Study of the Effect of Gasification Pressure on the Composition of the Producer Gas From Coal

S Timofeeva¹, D Ermolaev²

¹Kazan State Power Engineering University, Krasnoselskaya St. 51, Kazan, Russia, 420066
²Institute of Power Engineering and Advanced Technologies, FRC Kazan Scientific Center, Russian Academy of Sciences, Lobachevsky St. 2/31, Kazan, Russia, 420111

E-mail: zvezdochka198512@mail.ru, energoed@mail.ru

Abstract. The paper presents the results of studies of the effect of gasification pressure on the composition of the producer gas from different types of coals. Calculations of gasification process with determining the main indicators for different coals depending on the pressure and the recirculation fraction of the producer gas were carried out. The results of studies have shown that the elevated pressure and fuel heating by recirculation gases in combination with high values of gasification temperature and the use of oxygen or steam-oxygen blowing promotes to increase the calorific value of the producer gas, to reduce the time of the process and the gasifier sizes, which leads to improvement of conditions and intensification of the process.

1. Introduction

Among the various energy resources in the world, coal is the most common and cheapest, but its use leads to high carbon dioxide emissions. Therefore, clean coal technologies are currently being developed and implemented to reduce the level of harmful emissions from coal combustion and processing [1].

In Russia, coal is mined in the two largest coal basins - Kuznetsk and Kansk-Achinsk, the coal reserves of the latter being characterized by high ash content, sulfur content and moisture. One of the important problems when using such coal is formation of a large amount of harmful gaseous emissions and solid wastes, as well as the necessary of preliminary preparation of fuel on the basis of drying and milling stages. Improving the efficiency of using low-grade coal is possible through the introduction of multipurpose and waste-free technologies, one of which is gasification [2, 3]. Moisture included in the fuel, which is ballast during traditional coal combustion, during gasification serves as an additional oxidizer, contributing to the output of useful gasification products - H₂, CH₄ and intensification of carbon oxidation reactions.

Gasification is one of the universal and multipurpose methods of coal processing to obtain producer gas, which serves as an alternative to natural gas and can be burned in the combustion chambers of power plants. Depending on the gasification method, it is possible to obtain syngas or producer gas with any composition, the components of which can be used not only for combustion, but also serve as a raw material for synthesis of methanol or ammonia [4, 5]. The main indicators of gas are its...
composition, calorific value and yield per unit of fuel. As the operating parameters of the process are temperature, pressure, characteristics of the initial fuel, type and properties of the oxidizer and its supply to the gasifier.

One of the effective ways of gasification is the use of gasifiers under pressure [6]. Gasification under pressure allows to obtain gases of a specified composition and helps to increase the calorific value. In addition, the producer gas can be directly combusted in a gas turbine and transported over long distances without additional energy consumption for compression [3, 7-9].

In this regard, the purpose of this work was to study the effect of pressure and recirculation of the producer gas on the composition of the producer gas obtained from different types of coals, and the operating parameters of the gasification process.

2. Materials and methods of research

2.1. Materials

Several types of coals were selected as samples for the study, the main characteristics of which are presented in tables 1, 2. Five ranks of brown and hard coals were selected, which differ both in the ultimate analysis of the initial fuel and in their thermal and technical characteristics.

| Type and grade of coal | C   | H   | N   | O   | S   |
|------------------------|-----|-----|-----|-----|-----|
| Berezovsky brown coal, B2 grade | 4.3 | 3.0 | 0.4 | 14.4 | 0.2 |
| Bikinsky brown coal, B2 grade | 26.8 | 2.3 | 0.7 | 10.8 | 0.3 |
| Irsha-Borodinsky brown coal | 43.7 | 3.0 | 0.6 | 13.5 | 0.2 |
| Kuznetsky hard coal, G grade | 66.4 | 4.7 | 1.8 | 7.1  | 0.5 |
| Norilsky, hard coal, CC grade | 59.2 | 3.3 | 1.2 | 4.9  | 0.5 |
Table 2. Characteristics of coal.

| Type and grade of coal | Characteristics (raw mass) | Calorific value, MJ/kg | Volatile yield, % |
|------------------------|-----------------------------|------------------------|------------------|
| Berezovsky brown coal, B2 grade | 33 | 4.7 | 15.7 | 48 |
| Bikinsky brown coal, B2 grade | 37 | 22.1 | 9.05 | 56 |
| Irsha-Borodinsky brown coal | 33 | 6 | 15.7 | 48 |
| Kuznetsky hard coal, G grade | 8.5 | 11 | 26.3 | 40 |
| Norilsky, hard coal, CC grade | 4 | 26.9 | 22.7 | 48 |

The high values of moisture and volatile matter yield of the considered coals are negative for direct combustion in power plants. During heating from the initial substance of such coals volatile matters are released, containing a large amount of tars, which complicate the process and can lead to failure of the gas purification system.

In this regard, the use of gasification of such low-quality fuel will improve its fuel characteristics by obtaining combustible gas and expand the directions of its application in the energy industry.

2.2. Research methods

The research method is developed based on the following scheme of the gasification process in an inline gasifier under pressure, and includes 3 stages of gas formation from coal:

1) Evaporation of mechanically bound moisture from the surface of carbon particle samples and chemically bound moisture. These processes are accompanied by absorption of thermal energy. Physico-chemically bound moisture is retained on the inner surface of the pores by adsorptive forces. Chemically bound water is water of hydration of active groups of high molecular weight compounds and makes up less than 10% of all water contained in coal.

2) Release of volatile components from coal particles. In the process of decomposition of coal matter there is a release of gaseous components as CO$_2$, CO, H$_2$, H$_2$S, N$_2$ and CH$_4$. Theoretically, tar and some hydrocarbons may be formed, in particular, ethane, but in small amounts, so they are usually neglected in calculations. As a result, there is a significant change in the external and internal structures, characterized by the formation of cracks, pores in the coal particles, resulting in the formation of coke residue.

3) Gasification of coke residue with the course of homogeneous and heterogeneous reactions of formation of gaseous compounds and interaction of coke residue and volatiles with an oxidizer (Fig. 1).
Methods for calculating the composition of the producer gas are divided into thermodynamic, based on the determination of equilibrium ratios of gases, and energetic, taking into account the deviation of the gas composition from the experimental data. The existing calculation methods consider the basic reactions of carbon gasification, and do not take into account the composition of fuel [10-12].

The composition of the producer gas is determined based on the course of the main gasification reactions in their equilibrium form. Formation of the main components of the producer gas depends on the type and properties of the oxidizer, moisture and volatile components released from the fuel and operating parameters (pressure, temperature, type of gasification process). The calculation of the equilibrium gas composition is based on the laws of thermodynamics. The composition of the producer gas is determined by the parameters defining a particular thermodynamic state (e.g. temperature and pressure). Knowing the equilibrium constants of gasification reactions, it is possible to determine the equilibrium gas composition produced as a result of these reactions at given temperature and pressure.

The composition of the producer gas is determined on the basis of the following main gasification reactions:

\[
\begin{align*}
\text{C} + \text{CO}_2 &= 2\text{CO} - Q_1, \\
\text{CO} + \text{H}_2\text{O} &= \text{CO}_2 + \text{H}_2 + Q_2.
\end{align*}
\]  

(1)  

(2)

We assume that the produced gas contains the following components: \(\text{CO}_2, \text{CO}, \text{H}_2\text{O}\) and \(\text{H}_2\).

The equilibrium constants for reactions (1) and (2) are written in the following form:

\[
\begin{align*}
\frac{p_{\text{CO}}}{p_{\text{CO}_2}} &= K_{p_1}, \\
\frac{p_{\text{CO}_2}p_{\text{H}_2\text{O}}}{p_{\text{CO}}p_{\text{H}_2}} &= K_{p_2}.
\end{align*}
\]

(3)  

(4)

The total pressure of the producer gas is the sum of the partial pressures of the components [13]:

\[
\sum_j p_j = p_{\text{общ}},
\]

(5)
The process of formation of the producer gas from the fuel must obey the equation of matter conservation, according to which the mass of the chemical element in the producer gas must be equal to the mass of the element in the original fuel [106]:

\[
\sum_{x=1}^{S} a_{i_x} \cdot v_{s} + v_{n_x} = M_{\text{tonn}} \cdot b_{\text{tonn}},
\]

(6)

where \( a_{i_x} \) - atoms of chemical elements of the producer gas; \( v_{s} \) и \( v_{n_x} \) - number of moles of molecular substances and atomic matter in the producer gas; \( M_{\text{tonn}} \) - number of moles of fuel; \( b_{\text{tonn}} \) - atoms of the chemical elements of the fuel.

Based on gasification reactions, equations of equilibrium constants of reactions expressed through partial pressures of components are made. The composition of the producer gas is determined taking into account that the ratio of hydrogen to oxygen in the produced gas and the initial gasifying mixture are equal to each other, and is calculated by solving the following equation [13]

\[
\sum_{i=1}^{N} K_i = D,
\]

(7)

where \( D \) – ratio of hydrogen to oxygen in the gasifying mixture.

Usually, when calculating the equilibrium composition of gases, only the properties of the oxidizer supplied to the gas generator are taken into account. However, in the process of gasification, moisture is released from the coals, which serves as an additional oxidizer, and therefore it is necessary to take it into account when calculating the components of the producer gas. During determination of \( D \) value it is necessary to proceed from the ratio of hydrogen to oxygen in the gasifying mixture and moisture in the initial fuel:

\[
P_{O_2\text{ок}} + P_{H_2O\text{ок}} + P_{H_2O\text{ном}} = P_{дымф}.
\]

(8)

Then the ratio of pressures of the gasifying mixture can be represented as follows:

\[
D = \frac{P_{H_2O\text{ок}} + P_{H_2O\text{ном}}}{2P_{O_2} + P_{H_2O\text{ок}} + P_{H_2O\text{ном}}}.
\]

(9)

Taking into account expression (9), equation (10) can be represented as:

\[
\sum_{i=1}^{N} K_i = D = \frac{P_{H_2O\text{ок}} + P_{H_2O\text{ном}}}{2P_{O_2} + P_{H_2O\text{ок}} + P_{H_2O\text{ном}}}.
\]

(10)

The composition of the producer gas is determined by solving equations (1)-(10). The equilibrium constants of the reaction are determined by [35, 36]. The calorific value of the volatile components is determined by the following expression:

\[
Q_{\text{лет}} = Q_{\text{CO}} \cdot v_{\text{CO}} + Q_{\text{H_2}} \cdot v_{\text{H_2}} + Q_{\text{CH_4}} \cdot v_{\text{CH_4}} + Q_{\text{H_2S}} \cdot v_{\text{H_2S}}
\]

(11)

where \( Q_{\text{CO}} \), \( Q_{\text{H_2}} \), \( Q_{\text{CH_4}} \), \( Q_{\text{H_2S}} \) - the calorific value of carbon monoxide, hydrogen, methane, hydrogen sulfide, respectively, kJ/m³; \( v_{\text{CO}} \), \( v_{\text{H_2}} \), \( v_{\text{CH_4}} \), \( v_{\text{H_2S}} \) - content in the gas phase, respectively, of carbon monoxide, hydrogen, methane, hydrogen sulfide.

3. Research results

Based on the research methods, calculations were carried out to determine the composition and calorific value of the producer gases obtained during gasification of various coals at a pressure change.
Calculations were carried out for coals with a dust particle size of 500 µm, the temperature was taken 1400°C. The gasification process was carried out at atmospheric and elevated pressure from 1 to 4 MPa. Steam-oxygen blowing was used as an oxidizer, fuel particles were heated by the recirculation gas in an amount of 5% of the total amount of the obtained producer gas.

The results of calculations of calorific value as a function of pressure for different coals are presented in Fig. 2.

![Calorific value vs Pressure](image)

**Figure 2.** Comparison of theoretical and experimental dependences of the calorific value of the generator gas on pressure. The theoretical dependences obtained by the authors for: 1 - Berezovsky brown; 2 - Kuznetsky hard; 3 - Norilsky hard; 4 - Bikinsky brown; 5 - Irsha-Borodinsky brown; 6 - theoretical dependence of Altshuler for Irsha-Borodinsky brown coal; I, II, III, IV - experimental values for Irsha-Borodinsky brown coal [14].

As can be seen from the figure, increasing the pressure improves the yield of useful products and the calorific value of the producer gas. The highest value of calorific value of gas is observed for Bikinsky brown coal, which is associated with a large content of volatile matters and moisture in the coal, which serves as an additional fuel oxidizer and at higher pressure increases the yield of useful products of the producer gas. Values of calorific value of the producer gases obtained by gasification Berezovsky and Irsha-Borodinsky brown coals are the same, which is explained by similar characteristics of the original fuel. The lowest value of calorific value corresponds to the Norilsky coal, which is associated with low moisture content, high sulfur content and ash content.

The results of calculations according to the obtained dependences showed that the calorific value of gases obtained during gasification at a pressure of 4 MPa is higher by 10% than at atmospheric pressure.

The results were compared with theoretical calculations and experimental data of Altshuler V.S. for similar conditions of gasification process. The difference in values of the calorific value of the producer gas from Irsha-Borodinsky coal, calculated by the obtained dependences, and the calorific value of gas for a similar type of coal, determined by theoretical calculations of V.S. Altshuler, is less than 10 %. The calorific value of producer gas from Irsha-Borodinsky coal at 2 MPa differs from the experimental data of V.S. Altshuler within 12-20 %, that is connected with the fact that in the experimental studies the output of main components of gas is affected by the value of fuel entrainment from gasifier, and also by difference in organization of gasification process itself in the unit.

The calculation results are in good agreement with the available literature data on theoretical calculations and experimental data on the composition and calorific value of the producer gases, which shows the relevance of this calculation method, and can be used in the study of the gasification process of various coals. Analysis of the initial characteristics of the fuels showed that any types of solid fuels
can be used as feedstock for gasification under pressure, including low-quality ones, the reserves of which in Russia are large enough.

One of the ways to increase the degree of coal conversion in the gasification process is recirculation of the producer gas, which contributes to the heating of coal particles and intensification of the gasification process [15, 16].

In this regard, calculations of gasification process were carried out with determining the main indicators for different coals, depending on the pressure and the recirculation fraction of the producer gas. The results of calculations are presented in fig. 3.

![Figure 3](image)

**Figure 3.** Time dependence of gasification process of fuel with particle size 500 microns in a steam-oxygen blowing at temperature 1400 C on pressure for different coals: 1 - Berezovsky brown; 2 - Kuznetsky brown; 3 - Norilsky brown; 4 - Bikinsky brown; 5 - Irsha-Borodinsky brown.

During calculations it was assumed that heating of fuel particles was carried out by recirculation gas in an amount of 1-10 % of the total volume of the obtained producer gas. Calculations were carried out at a gasification temperature of 1400 C, atmospheric and elevated pressure up to 4 MPa. As an oxidizer was a steam-oxygen blowing with a temperature of about 300 ° C and a pressure of about 2 MPa, which is fed into the zone of direct gasification of coke residue of gasifier. Oxygen to water steam ratio was 11.5:88.5.

As can be seen from Fig. 3, the shortest gasification time is required for gasification of Berezovsky brown coal, which is associated with rapid processes of evaporation of moisture and volatile components from the coal particles. Volatile content in coal is almost 50% of the total composition, so less time is required for gasification of the remaining carbon, which is contained in the coke residue. In addition, the velocity of fuel particles increases with the intensive release of moisture and volatile components from the coal.
As can be seen from Fig. 4, increasing the amount of recirculation gas contributes to reducing the gasification time, which allows to conclude that this technical solution improves the design parameters of gasifier, reduces the cost of oxidizer preparation, and therefore it is advisable to supply it directly to the reaction zone, rather than to the burner devices of gasifier. As a result, there is a rapid heating of fuel particles, the process of volatiles yield is improved, and the depth of coal substance destruction is increased.

In general, studies have shown that in the case of application of coals with different characteristics the range of variation of gasification time of gasifier insignificantly changes at given rates of initial fuel and operating parameters. Therefore, when designing gasifiers, it is necessary to consider temperature, pressure, the recirculation fraction of the producer gas, fuel consumption, as well as the costs of manufacturing and operation of the gasifier, which directly depend on its dimensional size.

On the basis of the calculations we can conclude that the elevated pressure and fuel heating by recirculation gases in combination with high values of gasification temperature and the use of oxygen or steam-oxygen blowing increases the calorific value of the producer gas, reducing the time of the process and the overall dimensions of gasifier, which leads to improvement of conditions and intensification of the process as a whole.

The obtained results can be recommended when choosing the conditions for gasification process in an in-line gasifier, layout of the technological scheme of energy production for power supply of industrial enterprises when using a particular type of coal.

4. References

[1] Mishra A, Gautam S, Sharma T 2018 Effect of operating parameters on coal gasification International Journal of Coal Science & Technology vol 5 pp 113–125
[2] Petrov I V 2014 Economic evaluation of the energy efficiency of coal energy technologies Mountain Information and Analytical Bulletin 81 pp 180-189
[3] Ryzhkov A F, Popov A V 2012 Analysis of Efficiency of Modern Industrial Coal Gasification Technologies Energetik 10 pp 22 – 25
[4] Chen Z, Dai Z, Wang F-C 2013 Simulation analysis of ammonia distribution in methanol production from coal water slurry gasification Journal of Coal Science and Engineering (China) vol 19 pp 546–553
[5] Dai Z G, Zhou Z J, Chen X L, Liu H F, Yu G S, Yu Z H, Sun Z Q, Zhu M, Yang S Q, Liu Q, Zhu Q R 2006 Application of multi-opposed-burner coal water slurry gasification in chemical industry Chem. Ind. Eng. Process 25 pp 611–615
[6] Rokhman B B 2019 Two-dimensional model of solid fuel gasification in a fixed bed under pressure Investigation conversion of Shubarkol coal conversion in a steam-oxygen mixture with the mass past of H2O/O2=45/55” *Scientific and Applied Journal Vidnovlyvanna energetika* **1(56)**

[7] Torralvo F A, Pereira C F, Piqueras O F 2017 By-products from the integrated gas combined cycle in IGCC systems *Integrated Gasification Combined Cycle (IGCC) Technologies* pp 465-494

[8] Clair A M, Marinchenko A Y, Potanina Y M 2019 Optimization studies of a steam-gas plant with coal gasification and high-temperature preheating of blowing air *Bulletin of the Tomsk Polytechnic University. Engineering of georesources* **330(3)** pp 7-17

[9] Kislov V M, Glazov S V, Salgansky E A, Kolesnikova Yu V 2016 Gasification of coal by a mixture of air and carbon dioxide in the filtration combustion mode” *Physics of combustion and explosion* **52(3)** pp 72-78

[10] Sokolinskii S M, Khudyakov Yu, Lapidus D A 2020 Calculation of a Direct-Flow Coal Gasification Process with Liquid Slag Removal *Solid Fuel Chemistry* **54** pp 269-273

[11] Mishra A, Gautam S, Sharma T 2018 Effect of operating parameters on coal gasification *International Journal of Coal Science & Technology* vol 5 pp 113–125

[12] Cong W, Alade O S, Sasaki K, Sugai Y 2018 Experimental and simulation studies on gasification characteristics of a low-rank coal by rapid heating under CO2-rich condition *J. appl. res. Technol* vol 16 **4**

[13] Beloselsky B S 2005 Technology of fuel and power oils (Moscow”: MPEI Publishing House) 348 p

[14] Altshuler V S 1963 Processes in a fluidized bed under pressure (Moscow: USSR Academy of Sciences Publishing House) 214 p

[15] Novikov A A 2012 Circulation technological schemes of the Pintsch gas processing *Bulletin of Yugorsk State University* **3(26)** pp 45–49

[16] Savostyanov A P, Narochny G B 2010 Zemlyakov Grounds for using the circulation schemes in synthesis of hydrocarbons from CO and H2 *Proceedings of the RAS Samara Scientific Center* vol 12 **4(3)** pp 686–690

**Acknowledgments**

This study was supported by the Russian Science Foundation (Project no. 19-11-00220).