

# Heat exchange processes and productivity of carbon environment transformations of the water-plasma energy stream

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**Abstract.** The analysis of the process of thermal transformations of carbon environment at high temperature ( $T = 2000$  K) processing in a chamber of a plasma-jet reactor with the use of a water vaporizer as an oxidizer is done. The influence of heat exchange parameters on the heating of coal particles of different sizes is established. The method of mathematical modeling of the process of conversion of dispersed carbon raw materials in a stream of water plasma at a temperature in the reaction chamber  $T_g = 2000 - 5000$  K was developed. The technique allows to determine the influence of thermal and kinetic parameters on the process of heat exchange between coal particle and a steam-plasma environment. A conversion time of a coal particle into a gaseous state is determined. It is the time that laid the foundation for calculating the main geometric and regime parameters of the reactor. The expediency of increasing the temperature of the gases in the reactor  $T_g = 3000$  K is proved. This determines the minimum time for conversion of carbon under the combined influence of convective and radiation heat exchanges.

## 1 Formulation of the problem

The processes of the heat- and mass-transfer, aggregate and phase transformations in minerals and rocks during thermal action, oxidation-reduction processes with the release or absorption of the heat are associated with various technological recycling processes of the carbon-containing environment. Thermal processes are increasingly moving from the category of attendant to the purely technological category. This is influenced by the development of different ways of recycling and increasing requirements for the quality of the target product.

In recent years, interest has grown in the heterogeneous plasmachemical processes in which the input material enters the plasma in the form of a finely divided solid or liquid phase. As a result of reactions gaseous products are formed. High concentrations of  $CO$  and  $H_2$  (synthesis gas), which are generated in products of plasma gasification, allow them to be used as raw materials for the production of methanol, motor fuels and other types of chemical compounds. Also it helps to use them as working environments in the

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technologies of heat production and Electricity or direct iron recovery from ore.

At the present time, the serious problem of world economies is the growing negative impact on the environment of harmful emissions in the technologies of direct burning of all types of natural fuels, especially solid, which is considered the closest alternative to natural carbohydrates - oil and gas. Since these "cleanest" energy resources are becoming less accessible and solid fuel is environmentally "dirty", new, environmentally friendly energy and fuel must be synthesized. The main requirements for such fuel: it must satisfy the current environmental requirements, be accessible by economic and technical indicators, competitive in the market of energy resources. And there is no doubt that the work on the creation of technology, which allows you to solve all these problems at the same time, is relevant and demandable at the present time.

## 2 Analysis of the recent research

Plasma gasification processes must be carried out in plasma-chemical reactors. Depending on the method of introducing coal into the reaction zone, they are divided into reactors of a separate and compatible type [1]. Coal gasification is carried out both in the jet of the plasma-forming gas, which is introduced from the outside from an independent source (the reactor of the separated type), and directly in an open discharge of an electric arc (a reactor of a compatible type)

In the works [2-5] the results of theoretical and experimental studies of heating the polydisperse powder of coal in a jet of high-temperature gas  $T_g \leq 2000$  K are given. As a result of the research, it was concluded that a monodisperse raw material should be used to ensure uniform temperature treatment of the whole powder mass. This creates some difficulties in real conditions of the process. In the technologies of thermal transformation, the original material is usually used in the size of 100 - 200 microns. For these conditions it is necessary to create a modern efficient technology of chemical transformations based on local high-temperature controlled zones with a energy density of  $10^2 - 10^4$  W/cm<sup>2</sup> and a temperature in the reaction chamber  $T > 2000$  K. Steam-plazm technology has such properties. It is still theoretically supported and materialized by experimental research.

The research carried out in the Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine shows the possibility of obtaining gas with the preset physical and chemical properties by regulating the ratio of the main reacting components - coal and water. The gas with high hydrogen content was obtained. In comparison with traditional methods of processing, the proposed method allows the implementation of an environmentally friendly process without emissions into the environment of harmful substances [1].

It should be noted that the technology of heterogeneous plasmochemical processes is not developed enough and requires further synthesis and analysis of the results obtained in the process of research and technological development.

Due to the fact that the developed plasmochemical method for the processing of carbon environments has a relatively high energy intensity of the process, further research will be aimed at finding ways to improve its economic indicators. The central issue is the scientifically grounded choice and the study of the method of intensifying the process of heat- and mass-transfer in the reaction chamber of a plasma-chemical reactor.

The purpose of the work is to establish rational parameters of the process of thermal transformation of carbon environment in the water plasma and their effect on the basic geometric and regime parameters of the reactor chamber of the gas generator.

### 3 Presentation of the main material

In the theory of burning of dusty fuel conditionally the process is divided into relatively three independent stages: the particle is warmed up to the exit or the ignition of volatile, burning of volatiles near the particle, the conversion of the coke residue, consisting of carbon and ash. To determine the main characteristics of the process of conversion and gasification of solid fuels, methods of mathematical modeling of individual stages of the burning process and their conditions of transition from one stage to another are used. One of the main processes affecting the subsequent conversion stages is the process of heating the particles of coal, the effectiveness of which depends on the flow of further stages - the yield of volatile, the transformation of the coke residue.

Let's consider the influence of the parameters of the plasma-arc flux on the coal particle heating. The solid fuel particles are heated in the reactor chamber due to radiation and convective heat exchanges between the particle and the flue of hot gases. The equation of the thermal balance for a particle moving in the gas stream, assuming that there is no gradient of temperature along the intersection of the particle, the endo- and exothermic reaction of transformation of the organic mass of solid fuel, have the form [3]

$$m_p c_p \frac{dT_p}{d\tau} = \alpha_k (T_g - T_p) F_f + c_0 \varepsilon_p \left[ \left( \frac{T_g}{100} \right)^4 - \left( \frac{T_p}{100} \right)^4 \right] F_f, \quad (1)$$

where  $m_p$  – particle mass, kg;  $c_p$  – consumed heat capacity of the particle; J/(kg·K);  $\alpha_k$  – heat transfer coefficient, W/(m<sup>2</sup>·K);  $T_g$  and  $T_p$  – the temperature of the gas and particle accordingly, K;  $F_n$  – surface area, m<sup>2</sup>;  $\varepsilon_p$  – the degree of blackness of the particle;  $c_0 = 5.67$  – coefficient of radiation of a completely black figure, W/(m<sup>2</sup>·K<sup>4</sup>);  $\tau$  – time, s.

After transforming the equation (1) into account the values  $m_p = \frac{\pi d_p^3}{6} \rho_p$ ,  $F_f = \pi d_p^2$  and  $\alpha_k = Nu \lambda_g / d_p$ , where  $\rho_p$  – article density, we obtain the differential equation of the particle's heating

$$\frac{dT_p}{d\tau} = \frac{6Nu\lambda_g}{c_p \rho_p d_p} (T_g - T_p) + \frac{6c_0 \varepsilon_p}{c_p \rho_p d_p} \left[ \left( \frac{T_g}{100} \right)^4 - \left( \frac{T_p}{100} \right)^4 \right], \quad (2)$$

where  $\lambda_g$  – coefficient of thermal conductivity, W/(m·K); well  $Nu$  – the thermal criterion of Nusselt.

In equation (2), the first component of the right-hand side characterizes the convective, and the second – radiant component of the total heat flux.

The solution of the differential equation (2) is possible only by numerical methods. Integration of equation (2) with account of only the convective component gives such an expression of the current particle temperature

$$T_p = T_g - (T_g - T_{p,0}) \exp \left( - \frac{6Nu\lambda_g}{c_p \rho_p d_p} \cdot \tau \right), \quad (3)$$

where  $T_{p,0}$  – initial particle temperature, K.

For convenience, the parameter  $\tau$  of equation (3) can be written as

$$\frac{T_g - T_{p,0}}{T_g - T_p} = e^{\left( \frac{6Nu\lambda_g \tau_h}{c_p \rho_p d_p^2} \right)} \quad \text{or} \quad \ln \frac{T_g - T_{p,0}}{T_g - T_p} = \frac{6Nu\lambda_g}{c_p \rho_p d_p^2} \cdot \tau_h, \quad (4)$$

where  $\tau_h$  - particle heating time;  $e = 2.71$  is the basis of the natural logarithm.

The time to heat the coal particle from  $T_0$  to  $T_1 < T_p$  by radiation heat exchange is determined by the formula [4]

$$\tau_h = \frac{\rho_p c_p d_p}{6c_0 \varepsilon_p \varphi} \cdot \frac{1}{4T_r^3} \left\{ \ln \frac{(T_1 + T_r)(T_r - T_0)}{(T_p - T_1)(T_r + T_0)} + 2\text{arctg} \frac{T_1}{T_r} - 2\text{arctg} \frac{T_0}{T_r} \right\}, \quad (5)$$

where  $T_r$  is the radiation temperature of the surrounding space (in our case, the temperature of the arc discharge column), K;  $T_0, T_1$  - the initial temperature of the coal particle and the temperature of the particle heating, K;  $\varphi$  - angular particle irradiation factor.

Thermodynamic simulation of the heating process of polydisperse coal particles under the combined influence of convective and radiant heat transfer was solved by applying a method of successive approximations. With a set temperature of the gasification process  $T_g$  and the thermophysical parameters of the coal particle and arbitrarily chosen value of  $\tau_h$ , the equation (4) defines the convective component of the temperature of the heating of the particle  $T_{pk}$ . Then, according to the equation  $T_{pr} = T_1 = 1800 - T_{pk}$ , the radiation component of the heating temperature is determined. When the value  $T_1$  is obtained, the equation (5) is solved and it is determined by  $\tau_h$  under the radiant heat exchange between the gas and the share of coal. The true value of  $\tau_h$  is accepted with the condition when the received value  $\tau_h$  by the equation (5) coincides with the  $\tau_h$  from the equation (4). Otherwise, the calculation is repeated until the condition is fulfilled.

The proposed method for determination of  $\tau_h$  is applicable in the study of the gasification process in a separate type reactor, in which the convective and radiation heat transfer between the high-temperature gas and the carbon particle is carried out.

## 4 Results and discussion

Let's consider the influence of the parameters of the plasma-arc flux on the heating of the coal particle in the reaction chamber. It was previously established that the complete conversion (thermal transformation) of a coal particle from a solid to a gaseous state is carried out when heated to a temperature  $T_p = 1800$  K, apart from its dispersion. It is necessary to determine the important parameter of chemical kinetics - the time of complete conversion of coal particles, which is the basis for determining the efficiency of the process of fuel processing. The resulting value of the conversion time allows an assessment of the gasification process in the reactor of a separated type.

The resulting equations (4) and (5) are interesting in that they allow us to evaluate the role of individual factors in different methods of heating the particle. Thus, when the particle is heated due to convection from the gas medium, the heating time must be proportional to the square of the particle size and is a function of the temperature of the gas in the first degree. At radiation heating, there should be a linear dependence on the particle size and cubic on the ambient temperature.

As noted earlier, the heating of coal particles in the reaction chamber occurs due to the heat of gases, which acquire a temperature from 2000 to 5000 K at different fuel costs. The temperature of the coal particle in the gasification process varies from  $T_0 = 300$  K to the moment it passes into the gaseous state  $T_p = 1800$  K. The calculation of the convective and radiation components of the total temperature of the particle was carried out for sizes

$d = 50 - 200$  microns, the thermal Nusselt criterion  $Nu = 2$ , the coefficient of the particle blackness  $\epsilon_p = 0.85$ . The density and specific heat of coal are determined by the dependence of work [3] and have the following meaning:  $\rho_p = 1600 \text{ kg/m}^3$ ;  $c_p = 1410 \text{ J/(kg}\cdot\text{K)}$

The thermal conductivity of the dissociation water steam at the temperatures in the reaction chamber  $T_g = 2000 - 5000 \text{ K}$  was taken from the work [6]. The volume of the reaction chamber was determined by the ratio.

$$V_k = \frac{\tau_h m_g R_g T_g}{P_g} \tag{6}$$

where  $V_k$  - the volume of the reaction chamber,  $\text{m}^3$ ;  $R_g$  - the specific gas has become,  $\text{J/(kg}\cdot\text{K)}$ ;  $P_g$  - gas pressure in the reactor chamber, Pa.

Calculated data on the gasification of coal in a reactor of a separated type at a gas temperature in the chamber are given below.  $T_g = 2000 - 5000 \text{ K}$  (Table 1).

**Table 1.** Parameters of gasification of coal in a reactor of a separated type.

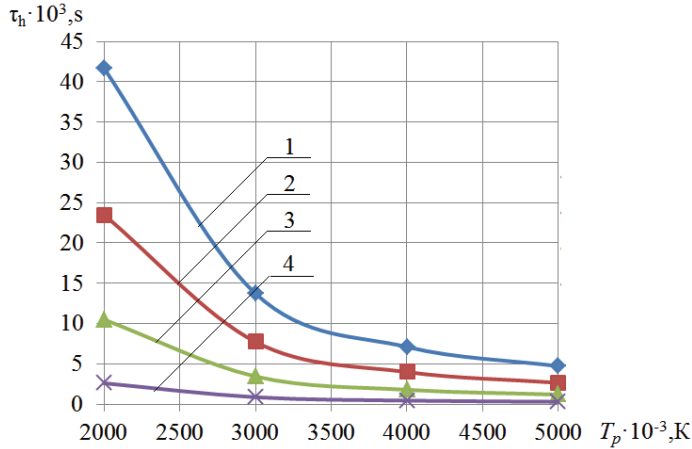
Particle diameter, $d_p$ , microns	Gas temperature, $T_g$ , K											
	2000	3000	4000	5000	2000	3000	4000	5000	2000	3000	4000	5000
	Particle temperature, K				Particle conversion time coal, $\tau \cdot 10^3$ , s				Camera volume, $V_k \cdot 10^3$ , $\text{m}^3$			
50	1404 <sup>†</sup>	1318	1237	1163	2.6	0.86	0.44	0.29	0.835	0.48	0.66	0.68
	396	482	563	637								
100	1327	1197	1080	980	10.5	3.44	1.78	1.18	3.37	1.93	2.67	2.77
	473	603	720	820								
150	1257	1044	952	967	23.5	7.73	3.99	2.65	7.55	4.35	6.01	6.22
	543	756	848	933								
200	1207	1028	873	785	41.7	13.72	7.10	4.71	13.40	7.72	10.68	11.06
	593	772	927	1015								

It follows from the analysis of Table 1 that all parameters of coal gasification in the reactor change significantly with increasing temperature of gas  $T_g > 2000 \text{ K}$  in the reaction chamber. The results of studies allow to establish the dependence of the rate of carbon conversion on the value of the temperature field, in which chemical reactions occur during gasification. It was established that for particles in the size  $d_p = 50$  microns, when the temperature of the gas changes from 2000 to 5000 K, the conversion process is completed more than 9 times. The maximum acceleration of the carbon conversion process takes place in the range of changes in gas temperature in the reaction chamber from 2000 to 3000 K, and the time of carbon conversion varies from  $2.6 \cdot 10^{-3}$  to  $0.86 \cdot 10^{-3} \text{ s}$ . At  $T_g > 3000$ , the acceleration rate of the gasification process is slowing down (Fig. 1). This pattern is observed for all particle sizes. This circumstance is due to the fact that during the process of gasification with a temperature  $T_g > 3500 \text{ K}$ , in the reaction chamber the composition of the water steam, which is dissociated and its thermophysical parameters, changes harshly. In addition, this is a consequence of the difference in the role of methods of supplying heat to a particle.

At low temperatures of the particle, convective heat transfer can play an important role. With further heating as a result of the separation of water vapor and volatile, the role of the radiation component in the heat supply increases, and the effect of convective heat exchange weakens. From the analysis of the table it is seen that when the temperature of the

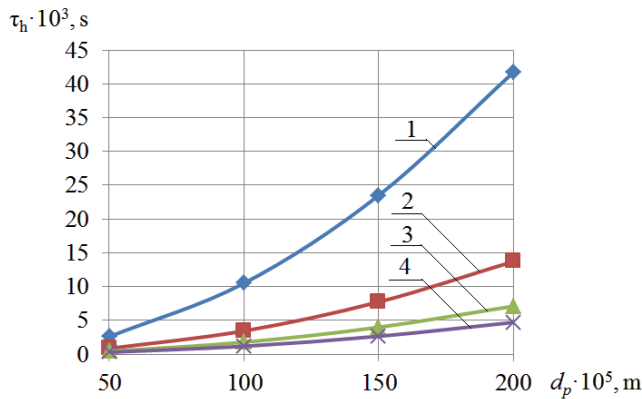
<sup>†</sup> over the line - the convective temperature, under the line - the radiation temperature

gas in the reaction chamber from 2000 to 5000 K changes, the convective component of the particle temperature  $d_p = 50$  microns decreases by 1.2 times, and the radiation component increases by 1.60 times. The layer formed in the surface of the particle through the separation of gases and vapors weakens the convective heat exchange, but less prevents the radiation heat exchange between the particle and the environment.



**Fig. 1.** Dependence of the particle heating time on the temperature of the gas in the reaction chamber: 1 -  $d_p = 200$  microns; 2 -  $d_p = 150$  microns; 3 -  $d_p = 100$  microns; 4 -  $d_p = 50$  microns.

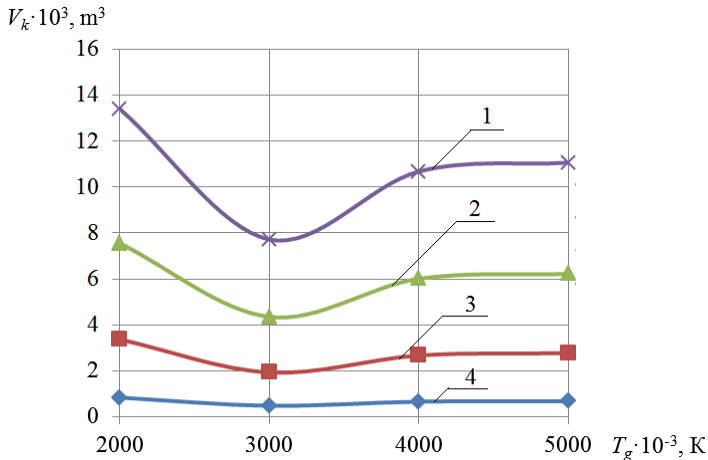
The effect of the particle size of the coal at the time of conversion at different gas temperatures is shown in Figure 2. It is seen that for  $T_g = 2000$  K, the maximum value of the conversion time takes place for all particle sizes. Therefore, we assume that the gasification process is better when  $T_g > 2000$  K.



**Fig. 2.** Dependence of the particle heating time on their size and temperature of the gas: 1 -  $T_g = 2 \cdot 10^3$  K; 2 -  $T_g = 3 \cdot 10^3$  K; 3 -  $T_g = 4 \cdot 10^3$  K; 4 -  $T_g = 5 \cdot 10^3$  K; 5 -  $T_g = 2 \cdot 10^3$  K.

It can be seen from formula (6) that the volume of the reaction chamber depends on the main mode parameters of the gasification process. Influence of gas temperature on the volume of the reaction chamber at constant fuel consumption ( $m_f = 90$  kg/hr,  $m_c = 100$  kg/hr) and the complete conversion of coal particles of various sizes is shown in Figure 3. The minimal volume of the reaction chamber in which the complete conversion of particles of different sizes occurs is taking place during the gasification process with a gas temperature  $T_g = 3000$  K. The volume of the chamber increases for particles in the size  $d_p \geq 15 \cdot 10^{-5}$  m with increasing temperature of gas  $T_g > 3000$  K. It can be explained by

changes in the composition and yield of dispersed steam components at constant pressure. The volume of the reaction chamber is almost unchanged when gasification of coal particles in the size  $d_p = 5 \cdot 10^{-5}$  m in a medium with a temperature  $T_g > 2000$  K (Fig. 3).



**Fig. 3.** Dependence of the volume of the reaction chamber on the gas temperature: 1 -  $d_p = 200$  microns; 2 -  $d_p = 150$  microns; 3 -  $d_p = 100$  microns; 4 -  $d_p = 50$  microns.

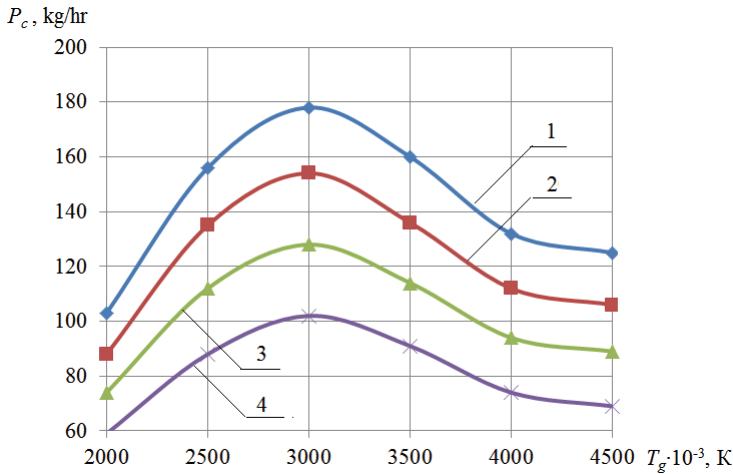
It has been established that with gas temperature rise up to 3000 K, gasification of large coal particles ( $d_p \geq 20 \cdot 10^{-5}$  m) should be carried out in a reaction chamber of volume  $V_k = 0.008 \text{ m}^3 = 8 \text{ l}$ . This volume of the camera is 1.7 times less than the volume at a gas temperature  $T_g = 2000$  K. Small particles ( $d_p = 5 \cdot 10^{-5}$  m) gasify much faster in a small-volume chamber, and the gasification process It is inappropriate to hold at  $T_g > 2000$  K.

The gas pressure in the reaction chamber is an important mode parameter for the gasification process. It is well known that with increasing pressure the chemical reactions in the chamber are accelerated and the temperature of the gas increases, as well as the time of conversion of coal particles changes. The dependence of the volume of the reaction chamber on the gas pressure is expressed by the formula (6). When the pressure in the chamber is increased, its volume decreases under constant fuel consumption. The minimal volume of the camera takes place during the gasification process with a gas temperature  $T_g = 3000$  K.

This temperature regime is appropriate in terms of coal reactor efficiency Figure 4 shows the results of calculations of  $P_c$  performance for different volumes of the chamber when the gas temperature changes  $T_g = 2000 - 5000$  K. It can be seen that the maximal productivity of  $P_c$  coals for chambers of different volumes takes place during the gasification process with a temperature  $T_g = 3000$  K. The calculation of  $P_c$  performance was as follows - according to formula (6), for the given basic regime gasification parameters, the gas flux  $m_g$  is determined. The heating time of the particle  $\tau_h$  to the temperature  $T_p = 1800$  K (conversion time) is taken from Table 1 at a temperature  $T_g = 3000$  K. It was previously established that during gasification of 1 kg of coal of mark «ASh 1» it is necessary to submit 0.9 kg of water steam. Then the reactor's productivity is determined by the formula  $m_c = m_g/1.9$ .

The increase of the gas temperature  $T_g > 3000$  K in the chamber at its constant volume and pressure leads to loss of productivity: at range  $T_g = 3000 - 4000$  K there is a sharp change in the thermophysical parameters of the gas (Table 1), and at  $T_g > 4000$  K the pace their changes are slowing down. This is a consequence of changes in the composition and yield of dispersed water steam components at high temperatures. At the same time, the time of conversion of coal particles is slightly changed compared with  $\tau_h$  at  $T_g = 3000$  K. As a

result of the change of these parameters, the gas flow  $m_g$  decreases and finally  $P_c$  productivity changes. For example, for a reaction chamber  $V_k = 0.008 \text{ m}^3$ , the maximal productivity for coal is  $P_c = 100 \text{ kg/hr}$ , and for  $V_k = 0.014 \text{ m}^3$  at the same operating parameters  $P_c = 180 \text{ kg/hr}$  (Fig. 4).



**Fig. 4.** Dependence of the reactor productivity on coal from the gas temperature in the chamber: 1 -  $V_k = 14 \text{ l}$ ; 2 -  $V_k = 12 \text{ l}$ ; 3 -  $V_k = 10 \text{ l}$ ; 4 -  $V_k = 8 \text{ l}$ .

Thus, on the basis of the performed calculations, it was established that in the real conditions of heating and gasification of carbon fuel in the reactor at a temperature of the gas environment  $T_g > 2000 \text{ K}$ , the radiation heat transfer will play a dominant influence. This will accelerate the gasification process and increase the reactor's efficiency.

## Conclusions

The method of mathematical modeling of the conversion process of disperse carbon raw materials into a stream of water plasma in a reactor of a separated type is developed. It firstly allows to estimate the influence of thermal and kinetic parameters of the process on the main geometric and regime parameters of the reactor. It was established that the process of conversion of coal particles in the size  $d_p = 50$  microns at a change in the temperature of gas in the reaction chamber from 2000 K to 5000 K proceeds rapidly up to 9 times. The maximal acceleration of the carbon conversion process occurs when the temperature of the gas in the reaction chamber is changed from 2000 K to 3000 K, and at  $T_g > 3000 \text{ K}$ , the acceleration rate of the gasification process is slowing down.

It is appropriate to implement the method of gas-plasma gasification of carbon environment in a reactor of a separated type to ensure efficient work (productivity), the process of thermal transformation is recommended at a temperature of  $2000 \text{ K} \leq T_g \leq 3000 \text{ K}$ . In the perspective, research results are recommended to use for designing technical devices for synthesis gas production in the chemical, metallurgical and other industries (for example, production of methanol, motor fuels, non-coke production of metallized materials, heat and power generation technologies).

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