thermal power of a plasma jet to ensure a stable burning of the pulverised-coal mix. The possibility of increasing the rate of burning of low-reactive coals through utilising technologically significant plasma effects was investigated. The investigations were conducted using the developed combined plasma-coal burners (Figure 6).

Pulverised coal of Donetsk anthracite of the ASh grade with particle size of up to 250 μm was used as a fuel. Thermal power of the plasma jet was regulated from 5 to 50 kW. The pulverised coal transported by air was fed from one, two and three feeders to the air plasma jet of the plasma burner. The rate of flow of the pulverised coal through one feeder was 1-15 g/s. The effect of the following factors on increase in the rate of oxidation of coal was studied: (1) length of the initial region of the plasma jet varied from 3 to 7 gauges at the identical mean-mass parameters at the exit section of the plasmatron nozzle; (2) high-frequency pulsation component of the plasmatron arc current with an amplitude of (0.1-0.5) I_n; (3) acoustic effects; and (4) electric potential of the plasma-coal flame.

The rate of oxidation of coal particles was estimated from their underburning at the exit of the plasma-coal burner. Comprehensive calorimetric study of the flame was carried out; quantity, particle size composition and ash content at the exit and entrance of the plasma-coal burner were determined. Also the temperature and velocity of the particles leaving the burner were measured.

It was proved that the above external low-power physical effects on the high-temperature zone of burning of the pulverised coal could provide an increase of 3-5 times in the rate of reactions of oxidation of the coal particles. In addition, this leads to a dramatic increase in the amount of the burnt-out coal and flame power. The required thermal power of the plasmatron can be raised almost by the same value. In operation at a decreased power of the plasmatron, removal (e.g.) of potential from the dusted jet leads to attenuation of the flame in blowing of dust through the incandescent muffle.

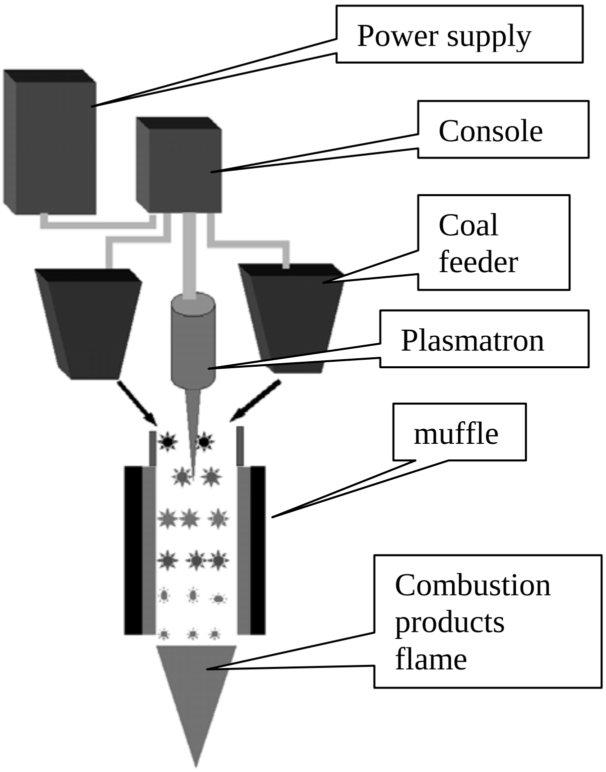
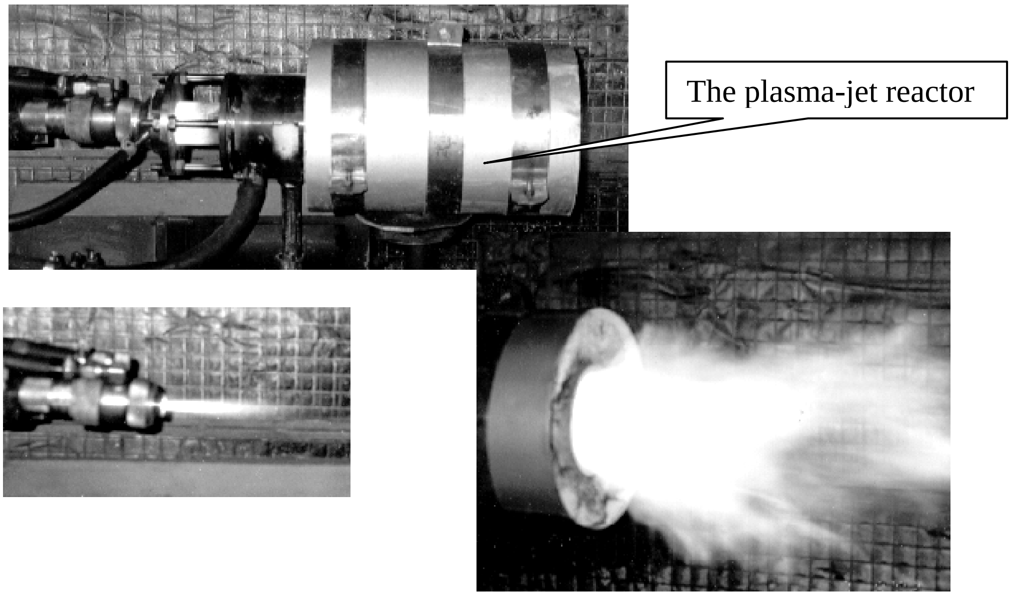


Figure 6. Combined plasma-coal burner

Regulation of power of the pulverised-coal flame and plasma stabilisation of burning of the low-reactive pulverised coal, which is incombustible under such conditions, are shown in Figure 7.



F*igure 7. Plasma jet (10 kW)* *Pulverised-coal flame (200 kW)*

5. Calculation of the combined plasma-coal burner

The model of combustion of pulverised coal in the plasma-jet reactor (Figure 8) allows for a jet character of the gas-disperse flow to a point of its contact with the channel walls, phase transitions in particles (evaporation of water and melting of ash), reverse effect of particles on the gas flow that accelerates and heats them, and radiant heat exchange between the particles and walls. It is thought that molten ash in the finely dispersed state is "blown off" from the coal particles into the gas flow, where it instantaneously takes up its velocity and temperature. Deposition of ash on the channel walls is ignored. Burning of particles is described by the Arrhenius' law, allowing for the final rate of diffusion of oxidiser to the particle surface.

This model is quasi-unidimensional. It allows for a jet character of the dust-air flow in the plasma-jet reactor. Averaging in the model is done not over the entire section of the channel, which is the case of unidimensional models, but over a smaller section of the jet growing along the flow. Moreover, it allows for the dependence of the rate of this growth upon the working process parameters. This calculation seems to yield more realistic values of temperatures and velocities (hence, time of dwelling in the reactor) of the gas and particles. Furthermore, it allows for the fact that the secondary air is added to the jet along the flow in more or less uniform portions, rather than readily contacts the fuel with all its volume. There is shortage of oxidiser in the initial region of the jet. So, thermal preparation of the working charge is performed particularly in this region. Complete contact of the secondary air with the fuel is achieved only at the end of the jet and in the non-jet part of the flow. Behaviour of the coal particles in the plasma-jet reactor is shown in Figure 9. The following was established as a result of the calculations. Thermal power of the plasma jet can be increased by a factor of 15 to 20 at carbon conversion of α_C = 0.3-0.6 by varying values of the process parameters. The pulverised-coal flame at the exit contains a large amount of coarse coal particles with a temperature of 1000-1500 ^{o}C and velocity of 40-80 m/s. The gaseous part of the flame has a bit lower temperature and velocity. It consists mostly of nitrogen. Its combustible components are carbon oxide and hydrogen.

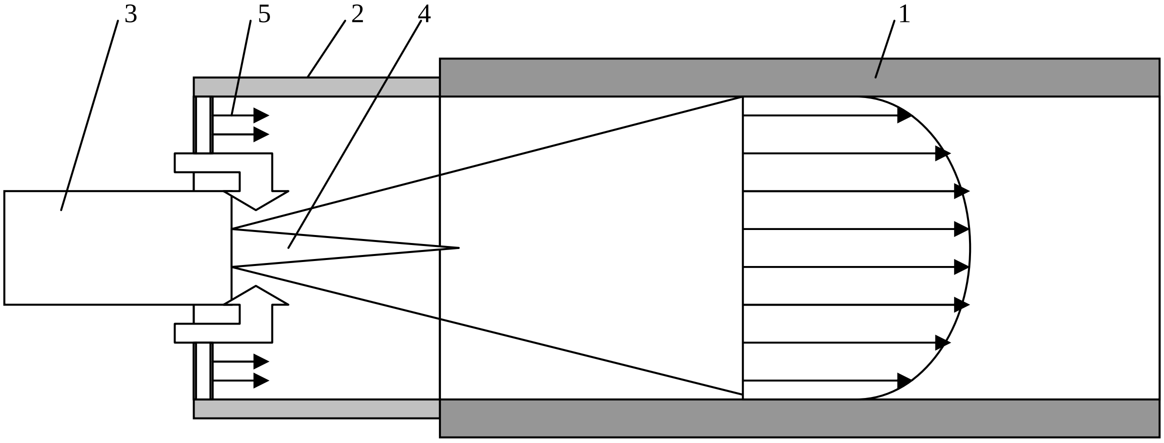


Figure 8. Schematic of the plasma-jet reactor

1- muffle, 2 - quartz pipe, 3 – plasmatron, 4 - air plasma jet, 5 - Secondary air

The calculations allow a conclusion that transverse blowing of the pulverised-coal flame initiated in the plasma-coal reactor (Figure 8) into the main flow of the ignited pulverised coal (as shown in Figures 2 and 3) provides a marked (several times) increase in its efficiency, compared with that of the plasma jet of the same thermal power. As the volume and range of the pulverised-coal flame are much larger, accordingly it will have a larger region of interaction with the ignited coal dust. Additionally, the flame contains a sufficiently large amount of coarse coke particles heated to a high temperature. Penetrating deep into the carrying-away flow, these particles ignite in contact with oxygen contained in it, thus increasing the igniting and burning-stabilising effect of the flame.

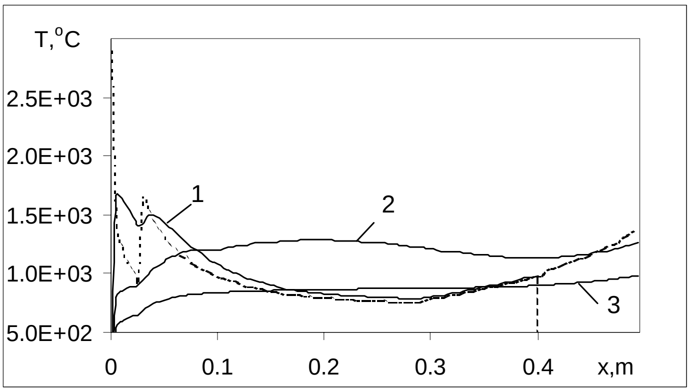


Figure 9.1. Temperature profiles of gas (dashed lines) and particles (solid lines) at $G_{pl} = 1.7$ *g/s,* $G_c = 10$ *g/s,* $G_{c.g.} = 1.2$ *g/s,* $r_{c.p.} = 0.0046$ *m,* $r_r = 0.05$ *m,* $T_{melt} = 4300$ *K,* $T_j = 1773$ *K,* $\alpha_T = 1.2$

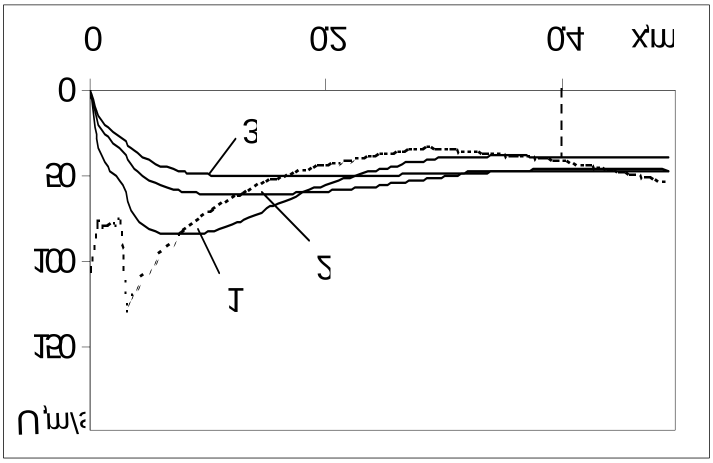


Figure 9.2. Velocity profiles of gas (dashed lines) and particles (solid lines) at $G_{pl} = 1.7$ *g/s,* $G_c = 10$ *g/s,* $G_{c.g.} = 1.2$ *g/s,* $r_{c.p.} = 0.0046$ *m,* $r_r = 0.05$ *m,* $T_{melt} = 4300$ *K,* $T_j = 1773$ *K,* $\alpha_T = 1.2$

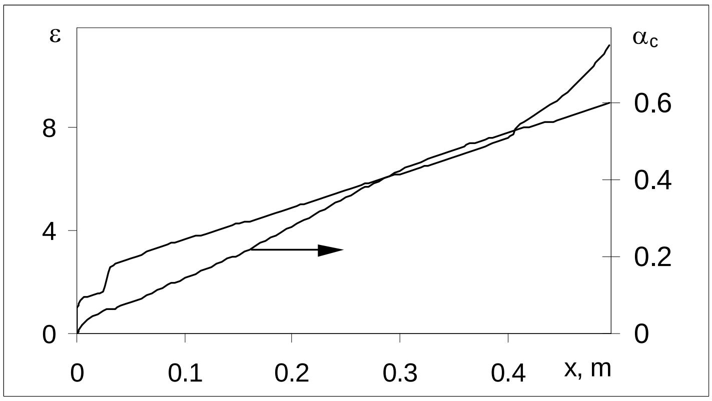


Figure 9.3. Profiles of increment in energy and conversion of coal at $G_{pl} = 1.7$ *g/s,* $G_c = 10$ *g/s,* $G_{c.g.} = 1.2$ *g/s,* $r_{c.p.} = 0.0046$ *m,* $r_r = 0.05$ *m,* $T_{melt} = 4300$ *K,* $T_j = 1773$ *K,* $\alpha_T = 1.2$

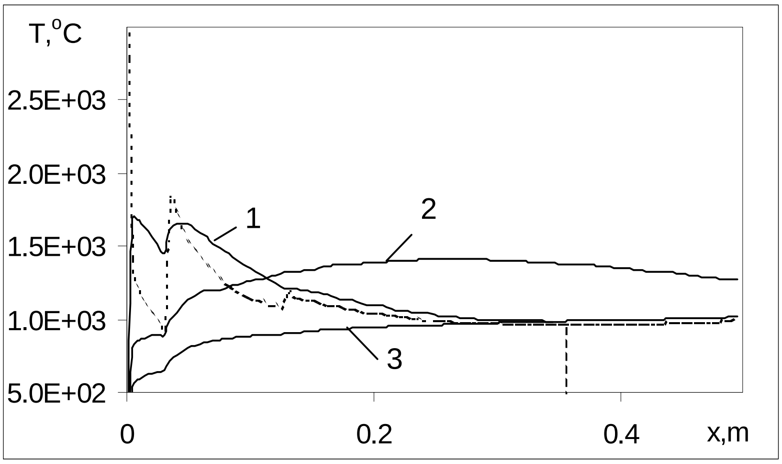


Figure 9.4. Temperature profiles of gas (dashed lines) and particles (solid lines) at G_{pl} = 2 g/s, $G_{c.}$ = 18 g/s, $G_{c.p.}$ = 1.3 g/s, $r_{c.p.}$ = 0.0045 m, r_r = 0.06 m, T_{melt} = 5000 K, T_j = 1773 K, α_T = 1.2

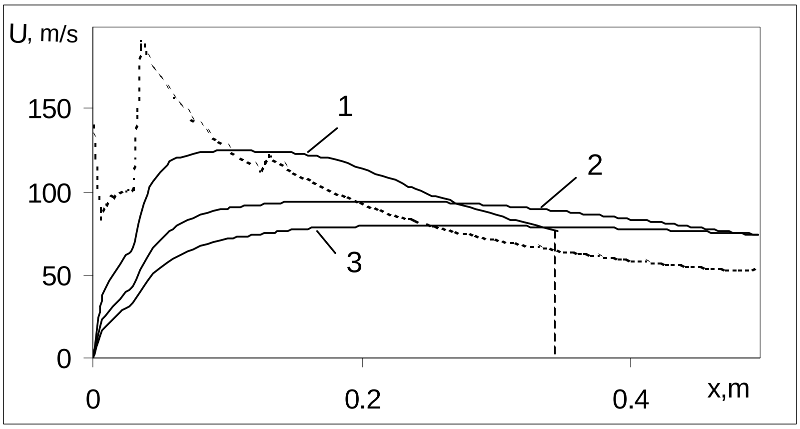


Figure 9.5. Velocity profiles of gas (dashed lines) and particles (solid lines) at G_{pl} = 2 g/s, G_c = 18 g/s, $G_{c.g.}$ = 1.3 g/s, $r_{c.p.}$ = 0.0045 m, r_r = 0.06 m, T_{melt} = 5000 K, T_j = 1773 K, α_T = 1.2

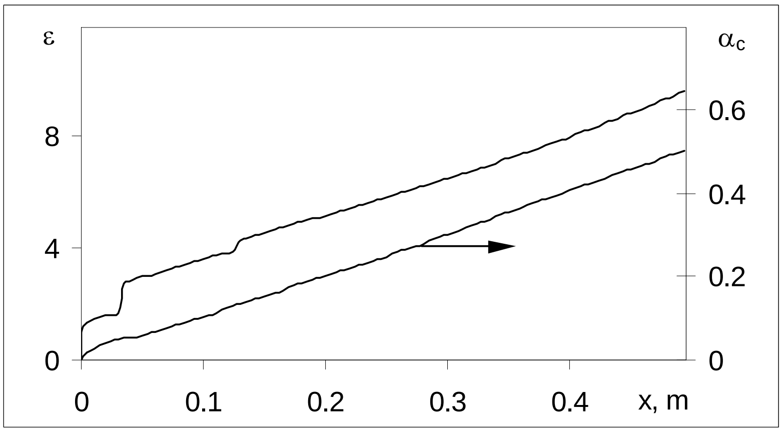


Figure 9.6. Profiles of increment in energy and conversion of coal at G_{pl} = 2 g/s, G_c = 18 g/s, $G_{c.g.}$ = 1.3 g/s, $r_{c.p.}$ = 0.0045 m, r_r = 0.06 m, T_{melt} = 5000 K, T_j = 1773 K, α_T = 1.2

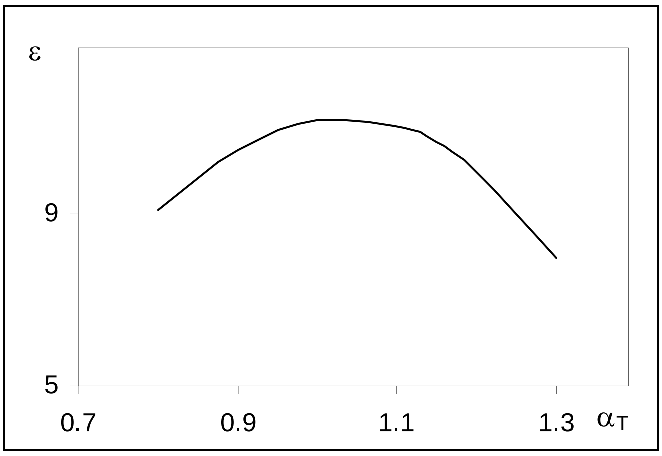


Figure 9.7. Relationship $\alpha_T(\varepsilon)$ *at* G_{pl} *= 2 g/s,* G_c *= 18 g/s,* $G_{c.g.}$ *= 1.3 g/s,* $r_{c.p.}$ *= 0.0045 m,* r_r *= 0.06 m,* T_{melt} *= 5000 K,* T_j *= 1773 K,* α_T *= 1.2*

Conclusions

1. Plasma-fuel systems improve combustion of coal and increase environmental and economical efficiency of utilisation of coal, when it is used instead of gas and fuel oil, in fuel balance of pulverised-coal heat power stations. Plasma-energy technologies include fuel oil-free (gas-free) methods for lighting up of boilers and intensifying of the pulverised-coal flame, stabilisation of yield of liquid slag in furnaces with liquid slag removal, plasma gasification and comprehensive processing of coals.
2. The most common advantages of plasma-energy technologies include decrease in the NO_x and SO_x emissions by suppressing formation of sulphur and nitrogen oxides, and increase in the efficiency of combustion of solid fuel by decreasing mechanical underburning. For example, in generation of 1 kW·h of electric power or 1 Gcal of thermal power a smaller amount of fuel is burnt, less CO_2 is evolved and the NO_x and SO_x emissions are decreased in the case of using the plasma-fuel systems. In other words, specific emissions of greenhouse gases per unit electric or thermal power generated are substantially decreased.
3. The efficiency of utilisation of the plasma technology grows in combustion of ballasted coals and under minimum loading conditions, where the share of fuel oil amounts to 30 % of total heat evolved in a boiler furnace.
4. The R & D Center PLAZER developed a fundamentally new technology for fuel-oil lighting up and stabilisation of burning of the pulverised-coal flame. The technology is based on use of electric-arc plasmatrons characterised by a decreased power and longer service life.

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