



Comparative study of coal plasma gasification: Simulation and experiment



V.E. Messerle^{a,b}, A.B. Ustimenko^{a,*}, O.A. Lavrichshev^a

^a Research Institute of Experimental and Theoretical Physics of al-Farabi Kazakh National University, Almaty, Kazakhstan

^b Institute of Thermophysics of SB RAS, Novosibirsk, Russia

HIGHLIGHTS

- Plasma steam and air gasification of high ash bituminous coal is fulfilled.
- Availability of the high ash power coal use for high-calorific syngas production is shown.
- High integral indexes of the gasification processes were achieved.
- Syngas from the coal at steam gasification is higher quality.
- The numerical and experimental results comparison showed their satisfied agreement.

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ABSTRACT

Results of complex experimental and numerical investigation of coal plasma gasification in steam and air are presented. To analyse numerically the universal thermodynamic calculation code TERRA was used. The data base of it contains thermodynamic properties for 3500 individual components in temperature interval from 300 to 6000 K. Experiments were fulfilled at an original installation for coal plasma gasification. Nominal electric power of the plasma gasifier is 100 kW and sum consumption of the reagents is up to 20 kg/h. High integral indexes of the gasification processes were achieved. The numerical and experimental results comparison showed their satisfied agreement.

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1. Introduction

The increasing interest in environmental problems has recently led to the development of clean coal technologies, designed to enhance both the efficiency and environmental acceptability of coal extraction, preparation and use, in particular for power generation [1–3]. Among clean coal technologies, gasification [4], and especially plasma gasification [1,2] is particularly interesting since it allows both power generation (in Integrated Gasification Combined Cycles power plants, IGCC) and environmental friendly fuel production, with a particular reference to hydrogen [3,5].

This paper describes numerical and experimental investigation of coal air and water steam gasification in arc-plasma reactor. First air–coal and steam–coal mixture gasification was investigated numerically with the aid of a thermodynamic program TERRA

[6]. Then these mixtures were investigated experimentally and the numerical results were validated against operational data got in the experiments. Kazakhstan ‘Kuuchekinski’ bituminous coal 40% of ash content was used for the investigation. Special plasma reactor for coal gasification allows performing processes thermo impact on coal for getting syngas ($\text{CO} + \text{H}_2$) from organic part of a low-rank coal free from nitrogen and sulfur 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 2–10 kg/h and gas-oxidant flow 0.5–10 kg/h. High calorific clean syngas was produced from the coal.

2. Numerical simulation

Software package TERRA [6] was used for thermodynamic analysis of the coal plasma gasification process. It was created for high-temperature processes computations and in contrast to traditional thermochemical methods of equilibrium computation

* Corresponding author.

E-mail address: ust@physics.kz (A.B. Ustimenko).

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 thermochemical properties for more than 3500 chemical agents over a temperature range of 300–6000 K.

The process of Kuuchekinski (Kazakhstan) high-ash bituminous coal (Table 1) gasification was calculated in temperature interval from 400 to 4000 K at pressure 0.1 MPa. The temperature is suggested to be kept at the expense of external heat source, which is an arc in a plasma-chemical reactor. Note despite of the fact that plasma reactor is not isolated system and there is an exchange of energy and substance with external medium, thermodynamic modeling of coal gasification inside the plasma-chemical reactors is possible. First, at preparation of heat and material balances of the plasma gasifier actual heat losses are taken into account, and in this case mean temperature in the plasma reactor corresponds to the temperature of thermodynamically isolated system. Second, residence time in plasma reactor (0.5–0.7 s) is enough for thermodynamic equilibration in the system at high temperature of the process [6]. Third, the plasma-chemical reactor is flow-type and quasi-stationary process of gasification is provided.

The first variant of calculations was performed for the system of 100 kg of coal +127.5 kg of air and the second one –100 kg of coal +62.75 kg of water steam.

The aim was to determine integral indexes of the coal gasification, which are carbon gasification degree, specific power consumptions, equilibrium compound of the products of coal gasification.

Figs. 1 and 2 present temperature dependence of the products composition in a temperature interval of 400–4000 K. The gas phase mainly consists of synthesis gas ($\text{CO} + \text{H}_2$) thermodynamically steady to co-products of coal gasification process (Fig. 1a). Its concentration reaches the maximum 54.79% at $T = 1800$ K. Concentration of oxidants (H_2O and CO_2) decreases to zero at temperature increase to 1400 K. Nitrogenated substances are presented mainly in form of molecular nitrogen (N_2). Nitrogen concentration decreases with temperature increase because of syngas appearance in gas phase and increase its concentration as well as due to the coal mineral mass destruction and mineral components from coal appearance in gas phase at temperatures over 1600 K (Fig. 1b). Carbon monoxide (CO) concentration reaches the maximal value (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) is appeared. Concentration of H 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 gas phase (Fig. 1b) with the process temperature increase. They are mainly aluminum (Al) and silicon (Si). In gas phase they appear at the

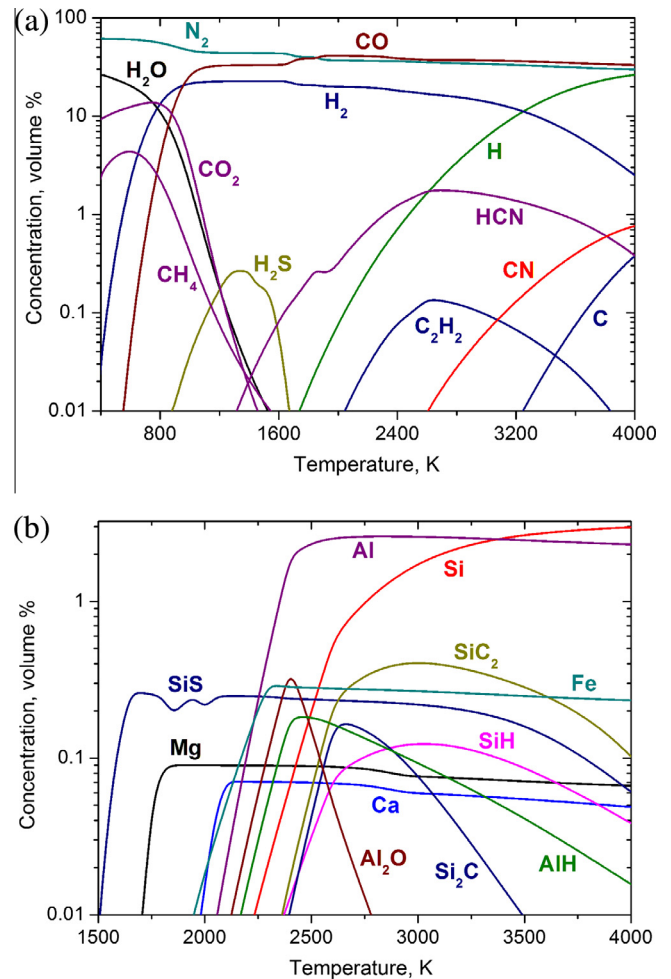


Fig. 1. Composition of organic (a) and mineral (b) components in gas phase versus temperature (air gasification).

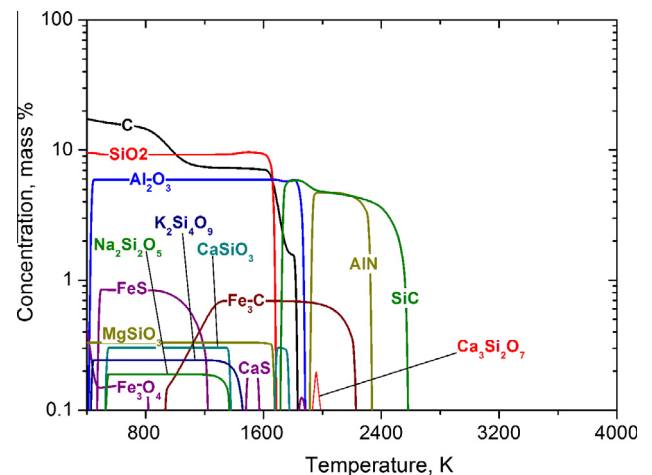


Fig. 2. Composition of condensed phase components versus temperature (air gasification).

Table 1

The bituminous coal proximate and ultimate analyses, weight%.

Proximate analysis		Ultimate analysis			
Moisture (total)	5.8	Hydrogen	3.05	SiO_2	23.09
Volatile matter	26.0	Carbon	48.86	Al_2O_3	13.8
Fixed carbon (by difference)	28.2	Sulfur	0.73	Fe_2O_3	2.15
Ash	40	Nitrogen	0.8	CaO	0.34
Total	100.0	Oxygen	6.56	MgO	0.31
Higher heating value (kJ/kg)	16632.0	Ash	40.0	K_2O	0.16
		Total	100.0	Na_2O	0.15

temperature 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%. Due to ballast nitrogen concentrations of highly volatile potassium (K) and sodium (Na) are out of the scale.

Carbon concentration in condensed phase (Fig. 2) decreases due to gasification in temperature interval from 800 to 1200 K. In the interval 1200–1600 K its concentration is practically steady because of absence of free oxygen. 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). With the temperature (1800–2600 K) all mineral components evolve into gas phase as Al, Si, SiS, Fe, Al_2O_3 , SiC_2 , et al. (Fig. 1b).

Gas phase of the products of steam gasification of the coal (Fig. 3) 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%. 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 components of mineral mass of the coal appearance in gas phase. They begin to convert from condensed phase to gas at temperature over 1600 K (Fig. 3b). At temperature 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 increase the last are decomposed intensively on to corresponding elements. As to the condensed phase (Fig. 4), with the 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.

The degree of coal carbon gasification (X_C) is determined from the carbon content of the solid gasification products calculated in accordance with the Eq. (1).

$$X_C = (C_{\text{bas}} - C_{\text{fin}}) / C_{\text{bas}} \cdot 100\% \quad (1)$$

where C_{bas} is the initial amount of carbon in the coal, and C_{fin} is the final amount of carbon in the solid residue. When determining the amount of carbon in the solid residue together with a fixed carbon, carbon of ferric and silicon carbides is taken into account.

Carbon gasification degree (Fig. 5a) increases with the temperature and reaches 100% at 2650 K for air gasification of the coal and 1300 K for steam one. At air gasification in the temperature interval from 1200 to 1600 K carbon gasification degree is practically permanent because of free oxygen absence and ferric and silicon carbides formation. In the temperature interval from 1600 K to 2000 K gasification degree increases intensively due to decomposition of ferric carbide and oxidation of carbon in the reactions of reduction oxygen-containing compounds like Al_2O_3 , CaSiO_3 , MgSiO_3 , et al. (Fig. 2). At temperatures above 2000 K gradual increase of carbon gasification degree up to 100% due to sublimation of silicon carbide is observed. At steam gasification of the coal carbon gasification degree reaches 100% by 1300 K. In the contrast to air gasification of the coal there is no “plateau” in temperature dependence of gasification degree. It is explained by different levels of temperature necessary for complete gasification of carbon in water steam ($T \sim 1200$ K) and formation of silicon, ferric and aluminum carbides in condensed phase ($T = 1200\text{--}2400$ K) (Fig. 2). It means when the temperature of carbides formation in condensed phase is reached carbon has completely transferred into the gas phase as CO.

Specific power consumptions (Fig. 5b), having minor fluctuations in temperature range from 1600 to 1800 K in which reducing endothermic reactions with carbon run, monotonously increase with the temperature. Specific power consumptions for steam gasification related to 1 kg of working medium (curve 1) are 1.5–2 times higher than specific power consumption for air gasification of the coal (curve 4). This effect is interrelated mainly with large endothermic effect of the reaction $\text{H}_2\text{O} + \text{C} = \text{H}_2 + \text{CO}$. For the curves 2 and 5 also exceeding of specific power consumptions for steam gasification is observed, but it is less in value essentially. Comparing specific power consumptions for the coal air and steam gasification related to 1 kg of syngas (curves 3 and 6) we can see

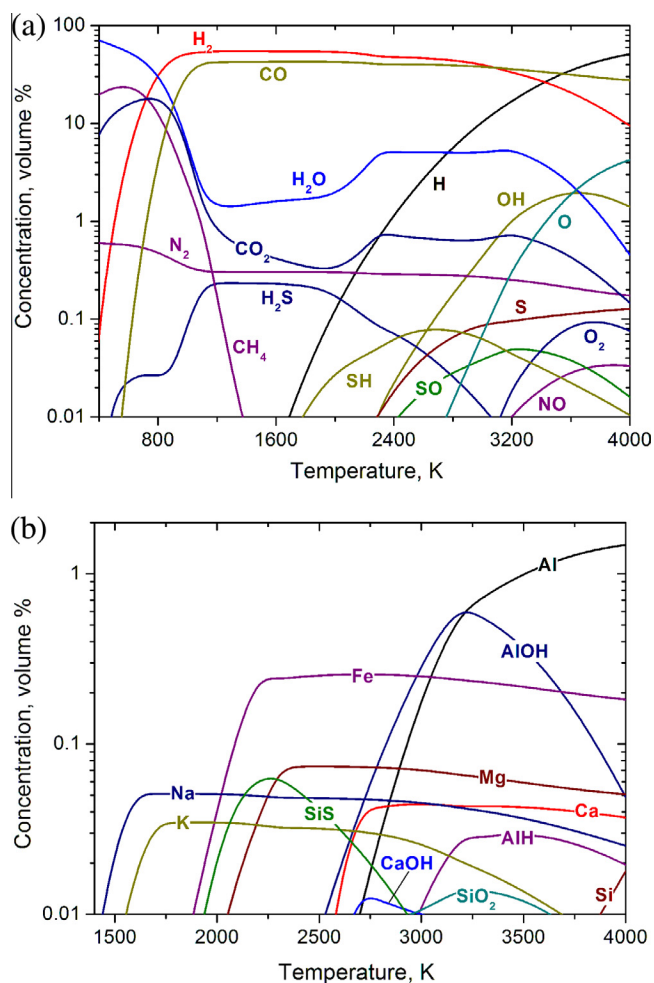


Fig. 3. Composition of organic (a) and mineral (b) components in gas phase versus temperature (steam gasification).

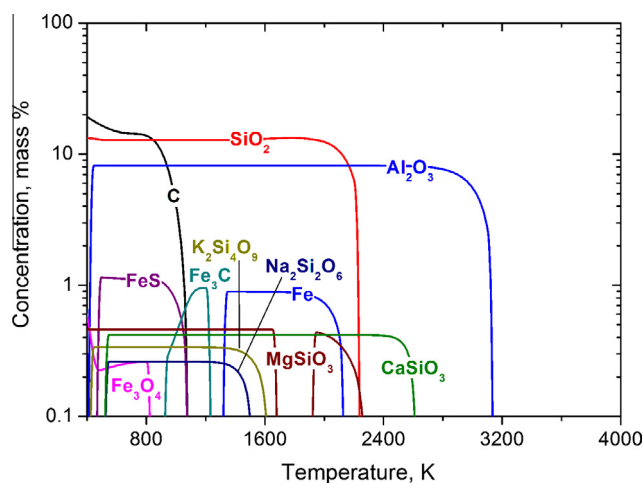


Fig. 4. Composition of condensed phase components versus temperature (steam gasification).

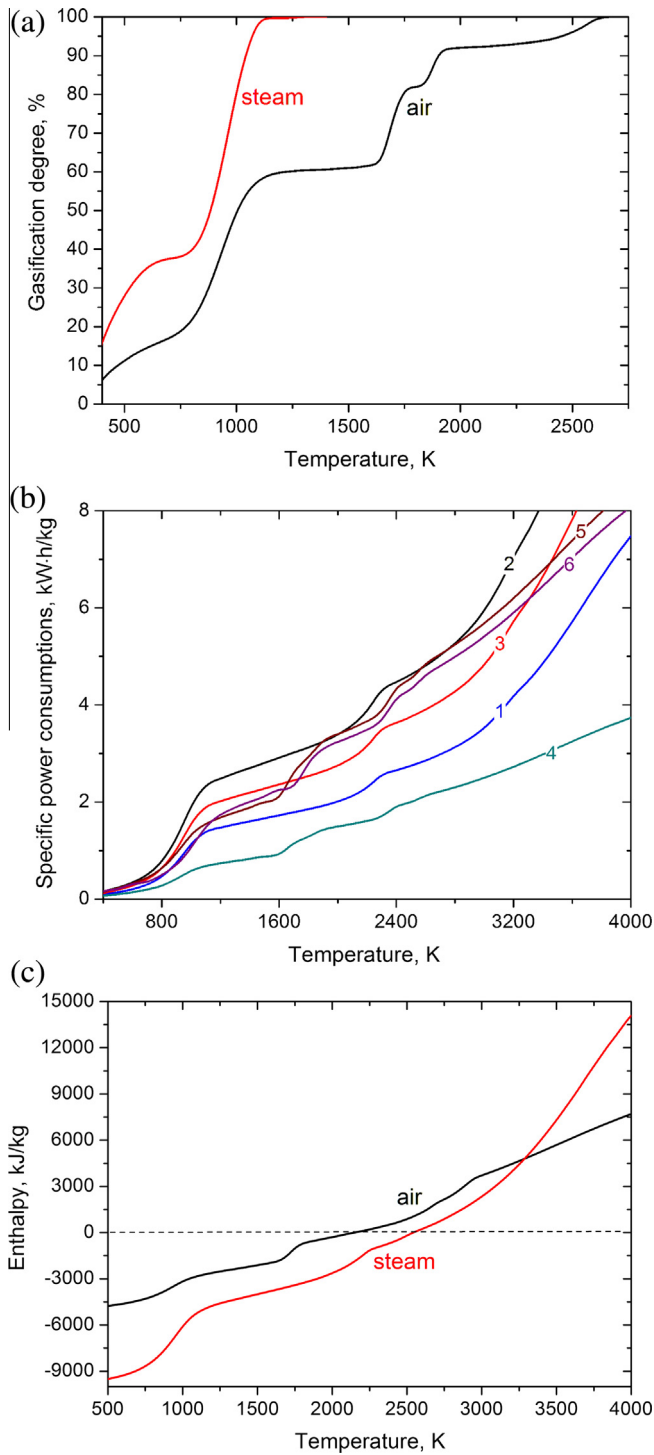


Fig. 5. Carbon gasification degree (a), specific power consumptions (SPC) for the process of plasma gasification (b) and full enthalpy (c) versus temperature: 1, 2, 3 is steam gasification of the coal; 4, 5, 6 is air gasification of the coal; 1, 4 is SPC related to 1 kg of working medium; 2, 5 is SPC related to 1 kg of coal; 3, 6 is SPC related to 1 kg of syngas.

that in the temperature range from 1700 to 3200 K specific power consumptions for steam gasification of the coal are less than for air gasification. It is significant, at the temperatures of reaching 100% the coal gasification degree, which is 1200 and 2000 K for steam and air gasification correspondingly, specific power consumptions for air gasification (3.2 kW h/kg) 1.6 times higher one for steam gasification (2 kW h/kg). At that syngas concentration at the coal steam gasification is higher essentially (see Figs. 1 and 5) and

reaches 99% against 55% at air gasification. At the same time syngas at steam gasification of the coal is of higher calorificity. E.g. hydrogen concentration at steam gasification reaches 59% against 20% at air gasification.

Fig. 5(c) demonstrates dependence of total enthalpy of the reacting system on temperature. The total enthalpy was calculated by the following formula:

$$H_T^0 = \Delta H_{T_0}^0 + \int_{T_0}^T C_p(T) dT,$$

where $\Delta H_{T_0}^0$ and $\int_{T_0}^T C_p(T) dT$ are standard enthalpy of formation of matter at temperature T_0 , and excessive enthalpy of the reacting system correspondingly. The figure shows that the total enthalpy of the reacting system, both in the air and in the steam gasification of coal increases with temperature. Note that in reacting systems standard enthalpy of formation is negative but excessive enthalpy of the reacting system is positive. At air gasification of coal total enthalpy is negative till $T = 2150$ K, and in steam gasification till $T = 2525$ K. This is due to greater in absolute value of the standard heat of formation of the steam–coal mixture, compared with that of the air–coal mixture. For temperatures below 3275 K the total enthalpy of the air–coal reacting system exceeds that of steam–coal reacting system. At higher temperatures there is an inversion of curves and enthalpy of steam–coal reacting system already exceeds that of air–coal reacting system. This is due to excess the endothermic effect over the exothermic effect in the reactions of coal gasification.

3. Experiment

3.1. Experimental installation and methods of investigation

The experimental installation for coal plasma gasification (Fig. 6) is cylindrical plasma reactor with systems for power, water, steam, gas and coal dust supply. The principal components are a: plasma reactor, 1 (Fig. 7); chamber for gas and slag separation, 3; slag catcher, 4; chambers of syngas sampling and cooling, 6; and pulverised fuel feeding system, 9, 10.

Power of the plasma reactor is varied from 30 to 100 kW. In the cover of the reactor graphite rod electrode and pipes for coal dust and oxidant feeding are mounted. Chamber of the reactor is lined with graphite of 0.02 m thick (Fig. 7). Inner diameter of the chamber is 0.15 m, and height is 0.3 m. It is bounded at its bottom side by a graphite orifice. Arc is started between rod 1 (0.04 m of diameter) and ring 5 (0.15 m of diameter) graphite electrodes. The distance between them is 0.055 m. The arc rotates under the influence of the magnetic field from electromagnetic coil 4 on the distance from the reactor cover 0.15 m. Erosive wear of supplied rod graphite electrode and a massive removable ring graphite electrode was 0.1 kg/h for each. This value corresponds to the 50-h resource of the ring electrode in the laboratory plasma reactor.

To control the installation operating regimes and to determine the process integral indexes, such as mass-averaged temperature, specific power consumptions, carbon gasification degree and syngas concentration, measurements of material and heat balance of the experimental plant is necessary. Detailed description of the experiments procedure was done earlier [5–8].

The equations of material and heat balance of the experimental set-up take the following form:

$$G_2 + G_3 + G_4 + G_5 = G_6 + G_1 + G_7, \quad \text{kg/h} \quad (2)$$

$$W_0 + W_1 = W_2 + W_3 + W_4 + W_5 + W_6, \quad \text{kW} \quad (3)$$

where G_2, G_3, G_4 , and G_5 are the flow rates of coal, steam, carrier gas (air, nitrogen, CO_2) for coal pulverisation, and electrode graphite,

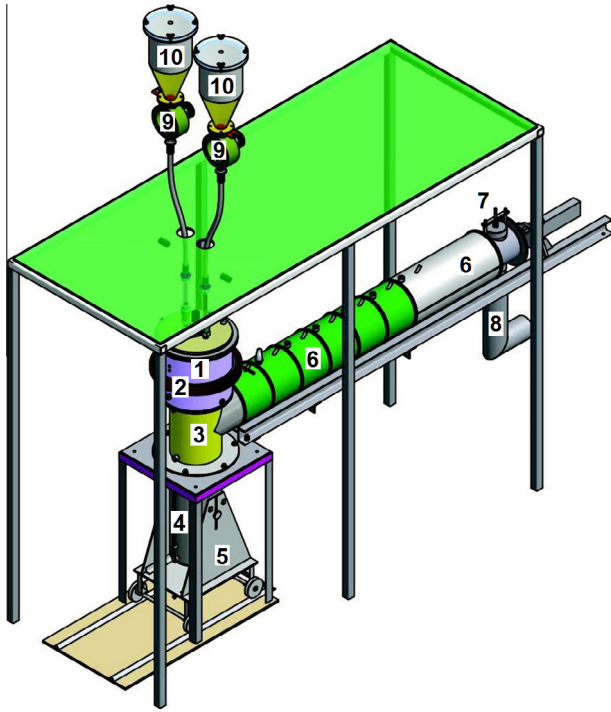


Fig. 6. Layout of plasma installation for gasification of coal: 1 – plasma reactor, 2 – electromagnetic coil, 3 – chamber for gas and slag separation; 4 – slag catcher; 5 – stand for slag catcher; 6 – chambers of syngas sampling and cooling; 7 – safety valve; 8 – chamber of syngas removal; 9 – pulverized fuel feeders; 10 – solid fuel dust hopper.

respectively; G_6 , G_1 , G_7 are the mass rates of slag (solid residue), effluent gases, and pulverised coal (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 synthesis-gas cooling chamber; W_5 from the slag catcher; W_6 from the heat carry-over in the effluent gas stream.

The arc heat output is determined from the electric power supplied. The heat input in steam is calculated as:

$$W_1 = G_3 \cdot H_1, \quad \text{kW}$$

where $H_1 = H^\circ_{405 \text{ K}} + \Delta H^\circ_{\text{steam}} = 0.05 + 0.63 = 0.68 \text{ kW h/kg}$ of steam. $\Delta H^\circ_{\text{steam}}$ is the heat of vaporisation.

The heat loss in 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 [6] 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:

$$W_6 = H_6 \cdot G_1, \quad \text{kW}$$

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 Eq. (3) are measured during the experiment.

The degree of coal carbon gasification is determined from the carbon content of the solid gasification products obtained from the chemical analysis of the samples and calculated in accordance with the Eq. (1).

A thermal efficiency for the plasma reactor (ξ) is defined as: $\xi = (W_0 - W_2)/W_0 \cdot 100\%$

The results of measurements showed that subsequent to arc ignition and the supplying of the steam–coal mixture to the reactor, a thermal steady state is established in about 0.4 h. The temperature of the reactor walls reach 1800–2100 K, while the temperature of the gaseous gasification products at the reactor outlet attain 1300–1600 K. Gas and solid residue sampling commences when the steady state is reached.

The specific power consumption, $Q_{SP} = f(T)$ is: $Q_{SP} = (W_0 + W_1)/(G_2 + G_3 + G_4 + G_5)$, kW h/kg.

Using this value, the mass-averaged temperature of the reactor contents, T_{AV} , is determined using the TERRA code. Reference to preceding equation shows that, when determining Q_{SP} , only the effective power consumption of the plasma reactor is taken into account.

To calculate the specific power consumption for the process, reduced to one kilogram of gaseous products of the gasification process (synthesis gas) output, the following formula is used:

$$Q_{SP}^{\text{SYNG}} = (W_0 + W_1 - W_2)/(G_1 - G_4), \quad \text{kW h/kg} \quad (4)$$

To measure temperature of gas phase chromel–alumel and platinum–platinum–rhodium thermocouples brand of “Cole Parmer Instrument” are used. They are installed in all sections of outgoing gas. The thermocouples are closed in special cover for damage protection and their work parts are located in gas flow. Compensation cables from thermocouples are commutated to displaying digital indicator, the last is connected with computer’s COM port. Application installed onto computer inquires every channel of thermocouples and performs the results in the form convenient for use. The gas temperature metering error is within ± 0.01 °C.

Pyrometers are used for high temperatures metering inside the reactor. Pyrometer Iacon Ultrimax Plus UX10P is used for temperatures from 600 to 3000 °C. Metering error depends on

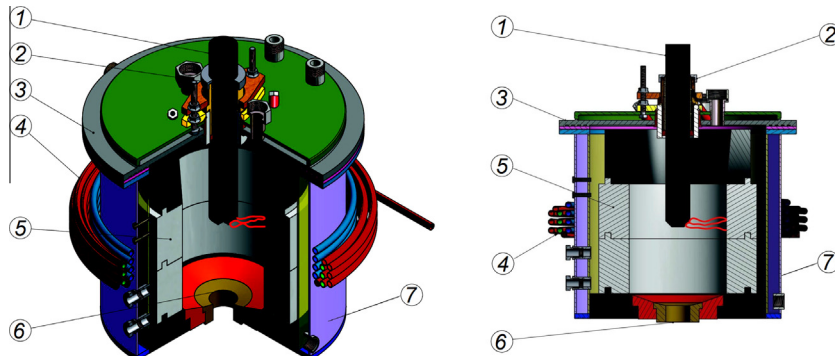


Fig. 7. Layout of DC plasma reactor: 1 – rod graphitic cathode; 2 – cathode insulator; 3 – water cooled cover; 4 – electromagnetic coil; 5 – ring graphitic anode; 6 – graphite orifice, 7 – water cooled cylindrical wall.

temperature range and it is $\pm 0.5\%$ of measured value for temperature range up to 1500°C , $\pm 1\%$ for the range $1500\text{--}2000^\circ\text{C}$ and it increases to $\pm 2\%$ for the temperature over 2000°C . Temperature resolution is not worse than 1°C . The device is equipped with COM port for connection to computer, and the temperature can be controlled by RS-232C protocol during experiment, and performs results on-line regime. Sampling interval of the device is 0.5 s . Infrared thermometer MIKRON M668 is used for temperature metering in cross section of the reactor. The device is equipped with lens system to changed focal distance to the target and flexible optical cable. This setting-up with cooling system allows mounting lens system near high temperature object. Range of the metered temperatures is from 1600°C to 4000°C . The temperature is controlled on the displaying indicator or with assistance of special transformer as the device is equipped with current terminal. The temperature metering error is $\pm 50^\circ\text{C}$.

Calculation of mass-averaged temperature of exothermic process air gasification was conducted in the following way. Using the software package for thermal equilibrium calculation TERRA the temperature dependence of specific heat capacity C_p for air and coal was found. Then the dependence was approximated polynomially, and the obtained analytical expression was numerically integrated by the temperature; the average heat capacity of air and coal was determined for the whole temperature range. Polynomial approximant for air is as follows:

$$C_{p(\text{air})} = (2.36 \cdot 10^{-10})T^3 - (8.36 \cdot 10^{-7})T^2 + 0.001T + 0.714, \quad \text{kJ/kg K},$$

where T is temperature, K.

Polynomial approximant for 'Kuuchekinski' coal is as follows:

$$C_{p(\text{coal})} = (7.22 \cdot 10^{-7})T^3 - (3.28 \cdot 10^{-5})T^2 + 0.043T - 11.24, \quad \text{kJ/kg K}.$$

The obtained value of heat capacity was inserted into equation for thermal flow used for further determining of mass-averaged temperature.

$$Q = (C_p M_{\text{air}} + C_{p(\text{coal})} M_{\text{coal}}) \Delta T, \quad \text{kJ},$$

$$M_{\text{air}} = G_{\text{air}} \cdot 3600, \quad \text{kg}; \quad M_{\text{coal}} = G_{\text{coal}} \cdot 3600, \quad \text{kg},$$

where M_{air} , M_{coal} , G_{air} , G_{coal} is mass (kg) and mass flow (kg/h) of air and coal, respectively.

$$\Delta T = T_{\text{fin}} - T_{\text{init}}, \quad \text{K},$$

where T_{fin} corresponds with mass-averaged temperature of the process.

To calculate mass-averaged temperature T_{av} of endothermic process coal steam gasification the software package TERRA was used too. First temperature dependence of specific power consumptions for the process ($Q_{\text{sp}} = f(T_{\text{av}})$) was calculated. Experimentally found values of Q_{sp} were plotted on to graphical dependence $Q_{\text{sp}} = f(T_{\text{av}})$ (Fig. 5b) and corresponding values of mass-averaged temperatures of the process were determined.

To reveal granulometric composition of the coal dust sieve analysis was done. Shaker "Tyler" RX-812 and set of calibrated sieves with meshes size of $43\text{--}1000\text{ }\mu\text{m}$ was used.

Chromatographs of two types implemented gas analysis. The first one is SRI 8610C and the second one is LCM 8MD. Carrier gas is helium or argon, detectors are thermal conductivity sensors. Analysis of light gases H_2 , CO , O_2 , N_2 , CH_4 was provided in columns filled with molecular sieve CaX and analysis of CO_2 in silica gel column. Method of absolute calibration was used for experimental data handling. A sampling was implemented in several points of

installation including the plasma reactor. Composition of the solid residue was investigated by chemical and X-ray phase analysis.

3.2. Experimental results and comparison with numerical data

Arc is initiated by vaporising a wire brought into contact with the rod and ring electrodes. The flow of steam or air and pulverised coal is then initiated. The steam(air)/pulverised coal 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 coal gasification process occurs. The solid residue so produced descends through the orifice plate into the slag catcher (Figs. 6 and 7). The gaseous products exit the gas and slag separation chamber and flow into the cooling chambers. Then gaseous products are exhausted to ventilation.

Duration of the experiments varied from 0.5 to 1 h . That is quite enough for all meters fulfilment and testing of the material and heat balance of the coal plasma gasification. The duct of 'Kuuchekinski' bituminous coal (Table 1) was used in the experiments.

The coal dust for the experiments was taken from Almaty Thermal Power Plant-2. The sieve analysis of it (Fig. 8) revealed that mean size of the coal dust particles was $75\text{ }\mu\text{m}$. It corresponds to the sieve residue $R_{90} = 25\%$ characterizing milling finesse.

As a result of the coal air and steam plasma gasification concentrations of gas species, carbon gasification degree X_c and mass-averaged temperatures T_{av} were revealed (Table 2).

As can be seen from the table, in the experiments 1 to 6 at steam gasification of the coal oxygen concentration on the outlet of the installation is not higher than 4% . This is evidence of right coal-oxygen ration. High concentration of nitrogen in the experiments 1 and 2 (37.4% and 45.6%) indicates about uncontrolled air inflow. Air inflows were determined with help of code TERRA using maximum concentrations of nitrogen in the gasification products, allowing closure of material balance Eq. (2). During the experiments 3–6 these inflows were practically eliminated, that allowed decreasing concentration of ballast gas (nitrogen) dramatically. Nevertheless, the results of gas analysis of the gasification products revealed the presence of nitrogen with concentration greater than that of nitrogen of fuel. This fact was taken into account in the calculation of steam gasification of coal (Table 2). Sum concentration of syngas was quite high and reached at steam gasification $94.2\text{--}96.4\%$. At that determined by residual content of carbon in gathered solid residue carbon gasification degree reached $89.7\text{--}93.7\%$. Mass-averaged temperature varied from 3500 to 3850 K .

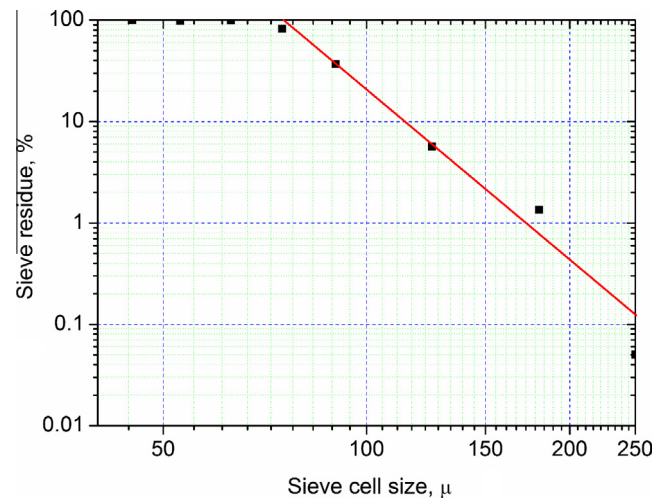


Fig. 8. Dispersed composition of the coal dust.

Table 2

Results of the experiments and comparison with numerical data.

No	T_{av} (K)	Consumption (kg/h)			Syngas compound, volume% (experiment/computation)				X_c (%)
		Coal	Steam	Air	H ₂	CO	N ₂	O ₂	
1	3550	4.7	1.6	10.8	32.6	26.0	37.4	4.0	90.2
					26.2	23.5	37.4	4.2	100
2	3350	4.7	1.4	14.1	26.8	24.6	45.6	3.0	91.3
					17.0	21.1	45.6	3.9	100
3	3350	4.7	1.4	0.4	48.9	45.8	4.3	1.0	92.8
					46.5	40.1	2.4	0.0	100
4	3500	4.0	1.92	0.4	55.1	41.3	2.7	0.9	93.7
					53.9	37.9	2.4	0.0	100
5	3550	4.0	2.4	0.3	60.8	34.9	4.0	0.3	89.7
					58.9	35.4	2.0	0.2	100
6	3850	4.0	2.5	0.5	58.7	35.5	5.4	0.4	93.7
					61.2	31.1	2.8	1.2	100
7	2755	4.0	0	4.8	16.8	33.0	48.6	1.6	92.8
					17.0	34.6	38.2	0.0	100
8	2755	4.1	0	4.4	17.6	32.4	47.1	2.9	91.2
					17.9	34.7	36.0	0.0	100
9	2850	4.0	0	5.1	17.7	38.1	43.7	0.5	95.8
					16.6	35.9	37.5	0.0	100
10	2690	4.1	0	4.9	16.8	34.3	48.8	0.1	90.9
					17.2	34.1	39.1	0.0	100
11	2730	4.1	0	4.8	16.8	33.4	49.4	0.4	95.1
					17.2	34.4	38.1	0.0	100

In the experiments 7–11 at air gasification of the coal oxygen concentration in exhausted gas was not higher than 2.9%. Total yield of syngas in the experiments was 49.8–55.8%. At that carbon gasification degree varied from 90.9% to 95.8%. Mass-averaged temperature varied from 2690 to 2850 K.

Thus in investigated processes of steam and air gasification high carbon gasification degree was achieved which is comparable for the both processes. At that syngas concentration for the coal steam gasification 1.7–1.9 times higher than one for air gasification of the coal. To achieve a high carbon gasification degree at steam gasification of coal it is required higher temperature exceeding 1.2–1.5 times of that at air gasification. The last mentioned causes a corresponding increase in specific power consumption for coal gasification process (Fig. 5b).

Comparison between the numerical (thermodynamic computation) and experimental results is shown in Table 2.

Note that mass-averaged temperature of the process is determined on the base of equations for mass (2) and heat (3) balance of the reactor with account of energy exchange with outside medium. As a matter of fact, determined in accordance with this procedure mass-averaged temperature of the process characterizes equilibrium temperature of isolated thermodynamic system.

As can be seen from the table the results of the calculations and experiments are in a satisfactory agreement. The maximal discrepancy of syngas concentrations does not exceed 10% for the coal steam gasification (excluding mode of coal gasification with uncontrolled air inflow) and 6% for air one. As regards values of carbon gasification degree, their discrepancy is within the limits of 12% for the both processes.

The observed discrepancies between calculated and experimental concentrations of syngas and carbon gasification degree can be explained by real process characteristics divergence from their equilibrium values calculated by the code TERRA. In particular the reason of these discrepancies can be the limited duration of reagents stay in plasma reactor at steam and air gasification of the high ash 'Kuuchekinski' coal. In accordance with estimation [8] the duration is less than 0.5 s.

Let us consider energy efficiency of plasma gasification of coal. Criterion of energy efficiency of the solid-fuel gasification process is a relative thermal power of produced syngas [9]. In accordance

with the following formula, relative thermal power of syngas (γ) was defined as a ratio of syngas specific-heat value ($(Q_{SYNGAS}, [kJ kg^{-1}])$) multiplied by the mass flow ($G_{SYNGAS}, [kg s^{-1}]$) to total consumed power ($P_{arc} + Q_{H_2O} \cdot G_{H_2O}, [kW]$), where P_{arc} , Q_{H_2O} , G_{H_2O} are electric power of arc, specific power consumptions for steam production and steam mass flow, correspondingly.

$$\gamma = \frac{Q_{SYNGAS} \cdot G_{SYNGAS}}{P_{arc} + Q_{H_2O} \cdot G_{H_2O}} [kW/kW].$$

Energy efficiency of air gasification of coal was estimated equal to 1.75 kW/kW and steam gasification – 2.3 kW/kW.

Estimation of economic efficiency for producing of syngas by plasma-steam gasification of low grade coal in the laboratory plasma reactor revealed that the cost of syngas was \$120 per ton, which is 40% less than that in conventional methods of syngas production. Thus, use of plasma gasification of high-ash coal for the production syngas will allow producing methanol by 47.3% less, while hydrogen – by 42.5% as compared to conventional technologies of production.

4. Conclusions

1. The complex of numerical and experimental investigations of plasma steam and air gasification of 'Kuuchekinski' bituminous coal showed availability of the high ash steam coal use not only for direct incineration in a furnace of a boiler but also for high-calorific synthesis gas production.
2. Syngas produced at the coal air gasification can be used as environmental friendly fuel, but syngas from the coal at steam gasification is a high quality reducing agent for metallurgy and also it is a valuable raw material for using in chemical industry to synthesise methanol.
3. In investigated processes of air and steam gasification of the coal high carbon gasification degree is achieved (up to 95%). At that syngas yield at the coal steam gasification (up to 96.4%) is noticeably higher one at the coal air gasification (up to 55.8%).
4. Syngas from the coal at steam gasification is higher quality. In particular hydrogen concentration in syngas at the coal steam gasification can reach 60% against 20% at air gasification of

the coal. It is quite perspective for production of hydrogen through water steam decomposition on coal in the process of its plasma gasification.

5. Comparison of calculated and experimental data on plasma gasification of high-ash coal in air and steam mediums showed good enough agreement. The maximal discrepancy of syngas concentrations does not exceed 10%, and discrepancy of carbon gasification degree is within the limits of 12%.

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