Plasma Gasification of Solid Fuels

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Abstract: - This paper describes numerical and experimental investigation of coal gasification in a combined arc-plasma entrained flow gasifier. Kazakhstan Ekibastuz bituminous coal of 40 % ash content, Germany Saarland bituminous coal of 10.5 % ash content and 14 % ash content bituminous coal from the Middleburg opencast mines, South Africa, were used for the investigation. Experimental investigations have been performed for Ekibastuz coal. Reactor power has been varied from 25 to 52.8 kWe. Plasma steam and air gasification of the coal has been compared. The numerical experiments were conducted using thermodynamic software codes TERRA and kinetic code PLASMA-COAL. It was shown that the synthesis gas concentration at the outlet of the gasifier reaches high values for all coals studied and varies in the range 96.4 - 98.7 %, whereas specific power consumption for the gasification process does not exceed 2.75 kW·h/kg. Regardless of the coal quality, its steam plasma gasification provides the high calorific value gas (4358 - 4555 kcal/kg) at the gas specific yield of 1.3 - 1.83 kg/kg.

Key-Words: - Coal, plasma, gasification, experiment, computation

1 Introduction

Coal is the major source of energy. It provides 64 % of heat and power generation in the world [1]. The share of coal in the world's proven reserves of fossil fuels is about 70 % in oil equivalent [2]. In particular, Kazakhstan is ranked eighth in the world in coal production, and its proven reserves reach 33.6 billion tons. In the near future increase of coal use is expected. But coal “reserves” remain huge [3]; depletion by 2030: coal 25 %, oil 84 %, gas 64 %.

Coal, being one of the most complex composition fossil fuels, is the richest source of valuable chemical products. In the world besides power generation more than 500 products (synthesis gas, fuel oil, methanol, sorbents, etc.) are obtained from coals.

Gasification of coal has been considered as one of the most important and efficient ways for converting coal into gases and useful chemicals. Gasification converts carbon-based materials in the presence of direct heat and with a limited supply of oxygen to a synthesis gas composed primarily of hydrogen and carbon monoxide. If the synthesis gas is cleaned of contaminants, it can be combusted in a reciprocating engine, producing electricity. Otherwise, the synthesis gas can be combusted in a boiler, producing steam for power generation [3-5]. Plasma technologies were developed over a hundred years ago, but extensive work with materials other than industrial high temperature metallurgical applications did not occur until work was needed to simulate re-entry temperatures on the heat shield of re-entry vehicles in the late 50’s and 60’s. Recently, plasma technologies have begun to emerge as a commercial tool in several industries such as ceramics, steel making, metallurgy, building and chemical industries, precious metal recovery, waste disposal and fossil fuels processing [6,7].

One of the new promising technologies for solid fuel processing is its plasma gasification. It allows producing a pure synthesis gas from solid fuel. This synthesis gas is not for incineration in power boilers but it is a raw material for hydrogen, methanol, dimethyl ether production in chemical industry and also it can be used as a high quality reducing agent in metallurgy. Plasma gasification is developing by several industrial corporations and scientific centres [8-18]. From these investigations one can conclude that plasma assistance is a possibility to

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Table 1. Coals thermotechnical characteristics and compositions

Coal	A^d, %	V^{daf}, %	Q^d, kJ·kg^{-1}	C	O	H	N	S	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO
				wt. %									
EC	40.0	24.0	16632	46.18	6.56	2.63	0.8	0.73	23.4	13.8	2.15	0.34	0.31
MC	14.0	25.8	27321	73.93	5.84	4.05	1.72	0.46	8.21	3.16	1.4	0.84	0.39
SC	10.5	32.22	29277	74.73	7.26	5.01	1.5	1.0	6.16	2.37	1.05	0.63	0.29

accelerate, manage and optimize the process of coal gasification. Both thermal and non-thermal plasma discharges can be used to convert coal into other fuels. The benefits of plasma application can be based on the high selectivity of the plasma-chemical processes, the high efficiency of conversion of different types of coal including those of low quality, relative simplicity of the process control, and significant reduction of sulphur, and nitrogen oxides emissions. The main problems in coal gasification modeling [14] are incomplete initial information on the properties of substances and characteristics of physical and chemical processes as well as the absence of reasonably "efficient" theories describing the processes. Neither plasma-assisted gas phase reactions nor plasma-assisted heterogeneous reactions of coal gasification are available in the open literature.

This paper considers numerical and experimental studies of plasma gasification of three kinds of coals: Kazakhstan Ekibastuz coal (EC), Germany Saarland coal (SC) and South Africa Middleburg coal (MC). The coals characteristics are given in Table 1. The study was carried out in four stages. The first stage was experimental investigation of EC plasma gasification, the second one – numerical calculation of EC plasma-steam and plasma-air gasification by kinetic program PLASMA-COAL and thermodynamic code TERRA. On the third step the comparison of the calculations results with experimental data on plasma-steam and plasma-air gasification of EC has been performed. The fourth stage has been devoted to comparative numerical study of plasma-steam gasification of the three coals mentioned above using the program PLASMA-COAL.

2 Experiment

Experiments and further numerical calculations were performed applied to an entrained flow plasma gasifier of the combined type of 100 kW nominal electrical power. The experimental setup is shown in Fig. 1 [15]. The electric arc is ignited between the rod and ring graphite electrodes in the combined plasma reactor 1, Fig. 1. The inner diameter of the reactor (i.e. of the graphite lining) is 0.15 m and its height is 0.3 m. Arc initiation is achieved by vaporizing a wire brought into contact with the rod and ring electrodes. The arc rotates under the influence of the magnetic field induced by water cooled electromagnetic coil which is fixed tip rode electrode-high in the middle of the reactor. It ensures covering the whole cross-section of the reactor by the rotating arc. The coal dust is fed to the reactor from dust feeder 7 through injectors in the top cover of the reactor. Dust is sprayed in the reactor arc zone by plasma-forming gas (steam or air), also introducing into the reactor through injectors in the top cover. The oxidizer-pulverized coal mixture entering the arc zone is heated to high temperature by the rotating arc to produce a two-phase plasma flow where the coal gasification process occurs. The gaseous products are withdrawn through the slag and gas separator chamber 2, the chambers of synthesis gas cooling 4 and hydration 6. The solid residue is removed through the diaphragm 2 into slag catcher 3. The distance from the top cover of the plasma reactor 1 to the exit of the gasifier (orifice 5) is 0.9 m.

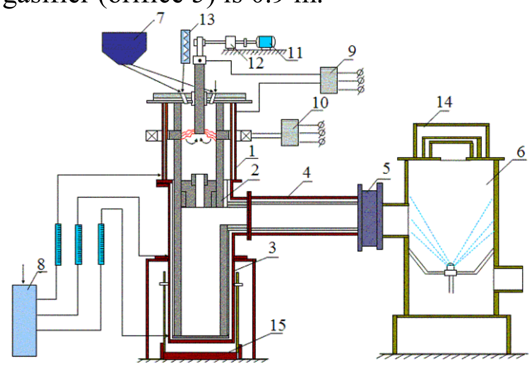

Fig. 1. Laboratory-scale plant for coals plasma gasification: 1 – plasma reactor; 2 – orifice, synthesis gas and slag separator chamber; 3 – slag catcher; 4 – synthesis gas cooling chamber; 5 – orifice; 6 – hydration chamber; 7 – dust feeder; 8 – cooling water system; 9, 10 – power supply system; 11, 12 – rod electrode moving system; 13 – steam generator; 14 –safety valve; 15 – slag catcher lifter

As a result of experiments on the basis of material and heat balancing of the plant, the main parameters of the plasma gasification of coal were measured. They are mass averaged temperature, coal gasification degree, specific power consumption and synthesis gas yield. To conduct

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Table 2. The main indices of the EC plasma gasification

No	Consumption, $kg \cdot h^{-1}$			P_{arc}, kW	Q_{SP}, $kW \cdot h \cdot kg^{-1}$	T, K	CO	H_2	N_2	X_C, %
	Coal	Water Steam	Air				Vol. %			
1	8.0	-	8.0	33	2.1	2100	27.4	15.9	55.3	89.6
2	4.0	-	5.1	30	3.3	2850	38.1	18.2	43.7	95.8
3	4.0	1.9	-	25	4.2	3100	41.6	55.7	2.7	94.2
4	6.5	3.0	1.9	52.8	4.6	3150	38.6	51.4	9.8	92.0
5	4.0	2.44	0.43	52.3	7.7	3500	41.5	55.8	2.7	93.7

Table 3. EC plasma gasification computation results by data of Table 2.

Computer-code	No (Table 2)	CO	H_2	N_2	X_C, %	T, K
		vol. %				
PLASMA-COAL	1	33.5	15.0	50.5	85.6	2051
	2	39.4	16.6	43.5	94.1	2643
	3	41.2	49.5	0.8	87.8	3030
	4	39.6	49.4	9.7	89.0	3140
	5	42.1	53.5	2.7	93.9	3559
TERRA	1	36.2	14.1	48.2	91.4	2100
	2	36.2	15.0	39.6	100	2850
	3	43.1	50.9	0.3	100	3100
	4	40.2	47.6	8.6	100	3150
	5	34.9	55.5	2.9	100	3500

high temperature measurements in the reactor optical pyrometers were used. They allowed measuring the temperature up to 4000 K at accuracy 0.5% of reading. Sieve analysis of dust showed that the average particle size of coal was 75 µm.

The experimental results, obtained for EC, are summarized in Table 2. Reactor power (P_{arc}) has been varied from 25 to 52.8 kW. Defined as a difference between arc power and wall heat loss by calorimetric method the thermal efficiency of the plasma reactor was 76%. The process specific power consumption (Q_{SP}) is related to one kilogram of the oxidizer-coal mixture.

The degree of coal carbon gasification X_C is determined from the carbon content of the solid residue. Specifically, to calculate X_C, the following formula was used:

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

where C_{bas} is initial amount of carbon in coal and C_{fin} is the final amount of carbon in the solid residue. Due to a high temperature at plasma gasification tars were destroyed and therefore was not detected in products of coal gasification in both mediums air and steam.

As it is seen from Table 2, experiments No 1 and 2, the coal gasification degree at plasma-air gasification of coal increases from 89.6 to 95.8% with the power consumption elevation from 2.1 to 3.3 $kW \cdot h \cdot kg^{-1}$. The yield of synthesis gas varies from 43.3 to 56.3%.

In plasma-steam gasification of coal, Table 2, experiments No 3, 4 and 5, the specific power consumption is higher: 4.2 - 7.7 $kW \cdot h \cdot kg^{-1}$. The degree of coal gasification remains at a high level, 92.0 – 94.2%. It is significant that the yield of synthesis gas (CO + H_2) is much higher, 90.0 – 97.3%, at plasma-steam gasification coal.

3 Comparison between Experimental Data and the Results by Computer-Codes TERRA and PLASMA-COAL

The computer-code PLASMA-COAL was designed for computation of the processes of flow, heating, and kinetics of thermo-chemical conversion of an oxidizer-coal mixture in a plasma gasifier alike, as shown in Fig. 1. This code is based on 1-D model which describes a two phases (coal particles and gas oxidizer) chemically reacting flow in a reactor with an internal heat source (electric arc) [17,18]. Coal particles and gas are supplied to the reactor with equal temperatures. There is a particle-to-particle, gas-to-particle and gas-to-electric arc heat–mass exchange. In addition, heat and impulse exchange between the flow and the wall of the reactor is accounted for. Chemical fuel transformations are also considered. They are the formation of primary volatile products, the conversation of evolved volatile products in the gas phase and the coke residue gasification reactions.

The computer-code TERRA [17] was created for equilibrium computations of high-temperature processes. 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. Note, despite of the fact that the 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 [17]. Third, the plasma reactor (Fig. 1) is entrained flow reactor and quasistationary process of gasification is provided.

To verify the programs PLASMA-COAL and TERRA the cases from Table 2 were calculated. Results of the calculations are presented in Table 3. Note that in the calculation the experimentally observed air leak was taken into account. Comparison between the results of calculations by these computer-codes for kinetic and thermodynamic computation was satisfied. Particularly, discrepancy of synthesis gas yield does not exceed 9.4 % at air gasification of EC, and 5.8 % at its steam gasification. Maximal discrepancy of the coal gasification degree is 12.5 %.

Comparing Tables 3 and 2 we can see that at application of the software-code PLASMA-COAL the discrepancy in the concentrations of gas phase components is not more than 22 %, coal gasification degree – 7 % and mass average temperature at the exit of plasma reactor – 7 %. When the software-code TERRA was used the temperatures were assigned from the experiments (Table 2). The discrepancy in the concentrations of gas phase components is not more than 24 % and coal gasification degree – 8 %. Such a relatively small discrepancy of the computed and experimental data confirms validity of the both the thermodynamic software-code TERRA and the kinetic code PLASMA-COAL for numerical investigation of coal plasma gasification. The validation showed the computational assumptions have not affected significantly on the results of calculations. However, despite the difference in temperatures of the compared variants, due to smaller discrepancies between numerical results and experimental data the kinetic computer-code PLASMA-COAL was used for subsequent numerical investigation.

4 Numerical Simulation of the Coals Plasma Gasification

Three widely used in the energy sector coals were selected for the numerical study. They are coals of Kazakhstan (EC), Germany (SC) and the South Africa (MC), Table 1. For the simulation the plasma reactor power was 52.3 kW, coal consumption – 10 $kg \cdot h^{-1}$, steam consumption was selected from an evaluation of the complete coal gasification. It was 7, 9.2 and 9.7 $kg \cdot h^{-1}$ for EC, SC and MC respectively.

Results are presented in Figs. 2 - 6. Figs. 2 - 4 show the composition of gases obtained by the coals plasma gasification. It is evident that pure synthesis gas is obtained from all three coals. Concentration of the synthesis gas at the outlet of the gasifier is 98.7, 96.4 and 97.15 vol. % for EC, SC and MC, respectively. In all three cases concentration of hydrogen (H_2) exceeds that of carbon monoxide (CO). This excess is 12.23 % for EC, 5.42 % for SC and 4.35 % for MC. Note that methane (CH_4) has been appeared in the products of SC and MC gasification (1.53 and 1.27 % respectively), whereas no methane has been calculated at the gasifier outlet at EC gasification. The methylene radical (CH_2) is a typical product with a concentration of 1 to 2 % calculated by the coal plasma gasification. The concentration of oxidant (H_2O) at the plasma reactor exit (X = 0.3 m) tends to zero. An increase of the gasifying agent (water steam) flow rate can lead to an increasing in the yield of the synthesis gas due to the conversion of hydrocarbon impurities (CH_4 and CH_2) [17]. Note, concentrations of the considered components tend to equilibrium by the reactor exit and further downstream. It is specified by required residence time of the reagents in the reactor for the process of coal gasification completeness and is directly connected to its length.

The coals gasification degree increases with the length of the gasifier and is 100% at the reactor exit. This indicates the completion of the gasification process of all three coals. Complete conversion of EC is reached faster than for SC and MC, which is associated with higher temperatures (Fig. 5), and, accordingly, higher specific power consumption for the gasification of EC (Fig. 6).

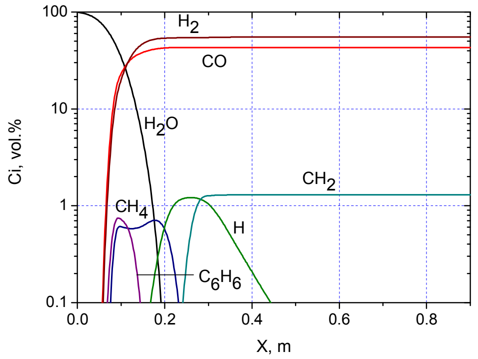

Fig. 2. Distribution of gas composition along the gasifier at EC gasification

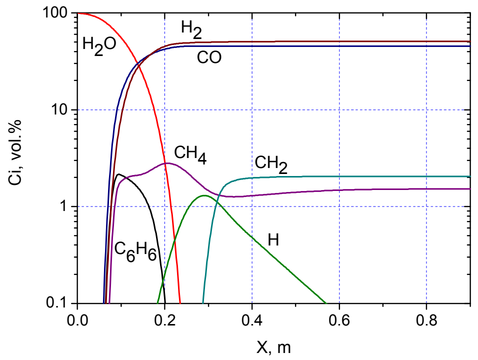

Fig. 3. Distribution of gas composition along the gasifier at SC gasification

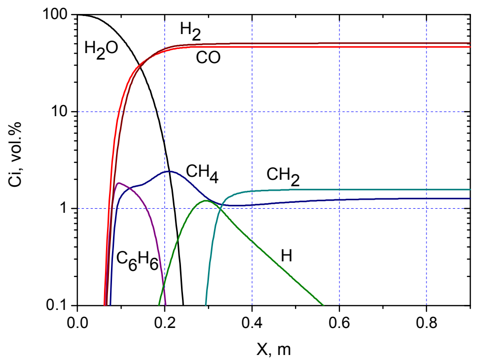

Fig. 4. Distribution of gas composition along the gasifier at MC gasification

Figure 5 shows that in all cases temperature has a maximum in the range 2000 - 2600 K at the reactor exit (X = 0.3 m). Moreover, for all the coals gas temperature near the maximum exceeds the temperature of coal particles by 250 - 300 degrees. This is due to the dominance of the heterogeneous endothermic reactions (7) and (8) over exothermic reactions (9) and (10) (see Table 3). At the gasifier exit the difference between gas and particles temperature decreases to 40-60 degrees, the temperature of gasification products is reduced to 1270 - 1400 K. In spite of different ash content of these coals (14 and 10.5 % correspondingly) the temperatures of the gas phase and particles for MC and SC are practically equal. This is due to the fact that heat of reactions are determined by thermochemical transformations of the fuel organic mass, which is 86 and 89.5 % for MC and SC (4 % difference). For EC gas and particles temperatures are 300 and 400 degrees correspondingly higher of the temperatures found for MC and SC. The reason is high ash content of EC and higher specific power consumption for the process (Fig. 6) needed to achieve maximal degree of coal gasification.

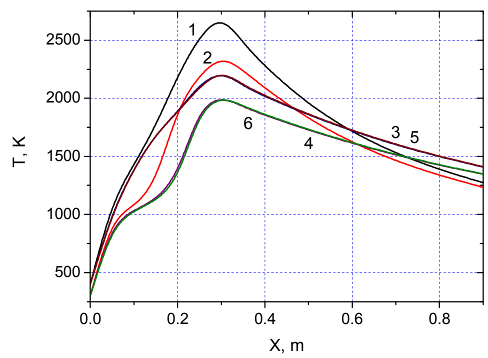

Fig. 5. Gas (1, 3, 5) and coal particles (2, 4, 6) temperature distribution along the gasifier: 1, 2 – EC; 3, 4 – SC; 5, 6 – MC

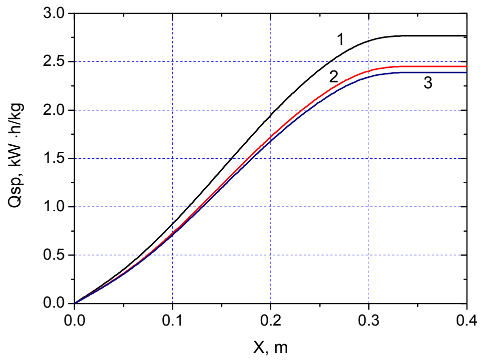

Fig. 6. Specific power consumption distribution along the gasifier: 1 – EC, 2 – SC, 3 – MC

Specific power consumption (Fig. 6) increases along length of the gasifier, reaching a maximum at the exit of the reactor (X = 0.3 m). Specific power consumption for EC gasification reaches 2.75 $kW \cdot h \cdot kg^{-1}$, which is considerably higher than for SC and MC gasification (2.45 and 2.39 $kW \cdot h \cdot kg^{-1}$,

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respectively). That is effect of EC high ash content and correspondingly its low content of organic matter, and as a consequence higher temperature of the process to achieve maximal degree of coal gasification.

Specific yield of the gas determined as the ratio of flow of product gas to coal consumption, increases along the gasifier, peaking toward the exit of the reactor. The yield of gas for low ash content coals (SC and MC) is 30 % higher than for the high-ash EC, although even in the latter case, 1.3 kg of gas is produced from 1 kg of coal.

Calorific value of the product gas for all three coals reaches a considerable value at the gasifier exit and varies in the range of 4358 - 4555 $kcal \cdot kg^{-1}$. Gas calorific value is determined by its chemical composition. Greater calorific value of gas produced at the high-ash EC plasma gasification is associated with a higher concentration of hydrogen in the obtained synthesis gas, in comparison to those obtained from SC and MC (Figs. 2 - 4).

5 Conclusion

Numerical and experimental investigations of three different power coals plasma gasification showed the possibility to produce the high-quality synthesis gas, regardless of the quality of the gasified coal. The produced gas can be used as a high-energy gas, high potential gas – reducing agent and as a raw material for methanol and dimethyl ether synthesis.

The computer-codes TERRA and PLASMA-COAL have proven their validity for simulations of solid fuels plasma gasification. As validation showed the computational assumptions have not affected significantly on the results of calculations.

Numerical simulations by the code PLASMA-COAL have shown that the synthesis gas concentration at the outlet of the gasifier reaches high values for all coals studied and varies in the range of 96.4 - 98.7%, whereas specific power consumption for the gasification process does not exceed 2.75 $kW \cdot h \cdot kg^{-1}$.

Regardless of the coal quality, the steam plasma gasification provides a high calorific value gas (4358-4555 $kcal \cdot kg^{-1}$) at a gas specific yield of 1.3-1.83 $kg \cdot kg^{-1}$ and at a ratio of H_2:CO close to 1.

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