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V.E. Messerle, A.B. Ustimenko*
The Combustion Problems Institute, Research Institute of Experimental and Theoretical Physics, Research Institute of New Chemical Technologies and Materials, Kazakhstan, Almaty
*E-mail: ust@physics.kz

Steam and air plasma gasification of bituminous coal and petrocoke

Abstract. This paper presents a numerical analysis and experimental investigation of two very different solid fuels, low-rank bituminous coal of 40 % ash content and petrocoke of 3 % ash content, gasification under steam and air plasma conditions with an aim of producing synthesis gas. Numerical analysis was fulfilled using the software package TERRA for equilibrium computation. Using the results of the numerical simulation, experiments on plasma steam gasification of the petrocoke and air and steam gasification of the coal were conducted in an original installation. Nominal power of the plasma installation is 100 kWe and sum consumption of the reagents is up to 20 kg/h. High quality synthesis gas was produced in the experiments on solid fuels plasma gasification. It has been found that the synthesis gas content at about 97.4 vol.% can be produced. Comparison between the numerical and experimental results showed satisfactory agreement.

Keywords: coal, petrocoke, gasification, arc plasma, plasma chemical gasifier, synthesis-gas.

Introduction

The world's petroleum reserves are limited. Based on current global consumption, it has been estimated that this reserve will be depleted in approximately 40 to 60 years. Coal is worldwide most abundant energy resource and the least expensive fossil fuel. One more energy resource is petrocoke derivable as a result of hydrocarbons production by oil sands thermal processing. For instance in Canada there are mountains of petrocoke. Petrocoke is a solid fuel consisting of fixed carbon, tar and ash. Direct utilization of petrocoke is difficult because of its hardness and high tar content. In connection with this, the development of solid fuels technologies, which would be environmental friendly and efficient, is of a primary importance. Coal gasification is a well-proven technology that started with the production of synthesis gas (CO + H_2) for urban areas. Gasification-based technologies can be used to convert carbon-containing resources into a clean synthesis gas with high value as a fuel for combined cycle power generation [1] or as a raw material for the production of liquid fuels and chemicals. Moreover, they have the advantage of being capable of co-generating electricity and fuel/chemical efficiently, economically, and in an environmentally acceptable manner. Environmental performance of these technologies can be tailored to any specific requirements. In addition, due to the high efficiency nature of these technologies, the emissions of CO_2 are relatively low.

Plasma gasification of solid fuels is one of the perspective technologies for effective and environmental friendly solid fuels utilization [2]. For instance China coal gasification in steam plasma conditions [3] showed quite high indexes (syngas yield of 75 %).

This paper presents numerical and experimental investigation of solid fuels gasification in air and water steam medium in arc-plasma reactor. First air-solid fuel and steam-solid fuel mixtures gasification was investigated numerically with the aid of code TERRA [4] validated for thermal equilibrium calculations. Then these mixtures were investigated experimentally and the numerical results were verified against operational data got in the experiments. Kazakhstan Kuuchekinski bituminous coal (KBC) 40% of ash content and Canadian petrocoke (CP) 3 % of ash content (Table 1) were used for the investigation. Their dry basis higher calorific values are 16632 kJ/kg and 47008 kJ/kg correspondingly.

Special combined plasma chemical reactor (CPCR) for coal gasification allows performing processes thermo impact on solid fuel for getting synthesis gas free from nitrogen and sulphur oxides. The experimental installation is intended for work in range of electric power 30-100 kW, mass averaged temperature 1800-4000 K, coal dust consumption 3-12 kg/h and gas-oxidant (air or steam) flow 0.5-15 kg/h. High quality syngas was produced from the both solid fuels.

Code TERRA [4] was used for thermodynamic analysis of the solid fuels plasma gasification process. This software was created for equilibrium computations of high-temperature processes and in contrast to traditional thermo chemical methods of equilibrium computation that use the Gibbs energy, equilibrium constants and Guldberg and Vaage law of acting mass, TERRA is based on the principle of maximizing entropy for isolated thermodynamic systems in equilibrium. TERRA has its own database of thermodynamic properties for more than 3500 chemical agents over a temperature range of 300 to 6000 K. Before discussing the results note, despite of the fact that in principle plasma reactor is opened, not isolated system and there is an exchange of energy and substance with external medium, thermodynamic modeling of solid fuel gasification inside the plasma-chemical reactors is possible. First, at preparation of heat and material balance of the plasma gasifier actual heat losses are taken into account, and in this case mass mean temperature in the plasma reactor is determined as for thermodynamically isolated system. Second, time of the reagents stay in zone of reactions is about 1 s which is multiply longer than thermodynamic equilibration time in the system at high temperature of the process [4]. Third, the CPCR is flow reactor and quasistationary process of gasification is provided.

The calculations were performed for the process of KBC and CP gasification in air and steam medium. The chemical composition of KBC and CP is presented in Table 1. All calculations were performed at atmosphere pressure P = 0.1 MPa and within temperature interval 400-4000K. The temperature is suggested to be kept at the expense of external heat source, which is an arc in a CPCR.

Table 1 – Solid fuels chemical analysis, % dry mass basis

Solid fuel	C	O	H	N	S	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O
KBC	48.86	6.56	3.05	0.8	0.73	23.09	13.8	2.15	0.34	0.31	0.16	0.15
CP	75.0	0.88	15.53	0.01	5.63	1.31	0.78	0.6	0.1	0.05	0.07	0.04

For the first set of calculations the feed was assumed to consist of 100 kg of KBC plus 127.5 kg of air, for the second one the feed was assumed to 100 kg of KBC plus 62.75 kg of water steam, for the third set the feed was supposed to be 100 kg of CP plus 460 kg of air and for the fourth one the feed was assumed to 100 kg of CP plus 120 kg of water steam. The gas phase species (Figure 1-3), degree of solid fuel gasification (Figure 4) and specific power consumptions for the processes (Figure 5) were calculated for all the variants.

Figure 1 presents the results of calculations of air gasification of KBC. The gas phase (Fig. 1 on the left) in a temperature interval of 400 to 4000 K mainly consists of nitrogen and syngas (CO + H_2) thermodynamically steady to co-products of coal gasification process. Its concentration reaches the maximum 54.79% at T=1800 K. Oxidant concentration (H_2O and CO_2) decreases to zero at temperature increase to 1400 K. Nitrogen content substances are presented mainly in form of molecular nitrogen (N_2). Its concentration decreases with temperature because of syngas appearance in gas phase and the last-named concentration increasing so as due to the species of the coal mineral mass conversion into gas phase at temperatures over 1600 K. Carbon monoxide (CO) concentration reaches the maximal value of 35.74 % at temperature 1800 K. Concentration of molecular hydrogen (H_2) in temperature interval from 400 to 1600 K increases promptly and reaches the maximum of 20.3 % at T=1600 K. At the temperature over 1600 K H_2 concentration decreases because of its dissociation, and in gas phase atomic hydrogen (H) appears. H concentration increases with the temperature and reaches 23.34 % at 4000 K. At the temperature over 1600 K in gas phase there is hydrogen cyanide (HCN) and cyanide (CN), total concentration of which reaches 2 % at temperature 2800 K.

Mineral components of the coal sublimate into the gas phase (Figure 1 in the centre) along with the temperature of the coal gasification process. They are mainly aluminum (Al) and silicon (Si). In gas phase they appear at the temperatures over 2200 K. Their sum concentration reaches 5.5 % at 4000 K. Total concentration of all the other species of mineral mass in gas phase reaches 1 %. Carbon concentration in condensed phase (Figure 1 on the right) decreases due to its gasification in temperature interval from 800 to 1200 K. In the interval of 1200 to 1600 K its concentration is practically steady because of absence of free oxygen in gas phase. In the interval 1600-1800 K carbon concentration decreases sharply due to its participating in the reactions of ferric and silicon oxides reduction to the carbides (Fe_3C and SiC). Within the temperature interval 1800-2600 K all mineral components evolve into gas phase as Al, Si, SiS, Fe, Al_2O, SiC_2 et al. (Fig. 1 in the centre).

Gas phase of the products of KBC gasification in steam medium (Figure 2 on the left) is presented generally by syngas, which the maximal concentration is 99 % at 1500 K. At that sum concentration of atomic and molecular hydrogen is higher than concentration of carbon monoxide all over the temperature range and varies from 48 to 59 % in volume. With the temperature concentration of carbon monoxide decreases from 47 % at 1500 K down to 34 % at 4000 K. Light decrease of syngas concentration at temperature increase is connected with appearance in the gas phase the components of mineral mass of the coal. They begin to convert from the condensed phase to the gas one at temperature over 1600 K (Figure 2 in the centre). At temperatures over 3000 K mineral components of the coal are presented in the gas phase mainly as elements Si, Al, Ca, Fe, Na and compounds AlH, AlOH, SiS et al. With the temperature the last are decomposed intensively. As to the condensed phase (Figure 2 on the right), with temperature increase to 3000 K all components of it are transferred into the gas phase. Note there are no carbides in the condensed phase except one minor peak of Fe_3C concentration.

Figure 3 presents gas species concentration versus temperature of the process of CP gasification in air and steam medium. As mineral mass of CP is very small we consider the behavior of inorganic species neither in gas no in condensed phase. Using air gasification (Figure 3 on the left) in a temperature interval of 1000 to 2600 K the gas phase mainly consists of molecular nitrogen (N_2) and syngas (CO + H_2). When the concentration of hydrogen is 26.9% (T=1400K), the concentration of carbon monoxide is 22.9% and the concentration of nitrogen is 47.4%. Under these conditions the sulfur is presented as hydrogen sulfide (H_2S) with a concentration of less than 0.7%. Oxidant concentration (H_2O and CO_2) in this temperature interval does not exceed 2.1%. At the temperature over 2000 K in gas phase atomic hydrogen (H) is present. Its concentration reaches 35.9% by the temperature 4000 K. At the temperature exceeding 2200 K hydrogen sulfide dissociates into atomic sulfur (S) and sulfur hydride (SH). Total maximal concentration of them is about 0.5%. In gas phase at temperature above 3000 K hydroxyl (OH) and atomic oxygen (O) appears. Their total concentration is about 1.5%. At temperature exceeding 3200 K in gas phase nitrogen oxide (NO) is noticed. Its concentration reached 1500 ppm.

Using CP steam gasification in a temperature interval of 1200 to 2800 K, the gas phase (Fig. 3 on the right) mainly consists of syngas. When the concentration of hydrogen was 67 % (T=1400K), the concentration of carbon monoxide was 29.8% and sulfur was presented as sulfur hydrogen (0.8%). The oxidants concentration (H_2O and CO_2) does not exceed 2.5 % in that temperature range. At temperatures greater than 2000 K atomic hydrogen appears in gas phase. Its concentration reaches 62.2% at temperature 4000 K. At temperatures greater than 2200 K hydrogen sulfide dissociates into atomic sulfur and sulfur hydride with total maximal concentration of them reaching 0.5%. At temperatures greater 3000 K in gas phase hydroxyl and atomic oxygen appears. Their total concentration was less than 1.5%. In contrast to the gasification in air medium, in the process of steam gasification nitrogen oxides are not formed.

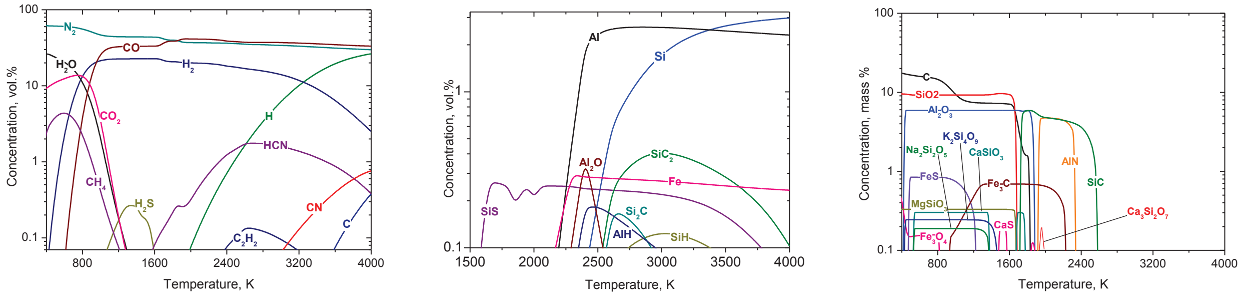


Figure 1 – Composition of organic (on the left) and mineral (in the centre) components in gas phase and condensed components (on the right) versus temperature at KBC air gasification.

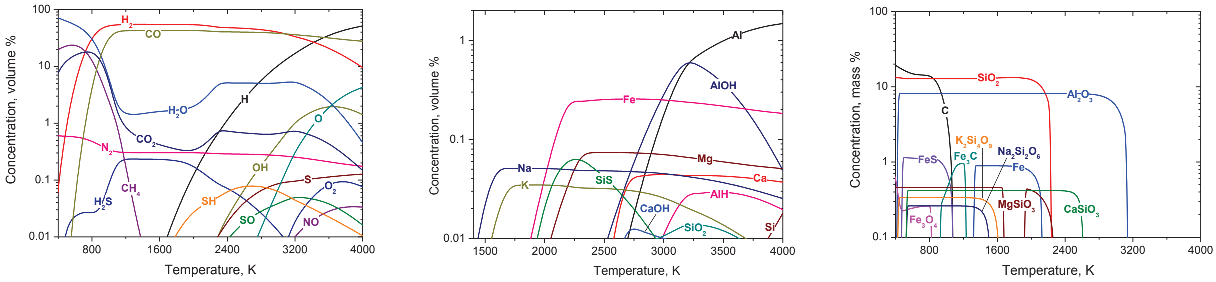


Figure 2 – Composition of organic (on the left) and mineral (in the centre) components in gas phase and condensed components (on the right) versus temperature at KBC steam gasification.

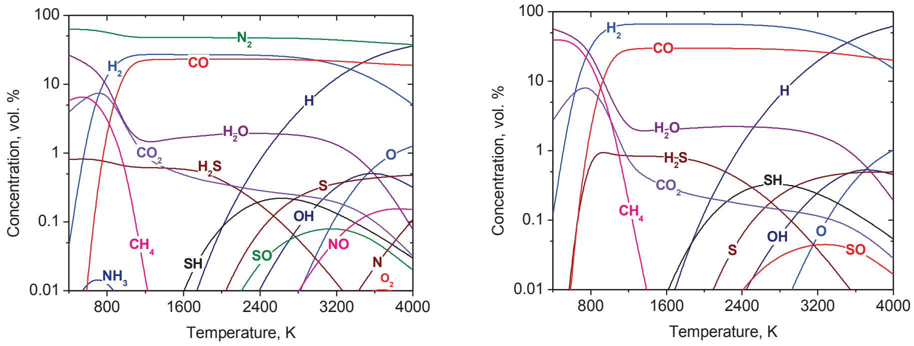


Figure 3 – Concentrations of gas phase species (organic mass) variation with temperature of the process of CP air (on the left) and steam (on the right) gasification

Note that concentration of syngas obtained in the process of steam gasification is significantly higher one got in the process of air gasification for the both solid fuels.

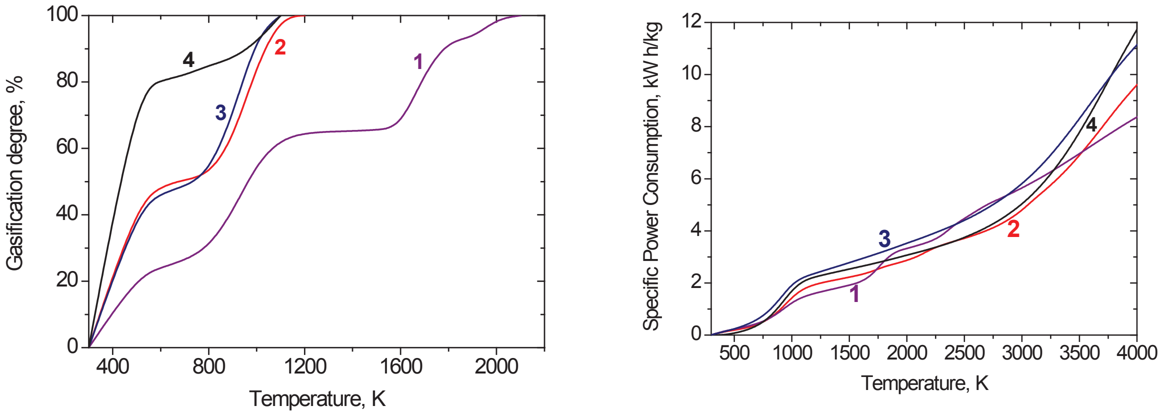
The degree of solid fuel carbon gasification X_C is determined from the carbon content in condensed phase. Specifically, X_C is calculated according to the following expression:

$$X_c = \frac{C_{bas} - C_{fin}}{C_{bas}} \cdot 100\%,$$

where C_{bas} and C_{fin} is initial carbon concentration in the solid fuel and final carbon concentration in the solid residue (condensed phase) at current temperature of the process correspondingly.

Carbon gasification degree (Figure 4) increases with the temperature in all variants and reaches 100 %. Thus carbon from the solid fuels completely transforms into the gas phase mainly in the form of CO (Figures 1-3). At KBC gasification in air medium in the temperature interval of 1200 to 1600 K carbon gasification degree is practically permanent because of free oxygen absence and carbides formation. At temperature exceeded 1600 K gasification degree increases sharply due to decomposition of ferric and silicon carbides and carbon oxidation in reduction reactions of oxygen containing compounds Al_2O_3, $CaSiO_3$, $MgSiO_3$ et al. and completely transforms to gas phase by temperature 2100 K At

KBC gasification in steam medium carbon gasification degree reaches 100 % by 1200 K. In the contrast to the KBC gasification in air medium there is no “plateau” in temperature dependence of gasification degree. It is explained by different levels of temperature necessary for carbon complete gasification in water steam (T~1200 K) and formation of silicon, ferric and aluminum carbides in condensed phase (T = 1400-2400 K) (Figures 1 and 2). It means when the temperature of carbides formation in condensed phase is reached carbon has completely transferred into the gas phase as CO. Carbon gasification degree increases with the temperature in the both variants of CP gasification and reaches 100 % at close and relatively low values of temperature, which is 1100 K.



1, 2 is KBC gasification in air and steam medium and 3, 4 is CP gasification in air and steam medium correspondingly.

Figure 4 – Carbon gasification degree (on the left) and specific power consumptions for the process of plasma gasification (on the right) related to 1 kg of syngas versus temperature

Specific power consumptions (SPC) for the gasification processes were calculated by the difference of working medium (solid fuel and oxidant) enthalpy in initial (T=298 K) and final (current temperature of the process) conditions. The calculations results for the both processes are presented in Figure 4. At the temperatures above 1,000 K SPC for syngas producing increase smoothly with the gasification processes temperature. Note that for the both processes of CP gasification in the temperature interval from 1400 to 2600 K, where syngas concentration is maximal and practically permanent, SPC related to one kilogram of syngas are different noticeably. For example at temperature 1,400 K SPC for the process of CP gasification in steam medium is less than one in air medium and amount to 2.43 and 2.64 kW h/kg of syngas correspondingly. SPC for syngas producing at KBC gasification in both air and steam medium, having minor fluctuations in temperature range from 1600 to 2200 K (curve 1) in which reducing endothermic reactions with carbon run, monotonously increase with temperature. In the temperature range from 1700 to 3200 K SPC for KBC gasification in steam medium are less ones in air medium. At the temperatures of coal gasification degree reaching 100 %, which is 1200 and 2000 K for KBC gasification in steam and air medium correspondingly, SPC for KBC gasification in air medium (3.32 kW h/kg) 1.7 times higher one for KBC gasification in steam medium (1.95 kW h/kg). At that syngas concentration at both KBC and CP gasification in steam medium is higher essentially (see Figures 1 to 3) and reaches 97 % against 50 % at gasification in air medium for CP gasification and 97 % against 61 % for KBC gasification. At the same time syngas at the solid fuels gasification in steam medium is of a higher quality. E.g. hydrogen concentration at CP and KBC gasification in steam medium reaches 67 % and 54.8 % against 27.1 % and 22.6 % at the solid fuels gasification in air medium correspondingly.

Thus numerical investigation showed that from both energy and ecology points of view for solid fuel gasification more perspective process is its gasification in steam medium with use of internal heat sourse. And this sourse can be plasma one. It allows getting the temperature required for the process of gasification without additional fuel incineration and the target product syngas dilution with inert products of combustion. Solid fuel plasma gasification under steam conditions allows converting the organic mass of the fuel into high-calorific syngas that is free from nitrogen and sulphur oxides. This conversion can be written as following gross-reaction: $C + H_2O = CO + H_2$. Plasma sourse energy compensates endothermic effect of this reaction, which is equal 130500 J/mol.

Experimental

The gasification experiments were conducted in a tube-type setup, which is schematically shown in Fig. 5. The principal components are a: plasma generator-reactor,1; slag trap, 2; syngas and slag separator chamber, 3; syngas cooling chambers, 4, 5, 6; pulverised fuel feeding system, 8; and a steam feeding system, 9. The zones of heat release, due to the arc plasma, and of heat absorption, by the solid fuel and gas streams, are combined in the same plasma generator-reactor chamber, 1. It consists of a cylindrical water-cooled jacket with a top cover carrying graphite rod electrode, diameter 0.04 m, and the inlet pipes for pulverised solid fuel (pf) and plasma-forming gas. It is lined with graphite, thickness 0.02 m, and bounded at its bottom side by a graphite orifice. The inner diameter of the reactor (i.e. of the graphite lining) is 0.15 m and its height is 0.3 m. The direct current arc is established as sketched between the rod and the graphite lining electrodes. It is localised at the ring electrode band of 0.07 m by an enveloping electromagnetic coil, 12, made of water-cooled copper pipe. The plasmotron power is variable between 30 and 100 kW.

The slag trap, *2*, is a water-cooled cylinder of height 0.56 m, containing a slag catcher basket. It is lined with graphite to give an inner diameter of 0.15 m. The syngas cooling occurs in chambers *4, 5, 6*, which are water-cooled stainless steel cylinders, some of which are also lined with graphite to the same diameter.

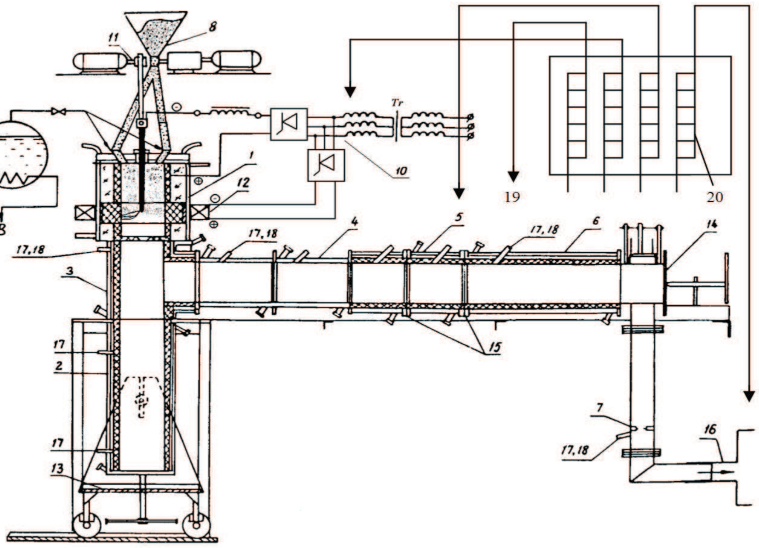
The pf supply system consists of a screw feeder, *8*. The steam feeding system consists of a hot-water boiler mounted on a weighbridge, *9*, and a steam reheater. The two streams are merged and partially mix just prior to admission to the reactor through pipes in its top cover. The pulverised fuel admission rate is determined by weighing to within an error of 1.5%. The steam rate is varied in the range 0-10 kg/h to within an error of 3%. On completion of an experimental run, all components of the apparatus are thoroughly cleaned of the condensed phase, which is weighed to determine the mass of the solid residue from the fuel conversion process. The yield of gaseous products is measured with Prowirl 77F flowmeter, *7*, at the outlet of syngas cooling chamber, *6*.

The gas to be analysed is withdrawn from syngas cooling chambers through the pipes, 18, by a quartz probe and directly admitted to the gas analysis system. The gas is subject to chromatographic analysis with the help of SRI 8610C gas analyzer. Carrier gas is helium or argon, detectors are thermal conductivity sensors. Analysis of light gases H_2, CO, O_2, N_2, CH_4 are provided in columns filled with molecular sieve CaX and analysis of CO_2 in silica gel column. Method of absolute calibration is used for experimental data handling. Composition of the solid residue was investigated by chemical and X-ray phase analysis. To determine carbon gasification degree absorption-weight method is used. According to this method carbon is determined through the carbon dioxide that is formed as a result of the solid residue sample combustion in oxygen and following absorption of it by ascarit (KOH or NaOH covering asbestos).

An overall calorimetric balance is performed on the setup using the coolant water flows and temperatures. The water temperatures are measured by thermocouples (Chromel-Copel) to within an absolute error of 0.2°. The overall error in the calorimetric balance is typically 6-10%.

The temperatures of the reactor wall and of the gases exiting from the graphite diaphragm are measured by standard tungsten-rhodium thermocouples. The thermocouple junction exposed to the exiting gases is 10^{-3} m in diameter; the radiation error does not exceed 50°C. The gas temperature in the reactor is not measured. Instead, the mass-averaged temperature of reagents is calculated from a reactor heat. Mass and heat balance is an important indicative of gasification experiments. The equations of material and heat balance of the experimental setup take the following form: $G_2 + G_3 + G_4 + G_5 = G_6 + G_1 + G_7$, kg/h , and $W_0 + W_1 = W_2 + W_3 + W_4 + W_5 + W_6$, kW, where G_2, G_3, G_4, and G_5 are the flow rates of pf, steam or air, carrier gas for fuel pulverisation, and electrode graphite, respectively; G_6, G_1, G_7 are the mass rates of slag (solid residue), effluent gases, and pulverised coke (fume and fine particles) being removed, respectively; W_0 is the heat output of the arc,

W_1 is the heat supplied with steam at T = 405 K; the heat losses to the cooling water in the unit assemblies are: W_2 from the reactor; W_3 from the gas and slag separation chamber; W_4 from the syngas cooling chamber; W_5 from the slag catcher; W_6 from the heat carry-over in the effluent gas stream.



1 – DC arc plasma reactor, 2 – slag trap, 3 – syngas and slag separator chamber, 4,5,6 – syngas cooling chambers, 7 – flowmeter, 8 – pf feeding system, 9 – steam feeding system, 10 – power supply unit, 11 – motorised electrode position system, 12 – electromagnetic coil, 13 – handcart-elevator, 14 – waste gas output section with safety valve, 15 – sections for sulphur clearing, 16 – gas extraction system, 17 – pipes for thermocouples, 18 – pipes for gas sampling, 19 – the installation units cooling system, 20 – flowmeters, *Tr* – transformer.

Figure 5 – Experimental setup for pf plasma gasification

The arc electric power is determined from wattmeter. The heat input in steam is calculated as: $W_1 = G_3 \times H_1$, kW, where $H_1 = H^\circ_{405K} + D\,H^\circ_{steam} = 0.05 + 0.63 = 0.68$ kW×h/kg of steam. $D\,H^\circ_{steam}$ is the heat of vaporization. The heat loss with the effluent gases is determined from the effluent gas temperature (T_g), flow rate (G_1), and composition obtained through the gas analysis. The measured temperature, pressure, and composition of gases are fed into the TERRA code [4] and the specific enthalpy of the effluent gases is computed for specified values of the parameters mentioned above. The gas mixture heat output is calculated as follows:

$$W_6 = H_6 \times G_1 \text{, kW, where } H_6 = \int_{300}^{T_g} C_p \cdot dT$$

is the specific enthalpy of the gas mixture.

Thus, except for W_6, all the components of the heat balance equation are measured during the experiment.

Experimental Results

Arc is initiated by vaporising a wire brought into contact with the rod and ring electrodes. The flow of steam or air and finally grained fuel is then initiated. The steam(air)/pulverised fuel mixture entering the arc zone is heated to high temperatures by the arc rotating in electromagnetic field to produce a two-phase plasma flow where the solid fuel gasification process occurs. The solid residue so produced descends through the orifice plate into the slag catcher 2 (Fig. 5). The gaseous products exit the gas and slag separation chamber 3 and flow into the cooling chambers 4, 5, 6. Then gaseous products are exhausted to ventilation.

Duration of the experiments varied from 0.5 to 1 hour. The dust of KBC and CP (Table 1) was used in the experiments. The sieve analysis of the pf using shaker "Tyler" RX-812 and set of calibrated sieves with meshes size of 43 to 1000 μm revealed that mean sizes of the KBC and CP dust particles were 75 μm and 105 μm correspondingly.

Prior to conducting an experiment, an estimate of the steam requirement was made from the water gas reaction. This estimate ignored the oxygen content of the inorganic material of coal. Conditions of the experiments and their results are shown in Table 2. To calculate the specific power consumption (SPC) for the process, reduced to one kilogram of syngas output, the following formula is used: $Q_{SP}^{SYNG} = (W_0 + W_1 - W_2)/(G_1 - G_4)$, kW×h/kg. Thermal efficiency of the reactor was determined as 76 % for all experiments. As a result of KBC plasma gasification in steam and air medium and CP gasification under steam plasma conditions concentrations of gas species, carbon gasification degree X_C and mass-averaged temperatures T_{AV} in the reactor were revealed.

Table 2 – Main Indexes of the Solid Fuels Plasma Gasification

N	Solid fuel	Consumption, kg/h				W_0, kW	Q_{SP}^{SYNG}, kW h/kg	T_{AV}, K	CO	H_2	N_2	X_C, %
		fuel	steam	air	G_1				Volume %			
1	KBC	8.0	-	8.0	12.3	33	2.1	2100	27.4	15.9	55.3	89.6
2	KBC	4.0	-	5.1	7.4	30	3.1	2850	38.1	18.2	43.7	95.8
3	KBC	4.0	1.9	-	4.2	25	4.8	3500	41.5	55.8	2.7	94.2
4	KBC	6.5	3.0	1.9	8.5	52.8	4.7	3550	38.6	51.4	9.8	92.0
5	CP	2.5	3.5	-	5.1	60	9.4	3800	33.9	65.3	0.8	76.3
6	CP	2.5	3.0	-	4.9	60	9.6	3850	36.2	63.1	0.7	78.6

From the table it follows that KBC gasification degree in air increases from 89.6 to 95.8% at SPC rise from 2.1 to 3.1 kW h/kg of syngas. At that syngas yield increased from 33.3 to 56.3 %. It is a consequence of gasification products mass consumption G_1 decrease from 12.3 to 7.4 kg/h, mass-averaged temperature in the reactor increase from 2100 to 2850 K and corresponding intensification of the process. At KBC gasification under plasma-steam conditions SPC are noticeably higher (4.7 and 4.8 kW h/kg) under the keeping gasification degree on the high level of 92.0 to 94.2 %. At that it is typical syngas yield is appreciably higher (90.0-97.3 %). Note that contrary to the gasification under air-plasma conditions for the process of plasma gasification in steam medium the concentration of hydrogen in syngas is higher than the concentration of carbon dioxide. At that hydrogen concentration at gasification in steam 3-4 times higher one produced in air medium. This effect is connected with enriching syngas with hydrogen due to reaction of water steam decomposition by solid fuel's carbon.

As to CP, in view of high content of tar its direct use for redox is impossible and whereas CP reactivity is extremely low its utilisation in the conventional processes of combustion or gasification is very problematic. In connection with this the experiments by CP gasification under plasma-steam conditions were initiated. To get possessing good qualities syngas the process was carried out under relatively high SPC (9.4-9.6 kW h/kg of syngas). Under these conditions mass-averaged temperature varied from 3800 to 3850 K, CP gasification degree varied from 76.3 to 78.6 %. Note high content of hydrogen in syngas (63.1-65.3%) at syngas yield 99.2-99.3%. The received ratio H_2:CO≈2:1 corresponds to the optimal content of a gas for synthetic liquid fuel (methanol) synthesis: $CO + 2H_2 = CH_3OH$ [5].

The difference between CP and KBC ash content is more than ten times (3-40 %). But yield of syngas varies insignificantly, it reaches practically limiting values (90–99.3%). Note that H_2 concentration in syngas is substantially higher one of CO.

Note also that SPC related to syngas vary in broad interval from 2.1 to 9.6 kW h/kg. Evidently if for syngas producing to use water steam got utilizing the heat of the gasification products and to use exit gas as carrier one instead of air for pf feeding, SPC would be minimized and consequently efficiency of syngas producing would be higher. The second way of SPC decrease is based on application of plasma-autothermal principle of solid fuel gasification in two-stage gasifier. At first gasification of 30 % of fuel under air plasma conditions and following combustion of the gasification products up to CO_2 is realised. At that 33173 kJ/kg of carbon is evolved. This heat together with heat of the electrical arc is enough to compensate endothermic effect (10875 kJ/kg of carbon) of the water gas reaction ($H_2O+C=C+H_2$) at the rest 70 % of fuel gasification in steam medium. Particularly for the experiment 3 (Table 2) SPC are 8 kW h/kg of carbon. But for the same initial data at plasma-autothermal gasification of the same fuel SPC would be 0.8 kWh/kg of carbon. It is equal to the arc generation of heat W_0 decrease from 25 to 2.5 kW.

In order to estimate the reliability of the TERRA code, comparisons between the calculated results and the experimental data were made. The comparisons are presented in Table 3, which demonstrates that reasonably satisfactory agreement was achieved.

Table 3 – Comparison between the calculated results and the experimental data

Method	Content, volume %			X_C,%
	CO	H_2	N_2	
Experiment # 2 of Table 2	27.4	15.9	55.3	95.8
Calculation # 2	36.6	16.4	36.6	100
Experiment # 3 of Table 2	41.5	55.8	2.7	94.2
Calculation # 3	38.8	54.1	0.3	100
Experiment # 6 of Table 2	36.2	63.1	0.7	78.6
Calculation # 6	21.3	76.1	-	100

The difference between the calculated and experimental degree of pf gasification is not more than 21.4%, and for the yield of the syngas it is not more than 22.4%. Note that compound of syngas in the calculations and experiments is similar.

The discrepancies can be explained by deviations from thermodynamic equilibrium due to the limited residence times in the plasma reactor and impossibility to determine all species of the gas phase at chromatography fulfillment.

Conclusions

Fulfilled study of two essentially different in composition and in quality solid fuels gasification showed possibility to produce high quality syngas both in steam and air plasma. It has been found that syngas with the H_2 + CO content from 43.3 % at KBC gasification in air medium to 97.4% at CP gasification in steam plasma conditions can be produced.

The received syngas from the solid fuels is a high-quality power gas, and it can be used for synthetic liquid fuel (methanol) synthesis: $CO + 2H_2 = CH_3OH$ [4]. Syngas of this quality is high-potential reducing agent for iron ore direct reducing and can serve as a substitute of metallurgical coke. Also plasma steam gasification is perspective method for hydrogen production through water steam decomposition by carbon of a solid fuel.

Later on it is planed to conduct experiments by solid fuels gasification under steam plasma conditions with aim of gasification degree increase and specific power consumptions to the process decrease.

References

1 Messerle V.E., Ustimenko A.B. Plasma ignition and combustion of solid fuel. (Scientific-and-technological basics). - Saarbrucken, Germany: Palmarium Academic Publishing (ISBN: 978-3-8473-9845-5), 2012. – 401 p.

2 Messerle V.E., Ustimenko A.B., Slavinskaya N.A., Riedel U. Influence of coal rank on the process of plasma aided gasification // ASME Turbo Expo 2012, Bella Center, Copenhagen, Denmark, June 11-15, 2012. Final program – P. 39. Proceedings N. GT2012-68701. – P.1-10.

3 Jieshan Qiu, Xiaojun He, Tianjun Sun, Zongbin Zhao, Ying Zhou, Shuhong Guo, Jialiang Zhang, Tengcai Ma. Coal gasification in steam and air medium under plasma conditions: a preliminary study. // Fuel Processing Technology, 2004. – V.85. – P.969-982.

4 Gorokhovski M., Karpenko E.I., Lockwood F.C., Messerle V.E., Trusov B.G., Ustimenko A.B. Plasma Technologies for Solid Fuels: Experiment and Theory. Journal of the Energy Institute. – 2005. – V. – №78 (4). – P. 157-171.

5 Kruzhilin G.N. Plasma Gasification of Coal. Vestnik (Bulletin) of Academy of Science of the USSR, 1980. – N12. – P. 69-79.

Мессерле В.Е., Устименко А.Б.

Тас көмір және мұнай коксінің бу және әуе плазмалы газификациясы

Бұл мақалада екі әртүрлі қатты отындардың плазмалы әуе және бумен газификациясының сандық және эксперименттік зерттеулерінің, яғни синтез-газды алу мақсатымен күлділігі 40%-ды төмен сортты тас көмірдің және күлділігі 3%-ды мұнай кокстің нәтижелері келтірілген. Сандық талдау термодинамиялық есептеулерді жүргізуге бағытталған TERRA атты бағдарлама арқылы орындалған. Есептеу нәтижелері арнайы қондырғыда мұнай коксінің плазмалы бумен газификациялау, көмірдің бумен және әуе газификациялау бойынша тәжірибелерді өткізуі үшін қолданған. Плазмалы қондырғының белгіленген қуаты 100 кВт, 20 кг/сағ реагенттердің жиынтық шығынында. Тәжірибелерде 97,4% шығуымен жоғары сапалы синтез-газ алынды. Есептік және эксперименттік мәліметтер жеткілікті өзара сәйкес келеді.

***Түйін сөздер**:* көмір, мұнай коксі, газификация, электр доғалы плазма, плазмахимиялық газификатор, синтез-газ.

Мессерле В.Е., Устименко А.Б.

Паровая и воздушная плазменная газификация каменного угля и нефтяного кокса

В настоящей статье представлены результаты численных и экспериментальных исследований плазменной воздушной и паровой газификации двух различных твердых топлив: низкосортного каменного угля зольностью 40 % и нефтяного кокса зольностью 3 % с целью получения синтез-газа. Численный анализ выполнен с помощью программы термодинамических расчетов TERRA. Результаты расчетов были использованы для проведения экспериментов по плазменной паровой газификации нефтяного кокса и паровой и воздушной газификации угля на специализированной установке. Номинальная мощность плазменной установки 100 кВт при суммарном расходе реагентов 20 кг/ч. В экспериментах был получен высококачественный синтез-газ с выходом 97,4 %. Расчетные и экспериментальные данные удовлетворительно согласуются между собой.

Ключевые слова: уголь, нефтяной кокс, газификация, электродуговая плазма, плазмохимический газификатор, синтез-газ.