HIGH PRESSURE GAS DISCHARGE DEVICES APPLICATION FOR FUEL PROCESSING

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ABSTRACT

This paper presents the results of long-term studies of thermal plasma processing of gaseous and solid fuels. They are plasma pyrolysis, hydrogenation, thermochemical preparation for combustion, gasification and complex processing of solid fuels and cracking of hydrocarbon gases. The application of these technologies to produce desired products (hydrogen, carbon, hydrocarbon gases, synthesis gas, valuable components of the mineral mass of coal) meets modern ecological and economic requirements.

1. INTRODUCTION

The world's heat-and-power engineering is currently and foreseeable future (till 2100 year) oriented to use fossil fuel, mainly coal. Fraction of coal in electric power production is 40 % and in heat – 24 %. Thus development of the technologies for efficient and ecology friendly utilization of coal is the prime task. Considered in this paper plasmochemical technologies meet these requirements. Actuality of fuel processing plasmochemical technologies is increasing in accordance with oil and gas reserves depletion, solid fuels quality and nuclear power plants growth rate decrease.

Application of plasmochemical technologies of pyrolysis, hydrogenation thermochemical preparation for combustion, gasification, hybrid (radiant-plasma) and complex processing of solid fuels and cracking of hydrocarbon gases [1-6] to produce desired products (hydrogen, carbon, hydrocarbon gases, synthesis gas, valuable components of the mineral mass of coal (MMC) including rare earth) meets modern ecological and economic requirements of the power industry, metallurgy and chemical industry. Technologies of solid fuel plasma conversion are characterized mainly by different concentration of gaseous oxidant (air, water steam, carbon dioxide, oxygen) and therefore by different excess oxidant ratio αox (Table 1). In the table α_{ox}=0 corresponds to coal pyrolysis, and α_{ox}=1 – complete gasification of coal when oxidant is air. Note, required quantity of air for combustion of 1 kg of the coal is 5.25 kg, i.e. 2.5 times more than for its complete gasification (α_{ox} = 1.0).

2. TECHNOLOGIES DISCUSSION

Plasmochemical technology of cracking is to heat hydrocarbon gases in the combined electric arc reactor to a temperature of pyrolysis (1900-2300 K) with the formation of fine carbon and hydrogen in unified technological process. Plasmochemical hydrogenation of solid fuels, which is the pyrolysis of coal in a hydrogen atmosphere, provides acetylene and other unsaturated hydrocarbons (ethylene C_2H_4, propylene, C_3H_6, C_2H_6 ethane, etc.) from cheap low-rank coals by their treatment with hydrogen plasma. Plasmochemical hydrogenation of coal is a new process of direct production of acetylene and alkenes in the gas phase, in contrast to conventional hydrogenation (liquefaction) of

Table 1. Air-coal mixture compound

No	α_{ox}	Weight, kg	
		coal	air
1	0	1000	0
2	0,17	1000	360
3	0,30	1000	640
4	0,50	1000	1067
5	0,75	1000	1600
6	1,00	1000	2133

coal [5]. As a result of experiments on low-rank coal hydrogenation in plasmochemical reactor(Fig. 1) at its power of 50 kW, coal consumption of 3 kg/h, and propane-butane mixture flow of 150 l/h gas of the following composition is obtained, mass %: C_2H_6=50, C_2H_2=30, C_2H_4=10.

Plasma ignition of coal is based on plasmochemical preparation of fuels for combustion, which results in the formation highly reactive two-component fuel (fuel gas and coke residue) from low-rank coal. Highly reactive two-component fuel (HTF) is formed already at T = 900-1200 K, which allows the process at relatively low specific power consumption (0.05-0.4 kWh/kg of coal) and leverage at TPP for oil-free boiler start-up and pulverized flame stabilization [3, 5, 6]. Figure 2 demonstrates the process of HTF self-ignition out-of-doors.

Plasma gasification, radiant-plasma and complex processing of coal to produce synthesis gas and valuable components from MMC were investigated using universal experimental setup (Fig. 1). Their essence is heating of coal dust by the arc plasma, which is oxidant, to complete gasification temperature at which the coal organic matter is transformed into an

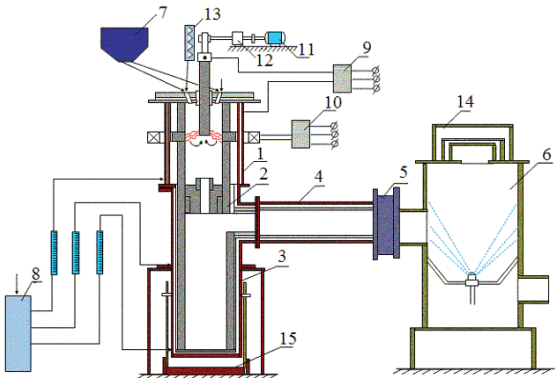

Fig. 1. Layout of experimental installation for the plasmochemical processing of fuel: 1 – plasmochemical reactor; 2 – an orifice and a chamber for gas and slag separation; 3 – a slag catcher; 4 – chamber for oxidation; 5 – an orifice; 6 – scrubber; 7 – solid fuel feeding; 8 – water-cooling system; 9, 10 – power-supply system; 11, 12 – rode electrode mobility system; 13 – steam generator; 14 – safety valve; 15 –the slag catcher lift.

Fig. 2. HTF flame (coal consumption is 1 t/h).

Table 2. Integral parameters of plasma gasification of low-rank brown coal

T, K	Q_{sp}, *kW·h/kg*	*CO*	H_2	X_C, *%*	X_S, *%*
		Vol. %			
3100	5.36	45.8	49.4	92.3	95.2

environmentally friendly fuel - synthesis gas free of ash particles, nitrogen oxides and sulfur oxides. At complex processing of coal simultaneously with gasification of organic matter in the same reaction volume coke carbon restores MMC oxides and valuable components, such as industrial silicon, ferrosilicon, aluminum and carbosilicon and microelements of rare metals: uranium, molybdenum, vanadium, and others, are formed. Material and heat balances-based integral parameters of the process were found. Table 2 shows typical results of plasma-steam gasification of low-rank brown coal of 28 % ash content and 13180 kJ/kg calorific value. Synthesis gas yield was 95.2 %, the degree of carbon gasification - 92.3 % and the degree of coal desulfurization - 95.2 %.

The degree of reduction of the solid residue samples from different sites of the installation for plasma chemical processing of fuel and from special bath melt around the graphite orifice 2 (Fig. 1) is presented in Table. 3. The table shows that the recovered material is located in the slag and presented in the form of ferrosilicon, silicon carbide and iron. The maximum degree of reduction of the MMC oxides reaches 47% in the slag from the walls of the reactor chamber in the arc zone of the maximum temperatures.

At the radiant-plasma processing coal dust was exposed to pre-activation by an electron beam, and then processed into the plasmochemical reactor 1 (Fig. 1). The experiments were performed in the plasma gasifier of 100 kW nominal capacity. As a result of the measurements of the process material and heat balances the following integral factors were found: the weight average temperature was 2200-2300 K, and the degree of carbon gasification was 82.4-83.2%. A significant positive effect of the preliminary radiant activation of pulverized coal to the yield of the synthesis gas during its processing was revealed. Synthesis gas yield at thermochemical preparation to burning of untreated coal dust was 24.5% and in the case of radiant activation of the coal synthesis gas yield reached 36.4%, which is 48% higher.

Table 3. Reduction degree (Θ) of MMC.

Site of sampling	*T, K*	*Θ , %*
Slag from the bath melt	2600-2800	8.5-44.0
Slag from the walls of the reactor chamber	2600-2900	16.5-47.3
Material from the slag catcher	2000-2200	6.7-8.3

Table 4. Integral parameters of the process of plasma processing of uranium-bearing shale.

G_f, *kg/h*	G_{steam} *kg/h*	$\gamma = \frac{G_{steam}}{G_f}$	T_{av}, *K*	Q_{sp}, *kW h/kg*	X_U, *%*	X_{Mo}, *%*	X_V, *%*	X_C, *%*
5.82	0	0	2900	2.84	48.0	54.5	58.6	56.2
8.40	0	0	2500	1.93	25.7	34.5	41.7	54.6
6.60	0.60	0.09	2700	2.20	78.6	79.0	81.3	66.4
4.33	0.40	0.09	3150	3.04	23.6	24.3	29.0	70.4

Essence of plasma technology for uranium, molybdenum and vanadium oxides from solid fuel is processing of the coal mixture with steam in the plasmochemical reactor 1 (Fig. 1) [6]. The process of uranium, molybdenum and vanadium extracting from coal (shale) using plasma heating is carried out as follows (Fig. 3). Coal dust from the hopper 1 and steam from the boiler 2 in a weight ratio coal - water steam equal to 8-12, enters the plasmochemical reactor 3. In the reactor 3 the steam plasma heats coal dust to the temperature of 2500-2900 K. As coal heating gasification of organic mass of coal is going on forming mainly synthesis gas and sublimation of vanadium, molybdenum and uranium in the form of oxides to the gas phase is taken place. Then the two-phase plasma flow (gas phase + molten slag) enters the chamber for gas and slag separation 4 (Fig. 3), slag goes to the slag catcher 5 and the gas directed to a series of heat exchangers 6, 8, 10 for step cooling and condensation of the separate target products. In the gas phase heat exchanger 6 is cooled to 2300-2400 K at which molybdenum oxides (Mo_nO_m) are condensed and trapped in the receiver 7. From the heat exchanger 6 gas enters the heat exchanger 8, where it is cooled to T = 2000-2200 K at which uranium oxides (U_nO_m) are condensed and trapped in the receiver 9. From the heat exchanger 8, the remaining exhaust gas

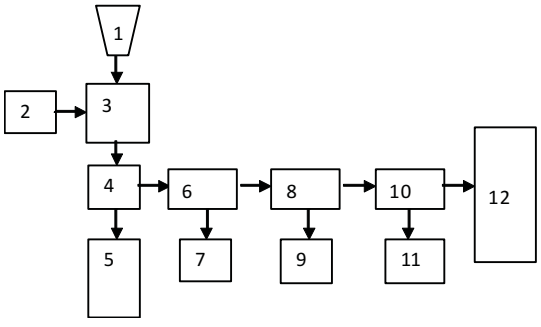

Fig. 3. Block diagram of plasma process for uranium, molybdenum and vanadium extracting from coal: 1 – coal dust hopper, 2 – water steam generator, 3 – plasmochemical reactor, 4 – chamber for gas and slag separation, 5 – clag catcher, 6, 8, 10 – heat exchanger, 7, 9, 11 – receiver, 12 – system for exhaust gas utilization.

enters the heat exchanger 10 where its temperature is reduced to T = 1800-1900 K, at which vanadium oxides (V_nO_m) are condensed and separated in the receiver 11. From the heat exchanger 10 the synthesis gas enters the utilization system 12. Table 4 shows the results of experiments on plasma processing of shale containing 0.02% of uranium.

Experiments on plasma pyrolysis (cracking) of propane-butane gas mixture were carried out in the plasmochemical reactor of 100 kW nominal power (Fig. 1). In the experiments propane-butane mixture flow was 300 l/min, and the electric power of the plasmochemical reactor was 60 kW [5]. During the experiments, hydrogen and carbon black were separated in the water-cooled chamber for gas and condensed phase separation 2. Hydrogen was withdrew into the oxidation chamber 4, and carbon landed on the reactor walls, water cooled copper spiral collectors beneath the lid and output orifice of the reactor, as well as slag catcher 3. After completion the experiments sampling from the aforementioned reactor units was carried out. Physico-chemical analysis of the samples of carbon black was performed using transmission electron microscopy (TEM). It showed that propane-butane mixture plasma pyrolysis products from the surface of the graphite electrode of the plasma reactor are different nanocarbon structures, mainly in the form of "colossal" nanotubes (Fig. 4) having high electrical conductivity and mechanical strength 30 times greater than the strength of Kevlar fabric [5]. On the negative 9091 sample is mainly composed of a "hairy" carbon nanotubes with a diameter of about 100 nm and a length greater than 5 microns. On the negative 9094 colossal carbon nanotubes with the inclusion of the teardrop shape metallic phase inside can be seen. Their diameter is 300 nm. Negative 9104 represents a "elbow" carbon nanotube with a diameter of 200 nm or more with an inner partition. Colossal nanotubes can be structures in the form of "octopus" (negative 9110). The

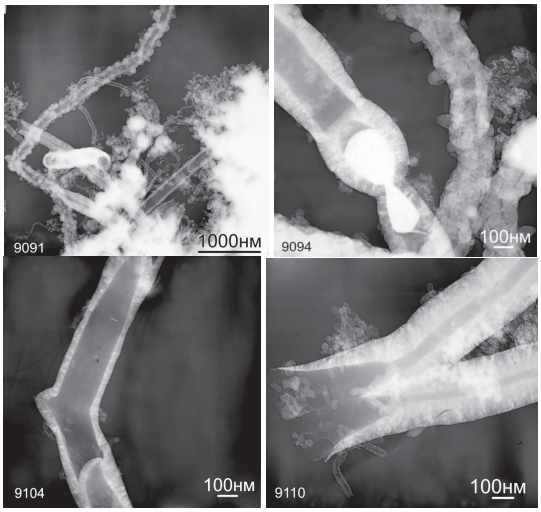

Fig. 4. Photographs of carbon nanostructures through TEM.

Table 5. The optimal ranges of the parameters for plasmochemical processing of fuel.

Fuel / plasma forming gas	*T, K*	*Specific power consumption kW·h/kg of fuel*	*Fuel conversion rate %*	*Concentration mg/Nm³*	
				NO_x	SO_x
1. Plasmochemical preparation of coal for combustion (air)					
1.5–2.5	800–1200	0.05–0.40	15–30	1–10	1–2
2. Complex processing of coal (water steam)					
1.3–2.75	2200–3100	2–4	90–100	1–2	1
3. Plasma gasification of coal (water steam)					
2.0–2.5	1600–2000	0.5–1.5	90–100	10–20	1–10
4. Radiant-plasma processing of coal (air)					
1.5–2.5	800–1200	0.1–0.45	22–45	1–10	1–2
5. Plasma processing of uranium-bearing solid fuels (water steam)					
8-12	2500-3150	2–4	55-70	1-3	1-2
6. Plasmochemical hydrogenation of coal (hydrogen)					
10	2800–3200	6.5–8	70–100	0	0
7. Plasmochemical cracking of a propane-butane mixture					
18 м³/ч	1500–2500	2.2–3.8	98–100	0	0

diameter of the octopus in its ramifications is about 400 nm. Characteristically, the thickness of colossal nanotubes can range from 30 nm (negative 9104) to 100 nm (negatives 9094 and 9110).

The experimental results confirmed the possibility of producing hydrogen and condensed carbon-containing nanostructures in form of colossal carbon nanotubes. Based on these results, a technical solution for a pilot installation with power of 1 MW and a capacity on the natural gas source 330 Nm^3/h for the implementation of plasmochemical cracking of hydrocarbon gases was developed. The expected yield of the desired product was 74 % of carbon (171 kg/h) and 25 % of hydrogen (58 kg/h).

Table 5 summarizes the results of studies of plasmochemical processing of solid and gaseous fuels. Mass ratios solid fuel / oxidizer vary in the range of 1.3-2.75, ratio carbon / hydrogen reached 10 kg/kg, and the consumption of propane-butane mixture for processing in the plasmochemical reactor of 60 kW power is 18 m^3/h. Weight average temperature of the processes ranged from 800 to 3200 K. Since the plasmochemical preparation of coal for combustion is based on a partial gasification (conversion 15-30%), the temperature (800-1200 K) and the specific power consumption for the process (0.05-0.40 kW h/kg) are reasonable.

REFERENCES

[1] M. Gorokhovski, E.I. Karpenko, F.C. Lockwood, V.E. Messerle, B.G. Trusov, A.B. Ustimenko, “Plasma technologies for solid fuels: experiment and theory”, Journal of the Energy Institute, V. 78, N 4, P. 157-171, 2005.

[2] M.F. Zhukov, R.A. Kalinenko, A.A. Levitski, L.S. Polak, *Plasmochemical processing of coal.* (in Russian), Moscow: Science, 200 p., 1990.

[3] V.E. Messerle, A.B. Ustimenko, *Plasma ignition and combustion of solid fuel. (Scientific-and-technological basics).* (in Russian), Saarbrucken, Germany: Palmarium Academic Publishing (ISBN: 978-3-8473-9845-5), 404 p., 2012, Available: http://ljubljuknigi.ru/

[4] V.E. Messerle, A.B. Ustimenko, “Radiant-plasma technology of coal processing” (in Russian), KazNU Bulletin. Chemical series. V. 4 (68), P. 107-113, 2012.

[5] V.E. Messerle, A.B. Ustimenko “Plasmochemical technologies of fuel processing” (in Russian), Izvestiya Vuzov (Proceedings of High Education). Chemistry and chemical technology, V. 55, N. 4, P. 30-34, 2012.

[6] E.I. Karpenko, V. E. Messerle, *Plasma-power technologies of fuel utilization* (in Russian), Novosibirsk. V. 1, Science, Siberian enterprise RAS, 385 p., 1998.