

## Equilibrium Models of the Gasification Process of Solid Low-reactive Fuel in The Steam-oxygen-air Flow

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**The goal of this work is to improve the efficiency of the solid low-reactive fuels use in thermal power plants. To achieve the goal we set the following tasks: to develop an equilibrium mathematical model that allows studying the gasification process of solid fuel in the steam-oxygen-air flow; analyze the influence of various mode factors on the composition of produced gas and the main indicators of the technological gasification process of coal particles in the flow, to determine the optimal values of mode factors.**

**Key words:** Coal gasification, Equilibrium mathematical model, Oxidant flow, steam-oxygen-air blast.

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Recently, the development of industry and agriculture has led to a gradual deterioration of the ecological situation. It should be noted that during the last decades there is a trend of the gradual deterioration of the quality of solid fuels, supplied to thermal power plants. This leads to decreased efficiency of boilers and premature wear and failure of boiler equipment. Fuel combustion of the worsened quality in thermal power stations, working with traditional technologies, increases the negative impact of energy companies on the environment. In this regard, the main problem of the energy coal use in the beginning of XXI century is the development of new environmentally friendly technologies for the production of electrical and thermal energy.

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One of the directions of the efficient use of low-grade coal is application of gasification technologies. In the<sup>7</sup> work, a method for the gasification of solid fuels in the upward oxidant flow is examined. It should be noted that the method is still little studied, mathematical models for it are not sufficiently developed, characteristics of the processes, occurring in the gasifier, are not defined. The problem of studying the processes occurring during coal gasification is a subject of many studies<sup>2-14</sup>; however, the existing models and methods do not allow calculating the basic parameters during the fuel gasification in an upward flow. The currently used methods of calculation, due to the considerable complexity of the gasification process and the lack of sufficient data on the kinetics of the main reactions are of empirical character, as some indicators are selected on the basis of practical data<sup>1,9</sup>. This work is dedicated to the generation of such models.

### Basic principles of constructing an equilibrium model

When coal is fed to the gasification chamber, complex processes of heat and mass transfer occur, accompanied by thermochemical transformations involving condensed and gas phases. However, several problems can be solved on the basis of relatively simple models. This is due to intensive mass exchange processes in the volume of the gasifier, and high rates of the chemical reactions at temperatures of  $\sim 1000^\circ\text{C}$ .

If during the operation of the gasifier, the time of chemical transformations of fuel components (at all their stages) to the moment of the almost complete utilization of oxygen, contained in the blast, is less than the time of coal particles remaining in the reaction volume (i.e., if the oxygen content in the flow of the reacting mixture at the outlet of the gasifier is close to zero), then the integral material and heat balances of the system are practically independent from the characteristics of individual process steps. In this case, the final composition of the fuel gasification products for all components can be found by using the quasi-static model in the assumption of equilibrium thermodynamic states of the initial components and products of the process.

Since the gasification efficiency (the ratio of the heat of gasification products combustion to the calorific value of coal) is one of the factors affecting the efficiency of the process, it seems feasible to identify the main technological parameters which have the most significant effect on it, on the basis of the mathematical model of coal gasification.

The consumption of coal gasifier is taken as a determining parameter that is why it is convenient to refer the consumption of main components (oxygen, air, steam and gasification products) to 1 kg of fuel as received, this allows achieving a known generalization of the results.

During the model development, the following assumptions were made:

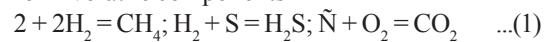
- all the oxygen, supplied to the gasifier, is used for the interaction of fuel with carbon to form CO and CO<sub>2</sub>;
- chemical composition of the formed generator gas at the outlet of the gasifier corresponds to the equilibrium composition, which is determined by the reaction  $\text{CO} + \text{H}_2\text{O} = \text{CO}_2 + \text{H}_2$ , for a given

temperature;

- coal gasification in the gas generator are schematically seen as a process occurring at three stages.

First stage

dry breakdown stage of coal. At this stage, drying of fuel and devolatilization of volatile components occur. The composition of fuel as received (working mass) : C<sup>r</sup>; H<sup>r</sup>; S<sup>r</sup>; O<sup>r</sup>; N<sup>r</sup>; A<sup>r</sup>; W<sub>f</sub><sup>r</sup>. When constructing the model, we take into account that at this stage some fuel components: C<sup>r</sup>, H<sup>r</sup>, S<sup>r</sup> and O<sup>r</sup> enter into a reaction with each other and form volatile components



At the same time, it is necessary to determine what part of C<sup>r</sup> is used for these reactions (i.e. the part of C<sup>r</sup><sub>v</sub> volatile carbon).

At this stage, the products of fuel dry breakdown form per 1 kg of the working mass of coal.

1) Fuel slag with the mass of  $m_{\text{sl}} = m_{\text{A}} = A^r/100$  kg/kg.

2) Gaseous products, m<sup>3</sup>/kg:

- amount of hydrogen sulfide

$$V_{\text{H}_2\text{S}} = \frac{22.4 \cdot S^r}{3200} = 0.007 \cdot S^r \quad \dots(2)$$

When determining the volume of gases, we take into account that a part of fuel hydrogen goes to the formation of hydrogen sulfide by the reaction of  $\text{H}_2 + \text{S} = \text{H}_2\text{S}$

$$\Delta m'_{\text{H}_2} = \frac{2 \cdot S^r}{3200} = 0.000625 \cdot S^r \quad \dots(3)$$

and the remainder of the  $\left(\frac{H^r}{100} - \Delta m'_{\text{H}_2}\right)$  hydrogen mass goes for the the formation of methane.

Then, the volume of methane, which is formed by the  $\text{C} + 2\text{H}_2 = \text{CH}_4$  reaction, will amount to

$$V_{\text{CH}_4} = \frac{22.4 \cdot (H^r - 2 \cdot S^r / 32)}{100 \cdot 4} = 0.056 \cdot H^r - 0.0035 \cdot S^r \quad \dots(4)$$

Part of the carbon (in % of the fuel working mass) goes for the CO<sub>2</sub> formation by the  $\text{C} + \text{O}_2 = \text{CO}_2$  reaction

$$\Delta C'_{\text{CO}_2} = \frac{12 \cdot O^r}{32} = 0.375 \cdot O^r \quad \dots(5)$$

in addition, part of the carbon (in % of the fuel working mass) is spent on the CH<sub>4</sub> formation by the C+2H<sub>2</sub>=CH<sub>4</sub> reaction

$$\Delta C'_{CH_4} = \frac{12 \cdot (H' - 2 \cdot S' / 12) \cdot 100}{100 \cdot 4} = 3 \cdot H' - 0.1875 \cdot S' \quad \dots(6)$$

The volume of carbon dioxide generated by the C + O<sub>2</sub> = CO<sub>2</sub> reaction

$$V'_{CO_2} = V_{CO_2}^C = \frac{22.4 \cdot O'}{3200} = 0.007 \cdot O' \quad \dots(7)$$

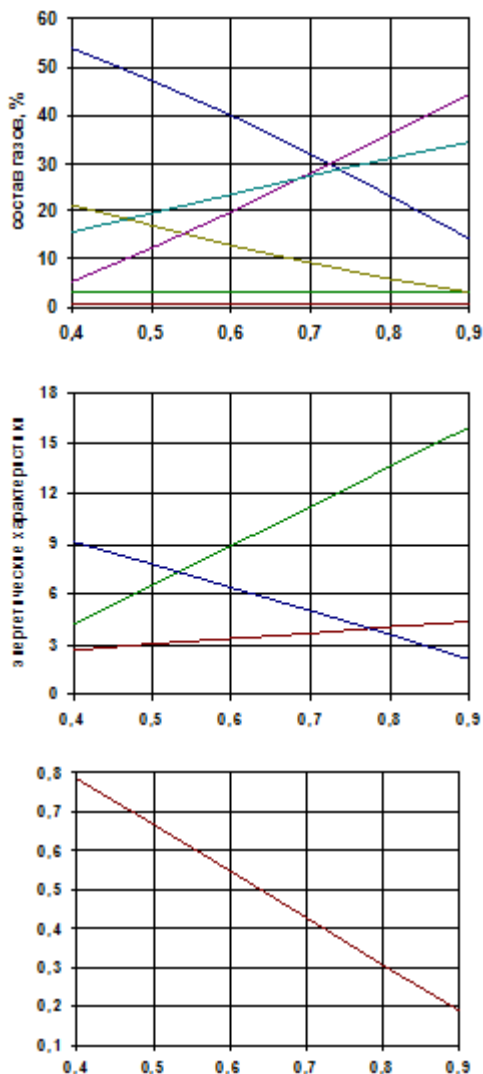
volume of nitrogen

$$V'_{N_2} = \frac{22.4 \cdot N'}{2800} = 0.008 \cdot N' \quad \dots(8)$$

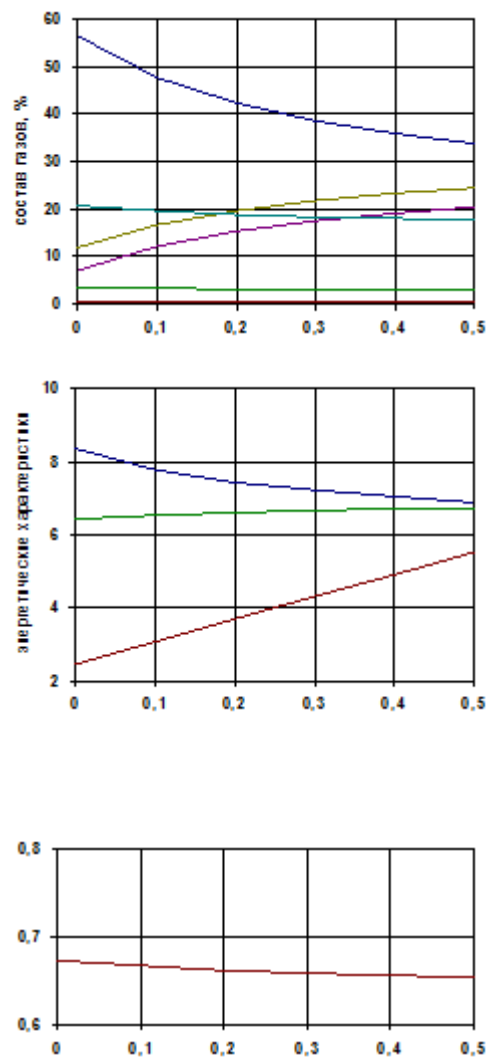
volume of steam

$$V'_{H_2O} = 0.0124 \cdot W'_t \quad \dots(9)$$

3) Carbon with the  $m_c^n$  mass (kg), except for the carbon that went for the formation of volatile compounds



**Fig. 1.** The dependence of the composition of gases (a), main energy characteristics (b) and the efficiency of gasification (c) on the oxygen consumption ( $\beta=0.1$ ;  $X=60\%$ ,  $C'_H=52\%$ ).



**Fig. 2.** The dependence of the composition of gases (a), the main energy characteristics (b) and the efficiency of gasification (c) on the water steam consumption ( $\alpha=0.5$ ;  $X=60\%$ ,  $C'_H=52\%$ ).

$$m_C^n = 0.01 \cdot (C^r - \Delta C_{CO_2}^r - \Delta C_{CH_4}^r) = 0.01 \cdot (C^r - 0.375 \cdot O^r - 3 \cdot H^r + 0.1875 \cdot S^r) \dots (10)$$

Thus, at the second stage, the  $C_n^r$  value is used in the model instead of the  $C^r$  value, i.e. the yield of volatile carbon during coal dry breakdown is taken into account, with non-volatile carbon entering the reaction zone. For example, the difference between  $C^r$  and  $C_n^r$  for the Donetsk coal of the anthracite culm brand is about 4 %, and for coal gas it can already reach about 25, 30 %. The second stage – is the actual carbon gasification process. At this stage (per 1 kg of the coal working mass)  $m_C^m$  kg of carbon is fed, the steam-oxygen-air blast (in the general case) is also supplied: air in the amount of  $C_A^m$  m<sup>3</sup>/kg, oxygen in the amount of  $C_O^m$  m<sup>3</sup>/kg and steam with the  $d_{st}^m$  kg/kg weight. The steam is fed into the gasifier in order to regulate the temperature and change the composition of resulting gases.  $m_{sl}$  kg/kg of slag and gaseous products of gasification are extracted from the zone.

Consider the mode in which water steam and oxygen are fed to the reaction volume in the amount bigger than the one necessary for stoichiometric carbon gasification, but smaller than the one required for its stoichiometric combustion, i.e.  $0.5 \leq \alpha + \beta \leq 1.0$ . Here, a and b are the delivery coefficients of oxygen and steam to the gasification zone, respectively. These coefficients represent the ratio of oxidant, fed to react with fuel carbon to the amount of oxidant, required theoretically (based on the stoichiometric ratios) for complete fuel oxidation by the reactions  $C+O_2=CO_2$  and  $C+2H_2O=CO+2H_2$  respectively.

Main reaction equations in this case are as follows:

$$m_1 \cdot C + 0.5 \cdot m_1 \cdot O_2 = m_1 \cdot CO + 117300 \cdot m_1, \quad \text{kJ/kmol C}, \dots (11)$$

$$m_2 \cdot C + m_2 \cdot H_2O = m_2 \cdot CO + m_2 \cdot H_2 - 134500 \cdot m_2, \text{kJ/kmol C}, \dots (12)$$

$$m_3 \cdot CO + m_3 \cdot H_2O = m_3 \cdot H_2 + m_3 \cdot CO_2 + 27700 m_3, \text{kJ/kmol CO}, \dots (13)$$

$$\Delta m \cdot H_2O = \Delta m \cdot H_2O, \dots (14)$$

where  $m_1$  and  $m_2$  – carbon fraction, going to the (11) and (12) reactions respectively,

$m_3$  – quantitative characteristic the CO

conversion reaction (13),

$\Delta m$  – share of the excess water steam in the blast that does not react in the gasifier volume and exits the gasification zone together with the gases.

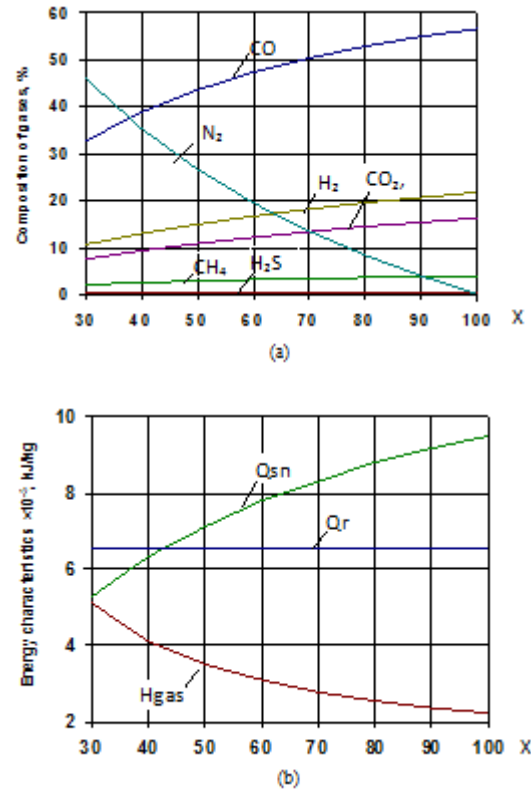
Summarizing these equations, we obtain

$$(m_1+m_2) \cdot C + 0.5 \cdot m_1 \cdot O_2 + (m_2+m_3+Dm) \cdot H_2O = (m_1+m_2-m_3) \cdot CO + (m_2+m_3) \cdot H_2 + m_3 \cdot CO_2 + Dm \cdot H_2O + 117300 \cdot m_1 - 134500 \cdot m_2 + 27700 \cdot m_3, \dots (15)$$

Replace the variables:  $m_1 = 2 \cdot a$  and  $m_2+m_3+Dm = 2 \cdot b$ . It is obvious that  $m_1+m_2=1$ , then  $m_2=1-m_1=1-2 \cdot a$ ,  $m_3=2 \cdot a+2 \cdot b-Dm-1$  and, according to these expressions,  $m_1+m_2-m_3=2+Dm-2 \cdot a-2 \cdot b$ . Then the (15) equation becomes as follows

$$C + a \cdot O_2 + 2 \cdot b \cdot H_2O = (2 + Dm - 2 \cdot a - 2 \cdot b) \cdot CO + (2 \cdot b - Dm) \cdot H_2 + (2 \cdot a + 2 \cdot b - Dm - 1) \cdot CO_2 + Dm \cdot H_2O + 559000 \cdot a + 55400 \cdot b - 27700 \cdot Dm - 162200 \dots (16)$$

Having set values of a and b, it is possible to determine the volume of oxygen in the supplied



**Fig. 3.** Dependence of the composition of gases (a) and the main energy characteristics (b) on the oxygen enrichment degree of the blast X ( $\alpha=0.5$ ;  $\beta=0.1$ ;  $C_n^r=52\%$ ).

blast

$$V_{O_2}'' = \frac{22,4 \cdot \alpha \cdot C_n'}{12 \cdot 100} = 0.01867 \cdot \alpha \cdot C_n' \quad \dots(17)$$

volume of pure oxygen blast

$$V_O'' = \frac{V_{O_2}''}{\alpha} \cdot \alpha_x = 0.01867 \cdot \alpha_O \cdot C_n' \quad \dots(18)$$

volume of air blast

$$V_A'' = \frac{V_{O_2}'' \cdot \alpha_A}{\alpha \cdot 0,21} = 0.0889 \cdot \alpha_A \cdot C_n' \quad \dots(19)$$

and the mass of steam, kg/kg

$$d_{H_2O}'' = \frac{36 \cdot \beta \cdot C_n'}{12 \cdot 100} = 0.03 \cdot \beta \cdot C_n' \quad \dots(20)$$

During the calculations we take into account that the dry blast may be supplied to the gasifier with varying degrees of oxygen enrichment, which are determined as the ratio of oxygen, supplied by the air and oxygen blast to the total volume of oxygen-air blast

$$X = \frac{V_O'' + 0,21 \cdot V_A''}{V_O'' + V_A''} \cdot 100 \% = \frac{100 \cdot \alpha}{\alpha + 3,762 \cdot \alpha_A} \quad \dots(21)$$

Here, we take the delivery coefficient of oxygen and atmospheric air is expressed through  $\alpha_A$ , and the delivery coefficient of oxygen with the pure oxygen blast through  $\alpha_O$ . Thus,  $\alpha = \alpha_A + \alpha_O$

From the (16) equation we can also determine the volumes of gasification products, m<sup>3</sup>/kg:

volume of carbon monoxide

$$V_{CO}'' = 0.01867 \cdot (2 + \Delta m - 2 \cdot \alpha - 2 \cdot \beta) \cdot C_n' \quad \dots(22)$$

volume of hydrogen

$$V_{H_2}'' = 0.01867 \cdot (2 \cdot \beta - \Delta m) \cdot C_n' \quad \dots(23)$$

volume of carbon dioxide

$$V_{CO_2}'' = 0.01867 \cdot (2 \cdot \beta + 2 \cdot \alpha - \Delta m - 1) \cdot C_n' \quad \dots(24)$$

volume of nitrogen

$$V_{N_2}'' = 0.79 \cdot V_A'' = 0.0702 \cdot \alpha_A \cdot C_n' \quad \dots(25)$$

volume of water steam

$$V_{H_2O}'' = 0.01867 \cdot \Delta m \cdot C_n' \quad \dots(26)$$

and the total volume of dry gases

$$V_{CO}'' + V_{CO_2}'' + V_{H_2}'' + V_{N_2}'' = 0.01867 \cdot (1 + 2\beta - \Delta m + 3,762 \cdot \alpha_A) \cdot C_n' \quad \dots(27)$$

Then the total volume of gases (including water steam) will be

$$V_{CO}'' + V_{CO_2}'' + V_{H_2}'' + V_{N_2}'' + V_{H_2O}'' = 0.01867 \cdot (1 + 2\beta + 3,762 \cdot \alpha_A) \cdot C_n' \quad \dots(28)$$

Let us write the composition of the gasification products (in volume percent);

$$CO' = \frac{V_{CO}''}{V_{CO}'' + V_{CO_2}''} \cdot 100 \% = \frac{2 + \Delta m - 2 \cdot \alpha - 2 \cdot \beta}{1 + 2 \cdot \beta - \Delta m + 3,762 \cdot \alpha_A} \cdot 100 \% \quad \dots(29)$$

$$H_2' = \frac{V_{H_2}''}{V_{CO}'' + V_{CO_2}''} \cdot 100 \% = \frac{2 \cdot \beta - \Delta m}{1 + 2 \cdot \beta - \Delta m + 3,762 \cdot \alpha_A} \cdot 100 \% \quad \dots(30)$$

$$CO_2' = \frac{V_{CO_2}''}{V_{CO}'' + V_{CO_2}''} \cdot 100 \% = \frac{2 \cdot \beta + 2 \cdot \alpha - \Delta m - 1}{1 + 2 \cdot \beta - \Delta m + 3,762 \cdot \alpha_A} \cdot 100 \% \quad \dots(31)$$

$$N_2' = \frac{V_{N_2}''}{V_{CO}'' + V_{CO_2}''} \cdot 100 \% = \frac{3,762 \cdot \alpha_A}{1 + 2 \cdot \beta - \Delta m + 3,762 \cdot \alpha_A} \cdot 100 \% \quad \dots(32)$$

Lower calorific value of dry gases, kJ/m<sup>3</sup>

$$\begin{aligned} Q_{H_2}'' &= 126 \cdot CO' + 108 \cdot H_2' = \left( 126 \cdot \frac{V_{CO}''}{V_{CO}'' + V_{CO_2}''} + 108 \cdot \frac{V_{H_2}''}{V_{CO}'' + V_{CO_2}''} \right) \cdot 100 = \\ &= 25200 \cdot \left( \frac{1 + 0,071 \cdot \Delta m - \alpha - 0,143 \cdot \beta}{1 + 2 \cdot \beta - \Delta m + 3,762 \cdot \alpha_A} \right) \quad \dots(33) \end{aligned}$$

Given this, the lower calorific value of dry gases, kJ/kg, will amount to

$$(Q_{H_2}^c) = Q_{H_2}'' \cdot V_{CO}'' = 470,5 \cdot (1 + 0,071 \cdot \Delta m - \alpha - 0,143 \cdot \beta) \cdot C_n' \quad \dots(34)$$

The enthalpy of gasification products, kJ/kg, is determined from the expression

$$H_{gas}'' = t \cdot (c_{CO} \cdot V_{CO}'' + c_{H_2} \cdot V_{H_2}'' + c_{CO_2} \cdot V_{CO_2}'' + c_{N_2} \cdot V_{N_2}'' + c_{H_2O} \cdot V_{H_2O}'') \quad \dots(35)$$

where  $c_{CO_2}$ ,  $c_{H_2O}$  – heat capacities of carbon dioxide and water steam respectively.

Determine the heat generation in the gasifier, kJ/kg

$$Q_{H_2}'' = 466 \cdot (\alpha + 0,098 \cdot \beta - 0,049 \cdot \Delta m - 0,24) \cdot C_n' \quad \dots(36)$$

and the efficiency of gasification

$$\eta^* = \frac{Q_{H_2}^c \cdot V_{CO}''}{Q_{H_2}'' \cdot V_{CO}''} = 1,31 \cdot \left( \frac{1 + 0,071 \cdot \Delta m - \alpha - 0,143 \cdot \beta}{1 + 0,03 \cdot \Delta m - 0,01 \cdot \alpha - 0,06 \cdot \beta} \right) \quad \dots(37)$$

To carry out the calculations it is necessary to determine the Dm value (from the equilibrium condition of the generator gases composition at the outlet of the gasification zone itself). To do this, we write down the expression for the equilibrium constant of the water steam

reaction (13):

$$C_{eq} = \frac{P_{CO_2} \cdot P_{H_2}}{P_{CO} \cdot P_{H_2O}} = \frac{V_{CO_2} \cdot V_{H_2}}{V_{CO} \cdot V_{H_2O}}, \dots(38)$$

where  $P_i$  and  $V_i$  – partial pressures and volumes of the  $i$ -th gases involved in the reaction respectively.

Then we can write

$$C_{eq} = \frac{(2 \cdot \beta + 2 \cdot \alpha - \Delta m - 1) \cdot (2 \cdot \beta - \Delta m)}{(2 + \Delta m - 2 \cdot \alpha - 2 \cdot \beta) \cdot \Delta m}, \dots(39)$$

where one can determine the value of  $\Delta m$ .

Third stage – reacting of the product mixture of the first and second stages in a gas atmosphere. At this stage, the first stage products are fed with the volumes:  $V_{H_2S}, V_{CH_4}, V_{N_2}, V_{H_2O}, V_{CO_2}$  and the second stage products with the volumes:  $V_{CO}, V_{H_2}, V_{CO_2}, V_{N_2}, V_{H_2O}$ . The equilibrium composition of the generator gas is determined by the equilibrium constant of the reaction  $CO + H_2O = H_2 + CO_2 + 27700 \text{ kJ/kmol}$  of CO at the outlet of the gasifier at a temperature.

The formed mixture of gases at the outlet of the generator includes CO,  $H_2$ ,  $H_2S$ ,  $CH_4$ ,  $CO_2$ ,  $H_2$  and  $N_2$ .

Having considered the main equations and calculated the volumes of reaction products at each of the three stages of the coal gasification process, we can determine the total volume of gases, exiting the gasifier,  $m^3/kg$

- volume of carbon monoxide

$$V_{CO} = V_{CO}^* + \Delta V_{CO} \dots(40)$$

- volume of hydrogen

$$V_{H_2} = V_{H_2}^* + \Delta V_{H_2} \dots(41)$$

- volume of carbon dioxide

$$V_{CO_2} = V_{CO_2}^* + V_{CO_2}' + \Delta V_{CO_2} \dots(42)$$

- volume of nitrogen

$$V_{N_2} = V_{N_2}^* + V_{N_2}'' \dots(43)$$

- volume of dry gases

$$V_{dg} = V_{H_2S} + V_{CH_4} + V_{CO} + V_{H_2} + V_{CO_2} + V_{N_2} \dots(44)$$

- volume of water steam

$$V_{H_2O} = V_{H_2O}^* + V_{H_2O}'' - \Delta V_{H_2O} \dots(45)$$

- total volume of gases

$$V_g = V_{dg} + V_{H_2O} \dots(46)$$

The  $\Delta V_{CO}, \Delta V_{H_2}, \Delta V_{CO_2}, \Delta V_{H_2O}$  formulas contain changes in the volume of gases due to their reaction in the mixture at the third stage.

The equation of heat balance with the stationary operation mode of the gasifier is as follows, kJ/kg:

$$Q_{fuel} + Q_{blast} + Q_{steam} = Q_{gg} + Q_{q^3} + Q_{sl} + Q_{cool} \dots(47)$$

where  $Q_{fuel}$  – chemically bound heat and sensible heat of fuel:

$$Q_{fuel} = Q_i^f + c_f \cdot t_f \dots(48)$$

where  $Q_i^f$  – lower calorific value of fuel, kJ/kg;  $t_f$  – fuel heat capacity, kJ/(kg $\times$ °C);

$t_f$  – fuel temperature, °C;

$Q_{blast}$  – sensible heat of the oxygen-air blast:

$$Q_{blast} = V_a \cdot c_a \cdot t_a + V_o \cdot c_o \cdot t_o \dots(49)$$

Here,  $V_a$  and  $V_o$  – are the volumes of air and oxygen in the blast process,  $m^3/kg$ ;  $c_a$  and  $c_o$  – are the heat capacities of air and technological oxygen in the supplied blast, kJ/( $m^3 \times$ °C);  $t_a$  and  $t_o$  – are the temperatures of air and oxygen, °C;

$Q_{steam}$  – sensible heat of the water steam, supplied with the blast,

$$Q_{steam} = d_{steam} \cdot H_{steam} \dots(50)$$

where  $H_{steam}$  – enthalpy of the steam supplied with the blast, kJ/kg;

$Q_{gg}$  – sensible heat of the generator gas,  $Q_{gg} = H_{gas}$

$Q_{q^3}$  – chemically bound heat of the generator gas;

$Q_{sl}$  – sensible heat of slag:

$$Q_{sl} = m_{sl} \cdot c_{sl} \cdot t_{sl} \dots(51)$$

where  $m_{sl}$  – slag yield in the gasifier, kg/kg;  $\tilde{n}_{sl}$  – slag heat capacity, kJ/(kg $\times$ °C);  $t_{sl}$  – slag temperature, °C.

$Q_{cool}$  – heat loss to the environment,

$$Q_{cool} = (q_o \cdot F_o + q_i \cdot F_i) / B \dots(52)$$

where  $q_o, q_i$  – are the densities of the heat flow on the outer and inner cylindrical surfaces of the gasifier annular channel, kJ/( $m^2 \times s$ ),  $F_o, F_i$  – areas of these surfaces,  $m^2$ ,  $B$  – fuel consumption on the gasifier, kg/s.

Analysis of the impact of various factors on the main parameters of the gasification process

Based on the above formulas, a

programme was drawn up, with which the calculations were carried out on a computer. Fig. 1-3 show the dependences of the composition of gasification products and main process energy characteristics and the consumption of oxygen, water steam and oxygen-enrichment degree of the blast.

The analysis of the graphic dependences (curves) showed (Fig. 1) that with the change in  $a$  from 0.4 to 0.9 ( $\beta=0.1$ ;  $X=60\%$ ,  $C_n^r=52\%$ ), a decrease in the volume content of  $\tilde{N}_1$  occurs from 54 to 14.2 %,  $H_2$  from 21.3 to 3.2 %,  $CH_4$  from 3.32 to 3.28 % with the  $H_2S$  content almost constant – 0.52 %. Moreover, due to the increased air supply, there is a decrease in the content of  $N_2$  from 15.6 to 34.4 % and  $\tilde{N}_2$  from 5.3 to 44.3 % in the gasification process. Energy characteristics are linear, depending on  $a$ . With the growth of  $a$ ,  $Q_R$  heat generation in the gasifier significantly increases from 4200 to 15980 kJ/kg. The  $H_{GAS}$  enthalpy of the gasification products also increases from 2690 to 4360 kJ/kg. However, the  $Q_{SN}$  calorific value decreases from 9100 to 2140 kJ/m<sup>3</sup> and the  $h$  gasification efficiency from 0.78 to 0.19.

With the change in the  $b$  consumption of water steam in the blast from 0 to 0.5 ( $\alpha=0.5$ ;  $X=60\%$ ,  $C_n^r=52\%$ ) (Fig. 2) the content of CO decreases from 56.2 to 33.7 %, content of  $N_2$  from 20.8 to 17.8 %,  $CH_4$  from 3.5 to 3.0 % and  $H_2S$  from 0.6 to 0.5 % in the gasification products. At the same time, the content of  $\tilde{I}_2$  increases from 11.9 to 24.5 % and the content of  $CO_2$  from 7.1 to 20.4 %. With the growth of  $\beta$ , the  $H_{GAS}$  enthalpy of gasification products increases from 2430 to 5530 kJ/kg and the  $Q_R$  heat generation in the gasifier increases insignificantly from 6420 to 6750 kJ/kg.

At the same time, the  $Q_{SN}$  calorific value decreases from 8360 to 6900 kJ/m<sup>3</sup>, and the  $h$  gasification efficiency decreases insignificantly from 0.67 to 0.65.

Thus, changes in the oxygen supply have more significant effect on the change in the gas composition and energy characteristics of the process, compared with the change of the water steam supply at constant values of all other factors (e.g., with the change of  $a$ , the content of  $\tilde{N}_1$  changes by 3.8 times,  $H_2$  – 6.6 times,  $Q_R$  – 3.8 times,  $Q_{SN}$  – 4.3 times and  $h$  – 4.1 times, at the same time, with the change in  $b$ , the same characteristic change by 1.7; 2; 1.05; 1.2 and 1.03 times respectively.

With the fixed values of the oxidant delivery coefficients into the melt ( $\alpha=0.5$ ;  $\beta=0.1$ ;  $C_n^r=52\%$ ) (Fig. 3) with the increase in the  $\alpha$  oxygen-enrichment degree of the blast from 30 to 100 %, the content of almost all the gas components increases by around 2 times: CO from 32.8 to 56.7 %,  $H_2$  from 10.8 to 21.9 %,  $CO_2$  from 7.7 to 16.4 %,  $CH_4$  from 2.3 to 4.1 % and  $H_2S$  from 0.4 to 0.7 %. At the same time, the content of  $N_2$  decreases significantly – from 46.1 to 0.3 % in the gasification products. With the growth of  $X$ , the  $Q_{SN}$  gas calorific value increases from 5300 to 9510 kJ/m<sup>3</sup>, melt temperature), the  $H_{GAS}$  enthalpy of gasification products decreases from 5120 to 2210 kJ/kg, but the  $Q_R$  heat generation in the gasifier and the  $h$  efficiency of gasification almost don't change (6520 kJ/kg and 0.67 respectively).

Calculations by the programme allowed determining that the optimum mode with the pure oxygen blast ( $X=100\%$ ) is the mode characterized by the following parameters:  $\alpha=0.36$ ;  $\beta=0.14$ , at the same time, the obtained gasification efficiency is maximum  $\eta=0.83$ . The maximum calorific value of gases  $Q_{SN}=12670$  kJ/m<sup>3</sup> is obtained when  $\alpha=0.5$ ,  $\beta=0$  and the oxygen enrichment degree of the blast being equal to  $X=100\%$ .

## CONCLUSION

We proposed an equilibrium balance mathematical model of the solid low-reactive fuel gasification in the steam-oxygen-air flow. The model allows calculating the volume and composition ( $CO$ ,  $CO_2$ ,  $H_2$ ,  $N_2$  and  $H_2O$ ) of the formed fuel gasification products per 1 kg of the working mass of fuel, as well as heat generation in a gasifier, enthalpy and calorific value of the generator gases, and the gasification efficiency. The proposed model can become the basis for the methodology development of engineering calculations for coal gasification units in the flow.

We analyzed the impact of various mode factors on the main indicators of coal gasification in the flow. It was found that the change in oxygen consumption has more significant impact on the composition of gases and energy characteristics of the process in comparison with the changes in other factors. We determined the optimal values of operating factors, in which the level of gasification efficiency and the combustion heat of generator

gases are the highest.

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