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PLASMA GASIFICATION OF SOLID FUELS

This article presents the results of thermodynamic analysis and experiments on plasma gasification of solid fuels from the example of Kuuchekinsky coal (KC). Thermodynamic calculations of plasma gasification showed that synthesis gas used in heat and power engineering, metallurgy and the chemical industry can be produced from solid fuels. Gasification (KC) allows to obtain synthesis gas with a maximum yield of 98.3% (CO – 43.5%, H2 – 54.8%).

To perform thermodynamic analysis, the TERRA software package is used, which is designed for numerical calculations of high-temperature processes and has an extensive database of its own thermodynamic properties of 3000 individual substances. The program allows you to determine the equilibrium composition of the thermodynamic system (coal + oxidizer), consisting of 20 chemical elements. The calculation is carried out automatically within the data bank created during the program. The thermodynamic data bank contains properties of more than 3000 individual substances formed by 65 elements in the temperature range 300-6000 K.

Experimental researches of plasma gasification of coal in various gasification agents were carried out at the facility, which is a cylindrical plasma reactor with systems of electricity, water, steam, gas and fuel supply.

Key words: plasma torch, plasma reactor, coal, gasification.

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Қатты отынның плазмалық газификациясы

Бұл мақалада термодинамикалық талдау және Кучеккин көмірінің мысалында қатты отынды плазмалық газдандыру бойынша эксперименттердің нәтижелері келтірілген. Плазмадағы газдандырудың термодинамикалық есептері жылу және энергетикада, металлургияда және химия өнеркәсібінде қолданылатын синтез газы қатты отындардан алынуы мүмкін екенін көрсетті. Кучечкин көмірін газдандыру синтез газын 98,3% (CO – 43,5%, H2 – 54,8%) ең жоғары өнімділікпен алуға мүмкіндік береді.

Термодинамикалық талдауды орындау үшін жоғары температуралық процестерді сандық есептерге және 3000 жеке заттардың термодинамикалық қасиеттерінің кең дерекқорына ие TERRA бағдарламалық пакеті қолданылады. Бағдарлама 20 химиялық элементтен тұратын термодинамикалық жүйенің (көмір + тотықтырғыш) тепе-теңдік құрамын анықтауға мүмкіндік береді. Есептеу бағдарлама барысында жасалған деректер банкі ішінде автоматты түрде жүзеге асырылады. Термодинамикалық деректер банкі 300-6000 K температуралық диапазонында 65 элементтен құралған 3000-нан астам жеке заттардың қасиеттерін қамтиды.

Түйін сөздер: плазмалық алау, плазмалық реактор, көмір, газдандыру.

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Плазменная газификация твердых топлив

В этой статье представлены результаты термодинамического анализа и экспериментов по плазменной газификации твердых топлив на примере Куучекинского каменного угля (ККУ). Термодинамические расчеты плазменной газификации показали, что синтез-газ, используемый в теплоэнергетике, металлургии и химической промышленности, может производиться из твердых топлив. Газификация (ККУ) позволяет получать синтез-газ с максимальным выходом 98.3% (CO – 43.5%, H2 – 54.8%).

Для выполнения термодинамического анализа используется программный комплекс TERRA, предназначенный для численных расчетов высокотемпературных процессов и обладающий обширной собственной базой данных термодинамических свойств 3000 индивидуальных веществ. Программа позволяет определить равновесный состав термодинамической системы (уголь + окислитель), состоящей из 20 химических элементов. Расчет осуществляется автоматически в пределах созданного при программе банка данных. В банке термодинамических данных записаны свойства более 3000 индивидуальных веществ, образованных 65 элементами, в интервале температур 300-6000 K.

Ключевые слова: плазмотрон, плазменный реактор, уголь, газификация.

Introduction

Since coal is one of the main sources of energy of the 21st century, much attention is paid to the problem of its efficient and environmentally friendly combustion throughout the world. Compared to other fossil fuels, coal reserves are approximately four times the oil reserves (estimated at 41 years) or gas reserves (at 67 years) [1].

The global energy industry at present and for the foreseeable future is focused on the use of fossil fuels, mainly low-grade coals. It should be noted that the deterioration of the quality of power coals is observed everywhere, and not only in the UIS countries, but also in developed European countries. Today in the world thermal power plants produce more than 40% of electrical and thermal energy. Despite the fact that in the whole history there have been ups and downs in the activity of using coal, it still remains one of the most important fuels for energy generation, especially electric. According to the statistics of 2011 [2], coal provides about 24% of thermal energy and produces about 40.6% of electricity in the world. At the same time, its use is expected to increase in the near future.

Direct combustion of low-grade coals with high ash content (40-50%), humidity (30-40%), sulfur content (1-3%) and low volatile yield (5-15%) in existing furnaces is associated with considerable difficulties from – due to deterioration of ignition and burnout of fuel, increase of mechanical burn and harmful dust and gas emissions (greenhouse gases, ash, nitrogen oxides and sulfur). Suffice it to say that the problem of greenhouse gas emissions (carbon dioxide, methane, etc.) and the resulting general warming has now grown into a human problem related to global climate change on earth, flooding of vast land areas, desertification, etc.

Coal is a universal fuel because it can be burned, hydrolyzed and liquefied, gasified, or even used as a raw material for the chemical industry [3]. Coal is a fuel suitable for mining, transportation, storage and use, including in the form of dust [4]. Its compactness and high energy density (about 30 MJ/kg) intensifies the burning process [5]. There are no leakage and spatter problems associated with other fossil fuels, while explosions and self-ignition are not as dangerous as fuel oil or gas [6]. The widespread availability and significant reserves of coal make its price stable and attractive [7].

The use of coal in the modern world is diverse. It is used to produce electrical energy (thermal coal), as a raw material for metallurgical (coking coal) and chemical industry, to obtain rare-earth elements, for the production of graphite.

The projected resources of coal on Earth are currently more than 14.8 trillion tons, and world industrial reserves of coal – more than 1 trillion. t, which significantly exceeds the reserves and resources of all other energy [8]. The global coal market is more competitive than oil and gas, since coal deposits exist on all continents, almost in all countries, and mining is carried out almost in all regions of the world.

The overwhelming number of long-term forecasts of the global fuel energy balance confirm that coal will remain the most significant of the available non-renewable energy sources until 2050. At the current level of consumption of these stocks will be enough for 250 years. For comparison, natural gas will be enough for 65 years and oil for 45 years. World coal consumption increases by about 2% per year and at the same time coal prices, unlike oil and gas, are highly stable.

Existing technologies of combustion and thermal processing of solid fuels and their mixtures do not fully meet modern requirements for improving the efficiency of fuel use and ensuring the environmental and economic indicators of energy facilities. Combustion of non-project low-grade coal in pulverized coal boilers presents significant difficulties, because poor fuel quality negatively affects the characteristics of the ignition process, stabilization of the flare combustion and the process of fuel combustion, and, in addition, significantly reduces the environmental and economic indicators of TPS due to the emission of harmful gases (NOx, SOx , CO) and fly ash [9].

The situation is exacerbated due to the fact that the reduction in the quality of power coals requires an increase in the consumption of fuel oil or natural gas in coal-fired TPS for kindling boilers, lighting the torch and stabilizing the output of liquid slag in furnaces with liquid slag removal [10,11]. For example, in countries such as Russia, Kazakhstan, and Ukraine, more than 15 million tons of fuel oil are spent annually on coal-fired power plants, which is economically inefficient.

Among the methods of coal processing, the processes of its full or partial gasification received considerable development. During coal gasification, thermochemical transformations can cover not only the organic, but also their mineral part, with the result that the target products are obtained from both organic and ash mass of coal [12]. The methods of partial gasification of low-grade fuels are based on the use of combustible gas obtained during gasification as a higher-reactive fuel than the original coal. In the case of complete gasification of coal in the air, a combustible gas (CO + H2 + CH4 + CO2 + N2) and an inert ash residue with a low carbon content are obtained. After separation of the solid residue, combustible gas can be burned in furnaces or used to illuminate a pulverized coal torch. When steam or steam-oxygen gasification of the coal receive synthesis gas (CO + H2) and inert ash residue. After separation of ash, synthesis gas is used as an environmentally friendly fuel and reducing gas in metallurgy and for chemical syntheses [13].

Thermodynamic calculations

The industry of Kazakhstan ranks eighth in the world and third after Russia and Ukraine among the UIS countries in terms of the amount of coal extracted. The balance of the energy resources of Kazakhstan is mainly represented by black coal and to a lesser extent brown. On the territory of Kazakhstan there are large basins (Ekibastuz, Karaganda, Turgai) and deposits (Borlinskoe, Shubarkolskoe, Kuuchekinskoe).

The work used Kuuchekinsky coal (KC) with the following thermal characteristics:

Kuuchekinsky coal – Karaganda region, Kazakhstan:

$$W^{w} = 7\ \%;\ A^{c} = 44\ \%;$$
$$V^{daf} = 21\ \%;$$
$$Q_l^w = 3960\ \text{kcal/kg}$$

The composition of this solid fuel is given in the table 1.

Table 1 – Composition of Kuuchekinsky coal (on dry weight), wt.%

C	O	H	N	S	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O+Na_2O
45,75	6,05	2,8	0,73	0,67	25,3	15,2	2,4	0,4	0,35	0,35

To perform thermodynamic analysis, the TERRA software package is used, which is designed for numerical calculations of high-temperature processes and has an extensive database of its own thermodynamic properties of 3000 individual substances. The program allows you to determine the equilibrium composition of the thermodynamic system (coal + oxidizer), consisting of 20 chemical elements. The calculation is carried out automatically within the data bank created during the program. The thermodynamic data bank contains properties of more than 3000 individual substances formed by

65 elements in the temperature range 300-6000 K [14].

The calculations were performed for the following model mixture: coal + water vapor. The calculations were performed in the temperature range of 500–4000 K at atmospheric pressure. The criteria for selecting a model mixture were: the achievement of the degree of complete carbon gasification, the maximum yield of synthesis gas.

From Figure 1 it can be seen that the gas phase of the plasma gasification products of the KC is mainly represented by synthesis gas, the concentration of which reaches at 1500 K 98.3%. Moreover, the total concentration of atomic and molecular hydrogen is higher than the concentration of carbon monoxide in the entire temperature range and varies in the range of 48 – 58%. With increasing temperature, the concentration of carbon monoxide decreases from 43.5% at 1500 K and to 30% at 4000 K. The mineral components of coal are completely transferred to the gas phase at temperatures above 3200K (Figure 2).

One of the criteria for selecting a model mixture was to achieve the degree of complete carbon gasification (Figure 2), which is an important characteristic of the process. The degree of carbon gasification of coal is calculated by the formula:

$$X_c = \frac{C_{start} - C_{finish}}{C_{start}} \cdot 100\% ,$$

where C_{start} and C_{finish} are initial and final concentrations of carbon in coal and solid residue, respectively.

Figure 3 shows the temperature dependence of the degree of gasification of carbon in the KC. It can be seen that the degree of gasification reaches 100% at a temperature of 1200 K.

The specific energy consumption (Fig. 4) was defined as the difference between the total enthalpy (the current process temperature) and the initial state of the system, reduced to 1 kg of the working substance (a mixture of KC and plasma-forming vapor). The specific energy consumption for the gasification process Q_{sp} increases with temperature throughout its range. For a temperature of T = 1500 K, at which the output of synthesis gas reaches its maximum (Fig. 1), the specific energy consumption for plasma gasification of the KC is 1.82 kWh/kg.

Experiment

Studies of plasma gasification of coal were carried out at an experimental facility (Figure 5), which is a cylindrical plasma reactor with systems of electro-steam-gas-dust supply. The installation includes the following main technological units: plasma reactor 1, slag collector 4, gas and slag separation chamber 3, synthesis gas oxidation and cooling chambers 6, coal dust preparation and supply systems 9 and 10, steam generation and supply systems or gas (not shown in the figure). The power of the plasma reactor is regulated from 30 to 100 kW [15].

The combined type plasma reactor is a cylindrical water-cooled body with a lid. A graphite electrode and nozzles for feeding coal dust and an oxidizer are installed in the lid. The chamber of the plasma reactor is lined inside with graphite (thickness 0.02 m). The inner diameter of this chamber is 0.15 m, height – 0.3 m. Outside the camera is covered by an electromagnetic coil 2, and below – by a graphite diaphragm. The plasma reactor 1 is supplied with current from a 200 kW power supply through an inductive air choke. The electric arc ignites between graphite rod (diameter 0.02 m) and ring (diameter 0.15 m) electrodes. The distance between the rod and ring electrodes is 0.035m. The arc is localized in the electric arc zone of the reactor (the distance from the reactor lid is 0.15 m), covered outside by the electromagnetic coil 2, which ensures the rotation of the arc in a magnetic field. Figure 6 shows a photograph of the plasma reactor during testing.

The coal dust supply system includes a coal dust bunker 10 connected to two dust feeders 9, of which coal dust is fed through quartz tubes with rotating springs to the plasma reactor 1.

Obtained in the process of plasma gasification of the solid residue is removed in the slag collector 4. It is a water-cooled cylinder, inside of which is a sampler. Its diameter is 0.22 m, height – 0.56 m. The slag collector is lined with graphite. The synthesis gas cooling chambers 6 are water-cooled stainless steel cylinders, also lined with graphite.

The steam generator and the steam supply system are equipped with a superheater and insulated piping connected to the reactor. Heaters are installed on the water supply pipeline, additional sections of the superheater and control of the water supply using a water rotameter make it possible to obtain steam overheated to 140–160 ° C and control its flow rate with high accuracy. This allows steam gasification in a given energy-efficient mode. In addition, in the case of supplying air to the reactor, an additional valve is provided, which is connected to an air compressor. Figure 7 shows a photograph of the reactor steam supply system.

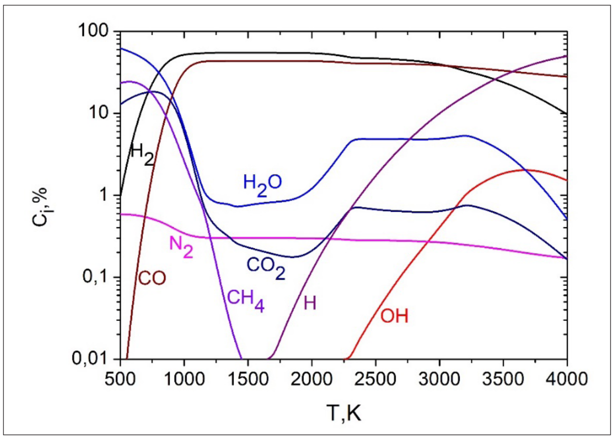


Figure 1 – The change in the concentration of the gas phase depending on the temperature of plasma gasification of the KC

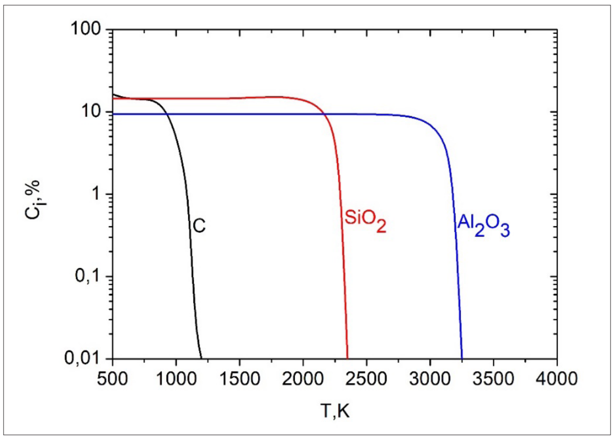


Figure 2 – Changes in the concentration of the condensed phase depending on the plasma gasification temperature of the KC

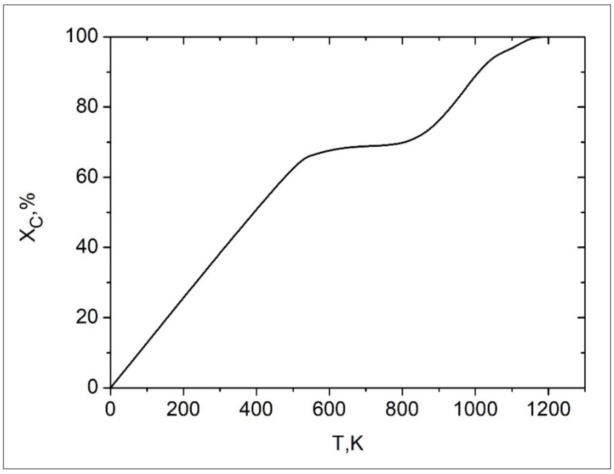


Figure 3 – The dependence of the degree of carbon gasification on the gasification temperature of the KC

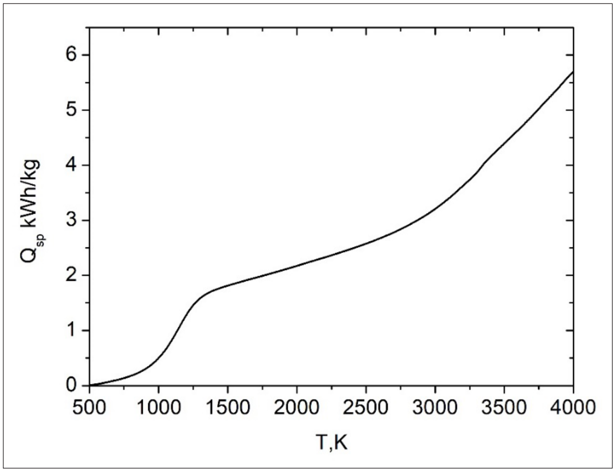
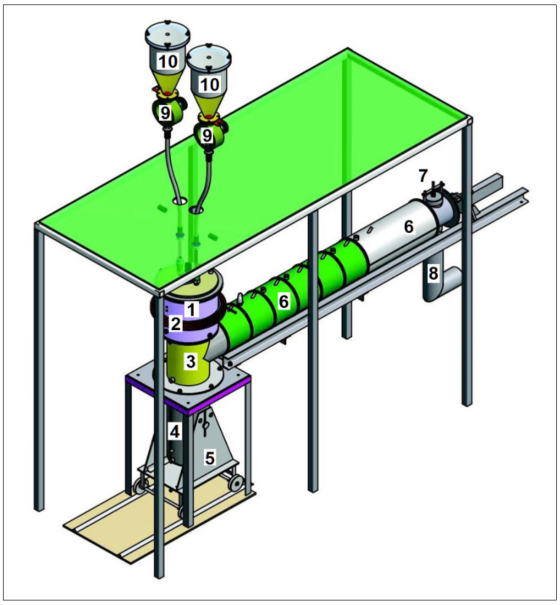


Figure 4 – Specific energy consumption for the plasma gasification process of the KC depending on temperature



1 – plasma reactor; 2 – electromagnetic coil, 3 – gas and slag separation chamber; 4 – slag collector; 5 – elevator slag collector; 6 – gas extraction and cooling sections; 7 – safety valve; 8 – synthesis gas outlet chamber; 9 – dust killer; 6 – dust bin

Figure 5 – Diagram of a universal installation for plasma fuel processing

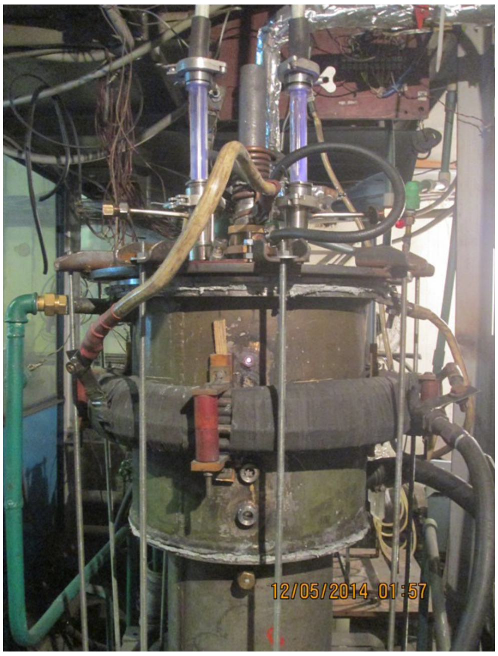


Figure 6 – Plasma reactor with a rated power of 100 kW

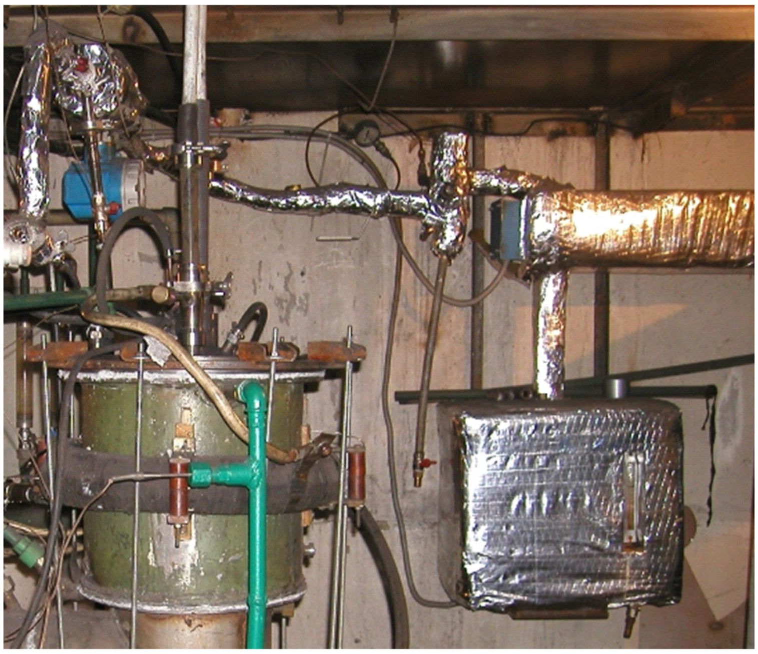


Figure 7 – Reactor steam supply system

To cool all the main components of the experimental setup, exposed to high temperatures, is a water cooling system. It consists of a storage tank, pipelines, pumps, as well as a system of valves and rotameters.

The system of removal of combustible gas includes a lined with graphite oxidation chamber synthesis gas and its cooling in the form of separate sections 6 and the system output gas 7 and 8.

The slag removal system consists of a slag collector 4, equipped with a lift carriage 5.

The plasma gasification experiments were carried out according to the following procedure. The arc is ignited by the method of wire explosion in a plasma reactor. Then from the bunker through two ejectors installed on the reactor lid, coal dust is fed, after which water vapor is fed into the arc burning zone. With the help of steam the pulverized coal mixture is sprayed in the arc burning zone. The pulverized mixture enters the zone of an electric arc rotating in an electromagnetic field and heats up to high temperatures, forming a two-phase plasma flow, where the processes of thermochemical preparation and gasification of coal take place. The solid residue obtained in the process is removed to a slag collector. Gaseous products are fed through the gas and slag separation chamber into the synthesis gas cooling chamber. Then the gaseous products are discharged into the ventilation system.

Experimental studies of plasma gasification of the KC were performed using water vapor as a gasification agent. The experimental data are summarized in Table 2, from which it can be seen that in all experiments a high degree of coal conversion was achieved, varying from 93 to 95.6%.

From table 2 it can be seen that the consumption of coal was 4.0 kg/h, steam – from 1.92 to 2.4 kg/h. In this case, the currents on the arc ranged from 240 to 250 A, the voltage ranged from 270 to 300 V, and the electrical power of the plasma reactor was from 65 to 75 kW.

Sampling was carried out after the plasma reactor in the cooling sections of the synthesis gas. The proportion of carbon in the condensed products of plasma gasification of coal was determined by the absorption weight method. When determining total carbon by the absorption weight method, carbon dioxide formed during sample combustion is absorbed by ascarite (KOH or NaOH applied on asbestos)

Table 3 shows the measured values of the concentrations of gaseous plasma gasification products, the degree of coal gasification Xc and the mass-average temperatures T_{mass}. As can be seen from the table, during the gasification of coal, the main component of the gas phase is hydrogen with a concentration of 57.8%, and the second is CO with a concentration of 40%, which provides a significant synthesis gas yield of 98.2%.

Table 2 – Indicators of experiments on plasma gasification of the KC

experiment number	G_{coal}, kg/h	G_{steam}, kg/h	I, A	U, B	P, кВт	X_c, %
1	4,0	2,4	250	300	75,0	95,6
2	4,0	1,92	240	270	64,8	93,7

Table 3 – Results of physico-chemical studies of the formation of the final gaseous and condensed products of plasma processing of the KC

experiment number	T_{mass}, (K)	Consumption, kg/h		The composition of the synthesis gas, vol.%				X_c, %
		coal	steam	H_2	CO	N_2	O_2	
1	3550	4,0	2,4	57,8	40,4	1,8	0,0	95,6
2	3500	4,0	1,92	55,8	41,5	2,7	0,0	93,7

In experiments with steam gasification of coal, oxygen at the outlet of the installation is absent, which indicates the correct choice of the coal-oxidizer mass ratio. The concentration of the ballast gas – nitrogen in both experiments does not exceed 2.7% and is explained by the release of nitrogen from the fuel into the gas phase together with volatile coal. The total yield of synthesis gas reaches a significant value and amounts to 97.3% and 98.2% during steam gasification. The degree of coal gasification, determined by the residual carbon content in the collected condensed product (solid residue), reached high values of 93.7% and 95.6%. The value of the mass-average temperature changed slightly and amounted to 3500K and 3550K. With steam gasification of coal, the maximum hydrogen concentration in the synthesis gas (55.8-57.8%) is achieved with a very high degree of gasification.

Conclusion

– Thermodynamic analysis was performed using the TERRA universal thermodynamic calculation program.

– Calculations were performed in a wide temperature range (500 – 4000 K) at atmospheric pressure in a plasma gasifier for Kuuchekinsky coal.

– For the calculations, a model mixture of coal + water vapor widely used in practice was chosen.

– Calculations showed that in all cases, as a result of the full gasification process, synthesis gas is obtained, which, depending on the composition, can be used as an energy gas, a high-grade reducing gas in metallurgy, and a raw material for the synthesis of motor fuels.

– Numerical experiments have shown that the concentration of synthesis gas in the gasification products of the investigated coals during steam gasification is 98.3%. The yield of hydrogen is 54.8%.

– The experiments carried out confirmed the results of thermodynamic calculations of plasma-steam gasification of coal. The degree of coal gasification, determined by the residual carbon content in the collected condensed product (solid residue), reached high values of 93.7% and 95.6%.

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