Design of structure and simulation of the three-zone gasifier of dense layer of the inverted process

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Abstract. Experts of LLC "New Energy Technologies" have developed gasifiers designs, with the implementation of the three-zone gasification method, which satisfy the following conditions: 1) the generated gas must be free from tar, soot and hydrocarbons, with a given ratio of CO/H2; 2) to use as the fuel source a wide range of low-grade low-value solid fuels, including biomass and various kinds of carbonaceous wastes; 3) have high reliability in operation, do not require qualified operating personnel, be relatively inexpensive to produce and use steam-air blowing instead of expensive steam-oxygen one; 4) the line of standard sizes should be sufficiently wide (with a single unit capacity of fuel from 1 to 50-70 MW). Two models of gas generators of the inverted gasification process with three combustion zones operating under pressure have been adopted for design: 1) gas generator with a remote combustion chamber type GOP-VKS (two-block version) and 2) a gas generator with a common combustion chamber of the GOP-OK type (single-block version), which is an almost ideal model for increasing the unit capacity.

There have been worked out various schemes for the preparation of briquettes from practically the entire spectrum of low-grade fuel: high-ash and high-moisture coals, peat and biomass, including all types of waste - solid household waste, crop, livestock, poultry, etc. In the gas generators there are gasified the cylindrical briquettes with a diameter of 20-25 mm and a length of 25-35 mm.

There have been developed a mathematical model and computer code for numerical simulation of synthesis gas generation processes in a gasifier of a dense layer of inverted process during a steam-air blast, including: continuity equations for the 8 gas phase components and for the solid phase; the equation of the heat balance for the entire heterogeneous system; the Darcy law equation (for porous media); equation of state for 8 components of the gas phase; equations for the rates of 3 gas-phase and 4 heterogeneous reactions; macro kinetics law of coke combustion; other equations and boundary conditions.

Introduction
The introduction of gas-generating technologies based on the use of small and easy-to-operate gasifiers operating on local types of solid low-grade fuel, including carbonaceous domestic waste, is becoming increasingly important now. The directions of using these technologies can be different, for
example, the combined production of synthetic liquid fuel (SLF), methanol or other chemical products, with the simultaneous generation of electrical and thermal energy. This direction is currently one of the key tasks of the world distributed power engineering and is widely and rapidly spreading, as utilization of household waste, with their preliminary briquetting and use as fuel in gasifiers, removes many environmental problems associated with their traditional utilization.

1. Design of structure of the generator of the inverted process

About ten years, the specialists of LLC "New Energy Technologies" are engaged in the design of a gasifier that would satisfy the following conditions:
- gas after the gasifier should be free of tar, soot and hydrocarbons with specified characteristics, including a given ratio of CO/H₂;
- be able to use as a source of fuel a wide range of low-grade low-value solid fuels, including biomass and various types of carbonaceous waste;
- gasifiers should have all the advantages of gas generators of a dense layer, that is, have high reliability in operation, do not require qualified operating personnel, be relatively inexpensive to produce, and use steam-air blowing instead of costly steam-oxygen;
- the line of standard sizes should be wide enough from gasifiers of mini-units with a unit capacity from 1-1.5 MW (for fuel) to gasifiers exceeding the existing ones of a dense layer, i.e. with a unit capacity up to 50-70 MW.

The development of gasifiers with the above capabilities requires a certain fuel preparation, that is, obtaining, to some extent, a universal fuel suitable for use in gasifiers. At the same time, universalization of fuel is desirable to implement in the system of its preparation. In our case, all kinds of low-grade fuel are crushed and briquetted. High-moisture fuels can be dried in two stages - at the stage of charge preparation, and then briquettes are dried. At the same time, the fuel preparation system is fully integrated into the installation together with gasifiers, and as a drying agent low-potential steam produced in it is used, possibly as a by-product. However, it should be noted that the universalization of fuel preparation concerns only their technical characteristics, such as working humidity, ash content, the form of briquettes, but other properties that depend on the chemical composition of the mineral part of the source fuel, on the availability of various chemical products in them remain inherent in the prepared fuel. And therefore, gasifiers should be flexible enough in terms of changing technological modes of operation.

Experts of TehnoResurs Ltd. have worked out various schemes for the preparation of briquettes from virtually the entire range of low-grade fuel of high-ash and high-moisture coals, peat and biomass, including all types of waste - hard domestic, crop, livestock, poultry, etc. In general, the whole process of fuel preparation can be illustrated by the scheme shown in Fig. 1 [1, 2]. We note that when briquetting the charge, depending on the initial characteristics of the constituent materials, it is possible to use the optimum fillers for them from non-expensive bonding materials. The cylindrical briquettes with a diameter of 20-25 mm and a length of 25-35 mm are gasified (Fig. 2). The three-zone gasification method, developed and studied at the laboratory facility at the Ural Federal University (USTU-UPI) [3], was used as a basis for the designs of gas generators developed by LLC New Energy Technologies. In the process of creating the device that meets the above requirements, two types of structures were developed - with a remote combustion chamber for pyrolysis gases (GOP-VCS) and a combustion chamber built in one housing together with a gasification zone (GOP-OK). The designs of gas generators working under pressure were developed taking into account the experience of construction and operation of the Coal Gasification Plant (CGP) of PAZ (Pavlodar) equipped with four Lurgi gas generators of the Mark-III type. The experts of LLC "NET" took an active part in the design and development of the CGP [4-7]. The characteristics of gas generators in the modes of their operation with steam-air and steam-oxygen blowing and with steam-air blowing enriched with oxygen in the concentration range from 21 to 97% were investigated.

In the development of three-zone gasifiers in the part of its mounts, namely, in the fuel loading and ash removal schemes, the principal decisions of the Lurgi gasifier were used. But there are also serious
differences - this is the use of hydraulic control in the rotation system of the bottom grate, instead of bulky electric.

Figure 1. The scheme of production of briquettes from carbon-containing materials with the use of structuring, binding materials (or without them)

Figure 2. Briquettes from a mixture of peat and manure

In both types of gas generators, the process is divided into three combustion zones and a separate air supply was performed into these zones, which made it possible to separate structurally the processes occurring in these zones from each other. The gasification process is carried out in an autothermal regime, at a given pressure from atmospheric to 3.0 MPa. The working pressure of the gas generator is determined as the technological process of the gas consumer (the gas pressure ahead of the power generating device or ahead of the corresponding synthesis reactor of the SLF or methanol) and the required capacity of the installation for gas.

The air supply to each combustion zone is regulated. The first zone is supplied with the amount of air necessary for the combustion of part of the carbon of the fuel and the maintenance at the expense
of the allocated heat of the temperature necessary for the complete pyrolysis of fuel, at which all vapor-gas substances are extracted from it, and the final product is semi-coke. In the second zone air is supplied in an amount of 40-60% of the total air flow to the gasifier for afterburning of steam-gas pyrolysis products of fuel, in which the end product is steam-gas combustion products of pyrolysis gases, including safe elements - moisture, carbon dioxide and nitrogen of blast air. In the third zone, with a controlled supply of air and steam, gasification of the char is implemented. Three streams enter this zone - semi-coke from the first zone, steam-gas products of burning pyrolysis gases from the second zone and air, in an amount of 30-35% of the total air flow to the gasifier, determined by the specified gasification regime. The air supplied to the third zone can be mixed with steam to control the gasification temperature and prevent the slagging process. By changing the combustion air regime in each zone, it is possible to obtain a generator gas with specified quantitative and qualitative characteristics, without the content of tar and other harmful substances.

In Fig. 3 shows the gas generator model of the reversed gasification process with three combustion zones operating under pressure of the GOP-VCS type (design of the gas generator in the process of patenting, application No. 2017105048/05 (009019)). The gas generator is structurally executed in a two-unit version - the main unit is the pyrolysis and gasification reactor and the remote unit for afterburning of pyrolysis gases.

The gas generator is structurally executed in a two-unit version - the main unit is a pyrolysis and gasification reactor and a remote unit - a unit for afterburning pyrolysis gases.

*Figure 3. Construction of a three-zone gasifier of the GOP-VKS type with mount designations*
The gasifier of the inverted gasification process operates as follows.

- The briquetted fuel is supplied from the fuel bunker 1 through the fuel lock chamber 2 to the first combustion zone, the pyrolysis zone located in the upper part of the reactor 4 into which a controlled flow of hot air is supplied through the distribution nozzle system 3. In the first combustion zone of the reactor of the gasifier 5, pyrolysis and drying of the fuel, their carbonization with the release of volatile and combustible components are carried out. With the amount of supplied air that is about 15-20% of the total air flow to the gas generator, there is controlled the temperature of pyrolysis gases, which must be maintained within 500-550°C.

- In the lower part of the first zone, the pyrolysis zone, there is a separation of gaseous and solid phase products of heat treatment of fuel; the vapor-gas products are withdrawn from the first zone 5 located in the main unit through the tuyeres for collecting and discharging the pyrolysis gases 9 and are fed to a low-pressure gas burner 18 with a vortex supply of hot air of about 50-60% of the total air flow to the gas generator set at the top fire chamber 15 located in the remote unit. The fire chamber 15 is a cylindrical channel shielded by a membrane panel of tubes of Ø60x6 mm and lined with refractory material from the firing side. In this chamber, incineration of tars, phenols and other combustible substances is carried out. The supply of air to the low-pressure gas burner 18 with the vortex supply of hot air is controlled and carried out in an amount close to the stoichiometric for combustion of the pyrolysis gases. In the lower part of the fire chamber 15 there are perimeter passages through which hot flue gases enter the convection chamber 16 where they are cooled to 500-600°C.

The semi-coke stream from the upper part of the reactor 5 is separately withdrawn down through the conically tapered channel 6 into the cylindrical channel 7 (gasification zone) of the gasifier.

- Three streams enter the inlet to the cylindrical channel 7 of the gas generator - a semi-coke along the conical channel 6 from the upper part of the reactor 4 located in the base unit, hot gases - the products of combustion of pyrolysis gases from the convection chamber 16 located in the remote unit and controlled air or steam-air blast. The introduction of air or steam-air blast is carried out in the flue gas duct from the convection chamber 16 of the removed unit just ahead of they are fed through the nozzles 8 into the cylindrical channel 7 - the gasification zone of the semi-coke.

The generator gas is withdrawn through the tuyeres 17 and the ash is discharged to the ash lock chamber 13 through the ash channel 16 which operates under pressure and serves as a connecting intermediate chamber between the ash channel 10 and the ash lock chamber 13. The ash lock chamber 13 operates under a cyclically variable pressure and serves as a receiver for ash discharged from the gas generator and periodically discharged into the ash transport mechanisms.

The control system of the grate drive and valves of fuel and ash locks 12 is hydraulic, it is operated by a single oil station.

In Fig. 4 shows the gas generator model of the inverted gasification process with three combustion zones operating under pressure of the GOP-OK type (design of the gas generator in the process of patenting, application No. 2016147098/05 (075612)). In Fig. 5 shows the scheme of a three-zone gasifier of the GOP-OK type with the notation of the main mounts. In Fig. 5 shows the scheme of a three-zone gasifier of the GOP-OK type with the notation of the main mounts. The GOP-OK gas generator, shown in Fig. 4 and 5, works as follows.

- Briquetted fuel is supplied from the fuel bunker 1 through the fuel lock chamber 2 into two fuel lines 3, in the vertical part of each of which the first zones are located, pyrolysis zones, and into which through the air pipes a regulated flow of hot air is supplied. In the first combustion zone, pyrolysis and drying of the fuel, its carbonization with the release of volatile and combustible components are carried out. The amount of supplied air is controlled by the temperature of the pyrolysis vapor-gas products, which is maintained within 500-550 °C.

- In the middle vertical part of the fuel pipes 3, at the end of the first zone there is a separation of gaseous and solid-phase products of heat treatment of fuel. Steam-gas pyrolysis products are withdrawn from the first zone, through tuyeres of collection and withdrawal 5 and supplied by gas pipelines to the upper part of the reactor 6, to the zone of their afterburning. Reactor 6 is a water-
cooled cylindrical vessel in whose internal volume there are two zones participating in the gasification process (zones II and III) and in its lower part there is an "ash bed".

In zone II - the zone of afterburning of steam-gas pyrolysis products, burning of tar, phenols and other combustible substances is carried out. Oxidation of pyrolysis products is carried out by means of air supplied tangentially through nozzles 8 to the cross-section for the input of pyrolysis vapor-gas products. The supply of hot air to this zone is controlled and carried out in an amount close to the stoichiometric for their combustion.

The separation of vapor-gas pyrolysis products is due to the difference in the aerodynamic resistance of the sections of fuel lines below the tuyeres of gas extraction and the upper part of the reactor.

Figure 4. Volumetric model of a three-zone gasifier of the GOP-OK type.

Figure 5. Scheme of a three-zone gasifier of GOP-OK type

- In the middle part of the reactor there is a semi-coke gasification zone, where three streams are fed: semi-coke from the fuel lines after the pyrolysis zone (zone I), hot gases - oxidation products of pyrolysis vapor-gas products from the afterburning zone (zone II) and controlled air (or steam-air) blast. The input of which is carried into the section of the reactor just before the gasification zone, tangentially through the nozzles 9.

- The generator gas is withdrawn through the tuyeres 12 and the ash is discharged to the ash lock chamber 11 through the ash channel 10 which operates under pressure and serves as a connecting intermediate chamber between the “ash bed” and the ash lock chamber 11. The ash lock-chamber 11 operates under a cyclically variable pressure and serves as a receiver for ash discharged from the gas generator and periodically discharged into the ash transport mechanisms.

The control system of the grate drive 7 and valves 12 of fuel 2 and ash locks 11 is hydraulic, it is operated by a single oil station.
Areas of application of the two types of gas generators considered are somewhat different. For example, gas generators of the GOP-VKS type with a remote combustion chamber for pyrolysis gases have a disadvantage of all the gas generators of the inverted process, namely, difficulties in uniform distribution of the blasting mixture together with the products of combustion of pyrolysis gases in the third combustion zone. This factor can limit the power of the gas generator. On the other hand, GOP-VKS gas generators can be used in open and semi-open modes. These modes imply the full or partial removal of hot flue gases after the combustion of pyrolysis gases from the gas generator in a parallel scheme and the utilization of their heat in other devices, for example, for drying fuel raw materials with the emission of exhaust gases into the atmosphere. The same scheme allows the gas generator to operate in the pyrolyzer mode with the withdrawal of semi-coke through the third zone without gasification.

Single case gas generators of the GOP-OK type are almost ideal models for increasing the unit capacity. Uniformity of the distribution of air over all three combustion zones is carried out without special difficulties, but for the design of relatively powerful gas generators, it is still necessary to regulate the regimes. For this purpose, a pilot gas generator with a reactor diameter of 1000 mm was constructed. The one shown in Fig. 4 and 5 model and is a model of this pilot gas generator installation with a reactor diameter of 1000 mm and capable of operating under pressure up to 1.0 MPa. A preliminary estimate shows that this pilot installation has a fuel capacity of up to 1.5-2.0 MW, but under pressure it can increase its power by more than twice. At present, working drawings of a pilot gas generator have been developed at LLC "New Energy Technologies" and estimates of the budget of its manufacture have been made. In this gas generator all the main mounts are made as self-similar units of the future more powerful (20 - 30 MW fuel) gas generator.

The goal of the construction of a pilot installation with a gas generator of an inverted process with three combustion zones is to obtain additional information for the development of more powerful gas generators of a dense layer, and also to optimize the process for obtaining gas without tar, soot and hydrocarbons, and the possibility of implementing a gasification process with increased operating pressures.

The proposed pilot gas generator using gasification technology with three combustion zones allows to obtain a gas of a given composition depending on the distribution of the oxidant (air) over all three combustion zones - from the minimum CO concentrations equal to 15-18% (at a hydrogen content of H2 of the order of 11-13%), up to maximum CO of 34-37% (with a minimum hydrogen content of H2 of the order of 2.5%) [1, 2]. These capabilities of the gas generator are especially important in the production of liquid fuels, methanol and other chemical products that require a certain ratio of CO/H2 gases for synthesis reactions.

It is planned to design and build a mini-thermal power station (Demo project) with a three-zone gas generator of an inverted process operating at atmospheric pressure with a fuel capacity of up to 1 1.5 MW (with a briquette consumption of 250-350 kg/h) and with the ability to work under pressure with an increase in power to 5-7 MW. The proposed mini-thermal power installation is designed for cogeneration of electricity with a capacity of 100-200 kW and thermal energy of about 700-800 kW.

Note that the design and construction of a pilot gas generator is performed using a 3D modeling program, one of which is Autodesk Inventor Professional. Using this program significantly reduces the probability of errors, especially when connecting mounts, while 3D-systems allow one to model the product before creating drawings or prototypes.

2. Mathematical model of the generator of the inverted process

At the input of the gas generator, in the model we assume conditionally that it is the beginning of zone III, it is supplied with blast mixture (air with water vapor). On the surface of solid particles (briquettes) heterogeneous (1-4), and in the pore space homogeneous (5-7) reactions of macro kinetics are proceeded, with the corresponding thermal effect [8]:

1) \( \text{C} + \text{O}_2 = \text{CO}_2 + 393.3 \text{kJ/mole} \);
2) \( \text{C} + \text{CO}_2 = 2\text{CO} -172.4 \text{kJ/mole} \);
3) $C + H_2O = CO + H_2$ - 131.4 kJ/mole;
4) $C + 2H_2 = CH_4$ + 74.9 kJ/mole.
5) $2CO + O_2 = 2CO_2$ + 565.7 kJ/mole;
6) $2H_2 + O_2 = 2H_2O$ + 483.7 kJ/mole,
7) $CO + H_2O = CO_2 + H_2$ + 41.0 kJ/mole.

For the phases of the heterogeneous system we take the indices for the solid phase "S" solid reagent, "b" ballast, and for the components of the gas phase - the general index "j", including 1 oxygen O_2, 2 nitrogen N_2, 3 water vapor H_2O, 4 argon Ar, 5 carbon dioxide CO_2, 6 carbon monoxide CO, 7 hydrogen H_2, 8 methane CH_4. We assume that the velocity of each j-th component of the gas phase relative to the solid phase is equal to the filtration velocity $w_j = w_f$, and the velocity of the solid phase relative to the reactor wall is constant $u_s = \text{const}$.

We write down the equations describing the gasification process [5, 9, 10]:

- the continuity equation for each j-th component of the gas phase

$$\frac{d}{dz} \sum_j \rho_j (w_j + u_s) = \sum_j M_j \sum_i \xi_j W_i,$$

which for specific gases will be written in the form

$$\rho_1 \frac{dw_1}{dz} + (w_f + u_s) \frac{d\rho_1}{dz} = -M_1 (W_1 + W_3 + W_6), \quad (1)$$

$$\rho_2 \frac{dw_2}{dz} + (w_f + u_s) \frac{d\rho_2}{dz} = 0, \quad (2)$$

$$\rho_3 \frac{dw_3}{dz} + (w_f + u_s) \frac{d\rho_3}{dz} = M_3 (-W_3 + 2W_6 + W_7), \quad (3)$$

$$\rho_4 \frac{dw_4}{dz} + (w_f + u_s) \frac{d\rho_4}{dz} = 0, \quad (4)$$

$$\rho_5 \frac{dw_5}{dz} + (w_f + u_s) \frac{d\rho_5}{dz} = M_5 (W_1 - W_2 + 2W_5 + W_7), \quad (5)$$

$$\rho_6 \frac{dw_6}{dz} + (w_f + u_s) \frac{d\rho_6}{dz} = M_6 (2W_2 + W_3 - 2W_5 - W_7), \quad (6)$$

$$\rho_7 \frac{dw_7}{dz} + (w_f + u_s) \frac{d\rho_7}{dz} = M_7 (W_3 - 2W_4 - 2W_6 + W_7), \quad (7)$$

$$\rho_8 \frac{dw_8}{dz} + (w_f + u_s) \frac{d\rho_8}{dz} = M_8 W_4, \quad (8)$$

where $\rho_j$ - the real density of the j-th component of the gas phase, $w_f$ - filtration velocity relative to the solid phase, $M_j$ - molar mass of j-th component, $W_i$ - rate of i-th heterogeneous or homogeneous reaction (for reaction products sign «+»);

- continuity equation for the solid phase

$$-\rho_8^0 u_s \frac{d\eta}{dz} = -M_8 (W_1 + W_3 + W_6 + W_7), \quad (9)$$

where $\eta$ - depth of coal burnup (varies from 0 to 1), $\rho_8^0$ - initial density of carbon, $M_8$ - molar mass of carbon;

- the heat balance equation for the entire heterogeneous system (an isothermal approximation $T(z) = T_s(z) = T_s(z)$ for any given thickness of a dense layer from $z$ up to $z + dz$)
\[
\left[ (w_j + u_s) \sum_j c_j \rho_j + u_s \left( c_s \rho_s^0 (1 - \eta) + c_b \rho_b \right) \right] dT \frac{dT}{dz} = \frac{d}{dz} \left[ \lambda \frac{dT}{dz} + \sum_i W_i Q_i - \frac{\alpha}{r_{\text{gen}}} (T - T_0) \right],
\]

(10)

where \( c_j \) - heat capacity of \( j \)-th component of gas phase, \( c_s \) - heat capacity of carbon, \( c_b \) - heat capacity of ballast, \( \rho_b \) - density of ballast, \( Q_i \) - molar heat of \( i \)-th homogeneous or heterogeneous reaction, \( \lambda \) – the reduced coefficient of thermal conductivity of a porous medium, \( \alpha \) - the reduced heat transfer coefficient between the porous medium and the wall of the reactor with temperature \( T_0 \).

\( r_{\text{gen}} \) - the internal radius of the gas generator;

- Darcy law equation (for porous media)

\[
\frac{dp}{dz} = \frac{w_f}{k_f},
\]

(11)

where \( p \) - pressure, \( k_f \) – filtration coefficient, which can be calculated using the Kozeny-Karman relation [11] (it should be noted that the law is applicable for Reynolds numbers less than or on the order of unity);

- equations of state for \( j \)-component of the gas phase

\[
p = \sum_j p_j = RT \sum_j \frac{\rho_j}{M_j};
\]

(12)

- equation for the rate of the \( i \)-th gas-phase (homogeneous) reaction

\[
W_i = k_i \prod_j A_{ij}^{\xi_{ij}} \exp \left( - \frac{E_i}{RT} \right),
\]

(13)

- macrokinetic coke burning law (reaction rate) for the \( i \)-th reaction of gasification of carbon with the \( j \)-th component of the gas phase

\[
W_i = K_{Ci} K_{Si} (1 - \eta).
\]

(14)

\[
S_C = \frac{6 \left( 1 - \varepsilon \right)}{d_0 \left( 1 + \frac{\rho_S^0 / \rho_b}{100 / A^r - 1} \right)},
\]

\[
K_{Si} = S_C \frac{A_{ij} / \xi_{ij}}{\sum_j A_j \frac{RT A_{ij}}{p \xi_{ij}}},
\]

\[
K_{Ci} = \frac{\beta_i A_{ij}}{k_{Wi} + \frac{D_j}{\text{Nu}_D D_j}},
\]

\[
k_{Wi} = k_i \exp \left( - \frac{E_i}{RT} \right),
\]

where \( S_C \) - reduced area of the active surface of the coal, \( A^r \) - ash content of the coal in\%, \( \varepsilon \) - porosity of the porous medium, \( d_0 \) - average diameter of the particles (briquettes) of the porous medium, \( K_{Si} \) - coefficient of the area of the \( i \)-th gasification reaction, \( A_{ij} \) - concentration of the \( j \)-th component of the gas phase participating in the \( i \)-th reaction, \( \xi_{ij} \) - stoichiometric coefficient, \( \text{Nu}_D \) - Nusselt diffusion number, \( D_j \) - diffusion coefficient of the \( j \)-th component, \( k_{Wi} \) - kinetic rate of the \( i \)-th reaction, calculated from the Arrhenius law with the activation energy and the assumption of the existence of a velocity pole [12].

The system (1) - (13) is supplemented by two closing equations:

- equation of an alternative condition for ceasing combustion

\[
p(1 - \eta) = 0,
\]

(15)
- kinematic condition of steadyness of the process (burning rate at the flame front) relative to the wall of the reactor

\[ u_f = u_s - w_f = 0. \]  

(16)

The boundary conditions of the problem:
(at the inlet to the reactor, the beginning of zone III, at \( z = 0 \))

\[ p = p_0, \quad T = T_0, \quad w_f \sum_j \rho_j = m_{gas}^0, \quad A_j = A_j^0, \quad \rho_s = \rho_s^0, \quad \frac{dT}{dz} = 0. \]  

(17)

(at the outlet from the reactor, at \( z = h \))

\[ p \neq p_0, \quad \eta = 0, \quad \frac{dT}{dz} = 0. \]  

(18)

In addition, at the flame front we have

\[ z = z_f, \quad \frac{dT}{dz} = 0, \quad A_t = A_{O_2} = 0. \]  

(19)

The system of equations (1) - (19) is solved by numerical integration by the Runge-Kutta method by successive iterations. Note that at present there are several alternative physico-chemical models of solid fuel combustion in porous media [13-17].

Fig. 6 shows the results of a numerical simulation of the gasification process in a three-zone gasifier of the GOP-OK type, model (1) - (19).

![Figure 6. Shows the results of numerical simulation of the gasification process](image)

**Conclusions**

1. Principal and detailed schemes of mini-thermal power plants with a nominal electric power of 100 kW on the basis of a gas generator of a dense layer of the inverted process.
2. The design of the gas generator based on gasification technology of the inverted process with three zones of solid fuel combustion with its hardware design is developed. The gas generator is an apparatus of a dense layer of a inverted process with hydraulic control, operating with steam-air blowing under pressure from atmospheric to 0.8 MPa.
3. Gas generator of GOP-VKS type is made with the possibility of its use in two additional modes - open and half-open. The latter regime implies a partial removal of hot gases from the CS in a parallel scheme and the utilization of their heat for drying fuel raw materials with the emission of exhaust gases into the atmosphere.
4. A mathematical model and a computer code for numerical modeling of synthesis gas generation processes in a gas generator of a dense layer of an inverted process during a steam-air blow have been developed.

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