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DETERMINING THE EFFECT OF THE STRUCTURAL AND TECHNOLOGICAL PARAMETERS OF A GAS BLOWER UNIT ON THE AIR FLOW DISTRIBUTION IN A GAS GENERATOR

The object of this study is the structural and technological parameters of the gas blower unit in the gasification chamber of a gas generator. The task to enable uniform distribution of air masses in the gas generator has been solved using the ANSYS Fluent software. The study is based on a simulation of the movement of air flows in the characteristic cross-sections of the gas generator, in particular the cross-section of the gasification chamber at the border of the oxidation and reduction zones. Seven structures of the gas blower unit were analyzed, the effectiveness of which was determined by the coefficient of variation. The most effective was the design whose value of the coefficient of variation is the smallest and equal to 93 %. At the same time, the total area of zones with no movement of air masses, that is, the absence of a gasification process, does not exceed 12 % of the total cross-sectional area of the gas generator. The speed of air masses at the boundary of the oxidation and reduction zones is aligned in the entire cross-section of the chamber and is $V \approx 4.5$ m/s. The average value of the vertical component of the speed of air masses in the cross-section at the inlet to the recovery zone of the gasification chamber is $V \approx 0.6$ m/s. Under such conditions, the production of synthesis gas of high calorific value with the absence of resins, acids, heavy hydrocarbons, and mechanical impurities is ensured. The correspondence of the simulation results with experimental data is confirmed by the coefficient of determination, which amounted to 0.87.

The results reported here could be the basis of a modernized methodology for the study of aerodynamic, heat and mass exchange processes that occur during biomass gasification. This would make it possible to define the rational structural and technological parameters of gas generators and improve the efficiency of the gasification process as a whole

Keywords: gas blower unit, gas generator, gasification chamber, reaction zone, oxidation, reduction, synthesis gas

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1. Introduction

The generation of cheap and affordable energy is one of the urgent tasks of modern civilization [1]. A significant part of energy needs is met by traditional fuels. Since fossil fuel reserves, due to high energy demand, are rapidly declining, renewable energy sources, in particular, plant biomass, are increasingly considered as the energy of the future [2]. This justifies the importance of scientific research into the area of available biomass conversion routes [3–5]. In terms of energy production, the chemical-thermal conversion of biomass, compared with the method of biochemical conversion, is more efficient [6, 7]. The quality of products made by the chemical and thermal conversion of biomass (synthesis gas, pyrolysis liquid, etc.), their environmental and technical indicators depend on the parameters of the technological process, the most significant of which is the temperature in the reaction zone. The temperature, in turn, depends on the selected blow mode [8].

Scientists from different countries have carried out a number of studies on the influence of the blow regime on the qualitative and quantitative characteristics of gasification products [9, 10]. However, the results obtained have significant differences. The reason is the variable characteristics of the input parameters, such as the structural parameters of the gas generator and the gas blower unit; different technological modes of operation of installations; various theories applied to the description of processes, etc. Therefore, the systematization of the knowledge of predecessors and obtaining scientific results on the influence of blow regimes on the efficiency of the biomass gasification process, which are universal for any type of gas generator and type of biomass, are important.

During scientific research to substantiate optimal technological solutions, modern world practice is increasingly using simulation methods [11, 12]. The analysis, based on a properly selected simulation, provides valuable information that complements experimental research, increasing the degree of its reliability. Thus, the application of simulation modeling to the study of the influence of structural and technological parameters of the gas blower unit on the uniform distribution of air flows in the gas generator is of high practical value. This will reduce the number and complexity of experimental studies, significantly reduce the time and investment in design work, perform quantitative and qualitative assessment of aerodynamic, heat and mass exchange processes with high accuracy for engineering operations.

2. Literature review and problem statement

In the design of modern gas generator units operating on plant biomass, the main unresolved issues are the development of a rational blowing regime and effective structures of reaction chambers. The designs of the latter must comply with quite stringent technical, operational, economic, and environmental requirements [13].

Paper [14] reports an experimental study into the influence of the geometrical parameters of the blower assembly on the degree of oxygen saturation of the cross-section of the reaction chamber and the quality of the produced synthesis gas. The aerodynamics of the free jet of air flowing out of the lance have been studied. The influence of axial and radial characteristics of lances, profile, diameter, and coefficient of resistance of lances, air flow rate, air blast speed, hydrostatic pressure on the working process of the gas generator and engine power on synthesis gas from biomass was established.

Numerical experiments have proven that even with a small height of the reaction layer of fuel, with an increase in the speed of air introduced into the fuel layer, the chemical composition of the gas improves. That study is not complete since it describes the movement of air jets in the layers of fuel of different height and granulometric composition. Consequently, the results are reliable only for the gasification of the fuels given in the cited work with the air blow modes corresponding to their physicochemical characteristics. In addition, in that paper, it is not described how the air jets will move in the reactor (empty and with fuel), depending on the design of the gas blower unit and the air supply modes. This would make it possible to identify reactor zones in which, due to the lack of air, the process of gasification of the fuel will not proceed and, accordingly, increase the efficiency of the process as a whole.

The results of a study into the effect of air (100 cm^3 air/min) and steam-air blow (0.41 g of steam/min+100 cm^3 air/min) on the hydrogen content in the synthesis gas produced from olive biomass were reported in [15]. To that end, an experimental gas generator was designed, which operated at atmospheric pressure in the temperature range of 700–900 °C. The ratio of steam to biomass was 1.2:1 by weight. Additionally, the effect of catalysts (dolomite and $ZnCl_2$) on the hydrogen content in gas at a temperature of 800–900 °C was studied. The paper considers the conditions under which chemical equilibrium took place. The influence of temperature and pressure on the state of chemical equilibrium, on the concentration of hydrogen in the gas, the molar composition of the gas and its calorific value have been studied. The highest hydrogen content in the synthesis gas (the molar fraction of H_2 was 0.7 during the time the biomass stays in the reactor for 7 minutes) was obtained at a temperature of 900 °C under the condition of steam-air blow. The use of catalysts reduced the time spent by biomass in the reactor to 5 minutes. The results of the experiments are significant and should be taken into account in further studies of steam-air gasification of other types of biomasses. However, the use of mathematical modeling to describe the motion of blow masses in air and steam-air gasification would make it possible to reconcile the blow parameters with the physicochemical properties of biomass and the design of the gas generator. This would significantly improve the planning of the experiment and reduce investment in research.

The authors of works [16, 17] recommend applying methods of mathematical modeling of hydro-gas-dynamic and physical processes for research. These methods make it possible to study the influence of technological and structural parameters of reaction chambers on the performance characteristics of research objects fully and deeply. The works contain simulation models that reproduce with high accuracy the phenomena that occur in the process of gasification. However, the authors do not substantiate the results of the study and do not assess the degree of influence of these results on the structural efficiency of the designed gas generators in general.

The dependence of the efficiency of the biomass gasification process on the structural and technological parameters of gas generators is tackled in [18, 19]. The study was carried out by numerical modeling by the method of finite elements. Despite the high accuracy of the obtained results, the given models do not contain algorithms that allow the finite element method to describe complex hydro-gas-dynamic, heat and mass exchange processes and flows with a free surface.

Studies into the processes of heat and mass transfer and the distribution of temperature fields in the working areas of the reaction chamber by numerical modeling are reported in works [20, 21]. In the simulation process, a computational grid was used that was not adapted to the shape of the test surface. This disadvantage leads to a significant error when working with models of complex geometry with a significant number of different elements.

Due to the ability to reproduce complex physical, chemical, and thermodynamic processes, ASPEN Plus software (manufacturer AspenTech, USA) is successfully used in scientific practice. With the help of ASPEN Plus, the process of biomass gasification in a fluidized bed [22], the processes of coal gasification [23], and biomass pyrolysis [24] were simulated. ASPEN Plus makes it possible to separately consider the influence of each of the variable factors on the dependent parameter of the process. In addition, variable factors can be combined into blocks and investigate the influence of each of the blocks on the parameter under study. For this purpose, they additionally use the Fortran programming language or the Microsoft Office Excel spreadsheet.

ASPEN Plus software is effectively used in [25, 26], which report a model of steam gasification of biomass that minimizes the free energy of Gibbs in order to obtain optimal process conditions. According to the simulation [25], the maximum concentration of hydrogen in the synthesis gas was 59.3 %, which corresponds to the temperature in the reaction zone of 700 °C and the vapor-to-biomass ratio as 1:1. In [26], based on Gibbs' free energy, a simulation model of the process of steam gasification of biomass using sorbents was developed. The disadvantage of the models in [25, 26] is the insufficient accuracy of calculations. The hydrogen content in the produced synthesis gas obtained by modeling was 16 % higher than the hydrogen content obtained experimentally. In order to reduce the error, the authors proposed to introduce corrective factors in the model. That increased the accuracy of calculations. However, for the cases of biomass gasification with different physicochemical parameters from those studied in works [25, 26], the corrective coefficients need to be refined. As usual, in the case of using unmodified equilibrium models, there is a significant difference between the data obtained by modeling and experimentally. This is explained by the fact that in the process of modeling it is difficult to take into consideration all the conditions that will ensure the thermodynamic equilibrium of the system.

To solve this task, it is proposed to simulate each of the working areas of a gas generator separately (drying zone, dry distillation, oxidation and reduction). Effective are the models of the quasi-stationary state [27], which also allow the use of experimental data to adjust the calculated values. The results from using the quasi-stationary state model have higher accuracy compared to the models from [25, 26].

According to the authors of [28–32], to reproduce complex hydro-gas-dynamic, heat and mass exchange processes, it is better to use the software ANSYS Fluent (developer Ansys, Inc., USA), which provides high accuracy of calculations. Paper [28] describes the process of coal gasification in a 10-kW plasma gas generator. The swirling effect of fuel particles built into the design made it possible to increase their residence time in the reactor. Applying ANSYS Fluent has established the effect of the blowing rate and pressure on the temperature in different sections of the reaction chamber (average value, 1350 K) and the content of combustible components in the gas (18.4 % H_2, and 37.2 % CO). The efficiency of the gas generator for cold gas amounted to 55.3 %.

In works [29, 30], the ANSYS Fluent medium was used to simulate the process of coal gasification in gas generators with circulating fluidized bed operating under pressure. The developed CFD models made it possible to predict with high accuracy the composition of the produced synthesis gas and give an idea of the processes occurring in the installation. The predicted gas composition at the gas generator outlet corresponded to the data obtained experimentally, although the real gas composition at individual points of the reaction chamber differed from the data obtained by simulation. However, the predicted temperature distribution in different sections of the reactor corresponded to experimental data with high accuracy. The addition of CO_2 to blow gases increased the CO content in the produced gas and reduced oxygen needs for the gasification process. The obtained results are suitable both for describing the processes of gasification of coal and wood but they are unsuitable for describing the processes of gasification of agricultural plant raw materials and for the conditions of use of gas generators of a different principle of operation.

Modeling of the processes of gasification of plant raw materials (straw, miscanthus) is given in works [31, 32]. In [31], the design of a gas generator with a downstream is presented, which was installed at a power plant. The use of the ANSYS Fluent environment made it possible to simulate the gasification process of plant biomass depending on the height of the layer and the fractional composition of the raw material. The simulation results substantiated the influence of the height, porosity of the fuel layer (0.5), and oxidant supply speed (5 m/min) on the temperature distribution in the reaction zone of the gas generator and the qualitative composition of the produced gas. The obtained temperature circuits made it possible to explain the phenomenon of stable asymmetric combustion in installations with a downward flow.

To study the process of gasification of miscanthus briquettes [32], a structure of a two-stage gas generator with a downstream was built. To describe the kinetics of chemical processes, chemical reactions, and predict the composition of the produced gas, in addition to the ANSYS Fluent medium, the probability density function was additionally used. This approach has reduced the number of calculations, while increasing their accuracy. The data obtained by modeling had high compliance with the experimental temperature profile inside the reactor, the composition of the gas (CO, H_2, and CH_4) and the lower calorific value. In the case of steam-air and oxygen blowing, accurate values of the concentration of the main gas components in the control points of the active zone of the reaction chamber were obtained by modeling, and an increase in the lower heat of combustion of synthesis gas was predicted. This approach makes it possible to investigate the effect of different types of blowing (oxygen, steam-air, steam-oxygen) on the efficiency of the process of gasification of plant raw materials in gas generators with a moving layer.

In [14–32], the focus is on modeling the temperature in the working area of the gas generator and determining the composition of the synthesis gas produced depending on the raw materials, the design of the gas generator, and the blow modes. However, none of the cited works investigated the conditions for uniform distribution of air flows in the working areas of gas generators in order to avoid zones where gasification processes will not occur in the absence of an oxidizer. It is also necessary to investigate the influence of the blow speed, the design of the gas generator and the blow unit on the quality of air coverage of the working volume of the gas generator. It is the correctly chosen blowing mode that provides the temperature necessary for the gasification process in the working areas of the gas generator and, accordingly, the high content of combustible components in the produced synthesis gas. Thus, despite the difficulty of taking into consideration all the parameters of gas dynamic and heat-mass exchange phenomena that occur in the process of biomass gasification, such research is necessary. And the prospects of using the ANSYS Fluent software environment to model these processes are obvious.

3. The aim and objectives of the study

The purpose of this work is to establish the influence of the structural and technological parameters of the gas blower unit in a gas generator on the movement of air jets in the working volume of the gas generator and the uniformity of overlapping by jets the chamber cross-section at the boundaries of the oxidation and reduction zones. This will make it possible to increase the efficiency of the synthesis gas production process from biomass.

To achieve the set aim, the following tasks have been solved:

– to identify by simulation patterns of the process of movement of air flows in the working volume of the gas generator;

– to experimentally investigate the influence of the diameter, quantity, and technique for arranging air holes in the gasification chamber on the change in the speed of air jets in the working volume of the gas generator.

4. The study materials and methods

The object of this study is the structural and technological parameters of the gas blower unit in a gasification chamber of the gas generator.

The subject of our study is the relationship between the structural and technological parameters of the gas blower unit and the uniformity of air flow overlapping the cross-section of the gasification chamber at the boundary of the oxidation and reduction zones.

The main hypothesis of this study assumes that there is a structure of the gas blower unit for a gas generator, which, with the selected volumetric flow rate and air speed, will ensure the uniformity of overlapping by air flows of the cross-section of the chamber at the boundary of the oxidation and reduction zones.

Simulation modeling of the process of filling the working volume of the gas generator with air jets is performed in the ANSYS Fluent (ANSYS, Inc., USA) programming environment.

For modeling, the gas generator is shown in a simplified form. The scheme of the gas generator is given in Fig. 3–9. The cross-sectional area of the gas generator was 0.037 m^2. For all cases considered, the volumetric air flow rate was 0.016 m^3/s, the air flow rate was 0.019 kg/s, the weighted average value of the speed V was 0.42959 m/s.

The assumptions accepted in the study are:

– the holes of the gasification chamber are made in such a way that air is supplied directly to the oxidation zone;

– air jets are endowed with the properties of a free jet.

Using ANSYS Fluent, we modeled (Fig. 3–9):

– the movement of air jets in the vertical cross-section of the gas generator;

– the movement of air jets in a cross-section, which passes through the central air hole, ∅10 mm, of the gasification chamber (oxidation zone);

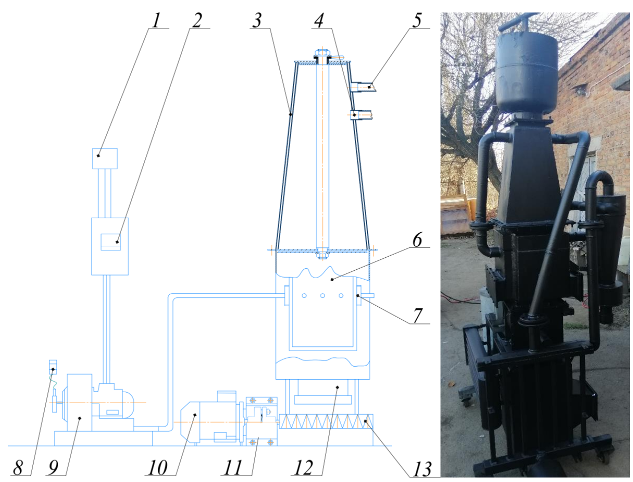
– the movement of air jets in the vertical direction at the inlet to the recovery zone of the gasification chamber.

The uniformity of air supply in the cross-section of the gasification chamber at the boundary of the oxidation and reduction zones was determined by the coefficient of variation (the ratio of the standard deviation to the average value of the speed).

Seven structural variants of the gas blower unit of the gas generator have been adopted (Fig. 3–9).

In order to conduct laboratory research, the Department of Tractors, Automobiles, and Bioenergy Resources at the National University of Life and Environmental Sciences of Ukraine together with Polissia National University designed a laboratory gas generator set (Fig. 1). Technical drawings of the installation are made in a CAD system, namely in the software package of three-dimensional solid-state modeling COMPASS-3D v20.

The main units of the laboratory installation (Fig. 1) are pyrolysis chamber 3 and the gas generator of the reverse gasification process 6. For the removal of pyrolysis and generator gases, appropriate pipelines 4 and 5 are provided. Under the condition of operation of the gas generator on fuel, ash accumulates in ash collector 12. The removal of ash from the ash tank is carried out by conveyor 13, which was driven by engine 10 through coupling 11. The fuel hopper was dismantled since it was assumed that the gas generator must be empty to conduct the study. Air was supplied to the gas generator through gas-blower unit 7 by blower 9, which was connected to the source of electricity 1 through frequency converter 2. The speed of air supplied to the gas blower unit was measured by anemometer 8. The speed and volumetric air flow corresponded to the values adopted during the simulation.



a *b*

Fig. 1. Laboratory installation:
a – schematic image; *b* – general view: 1 – electricity source 0.4 kV, 2 – frequency converter, 3 – pyrolysis chamber, 4 – pyrolysis gas pipeline, 5 – generator gas pipeline, 6 – gas generator of the reverse gasification process; 7 – gas blower unit; 8 – anemometer; 9 – blower; 10 – electric motor; 11 – coupling; 12 – gas generator ash pan; 13 – ash conveyor

For experimental studies, the gas blower unit was manufactured in a structural version shown in Fig. 8. The variant of Fig. 9, although it has a lower value of the coefficient of variation, however, in order to indicate the reliability of the results obtained when using lances, it is necessary to establish their structural and technological parameters, axial, radial characteristics, and the coefficient of contraction. The gasification chamber was made of steel 20X25H20C2.

To measure the speeds of movement of air jets in the working area of the gas generator, the anemometer Testo 425 with a telescopic probe (Testo SE & Co. KGaA, Germany) was used. The scheme for measuring the speed of air movement in the gas generator with an anemometer is shown in Fig. 2.

The main unit of gas generator 2 is the gasification chamber (GC), which contains oxidation zone 4 and reduction zone 6, separated by conditional limit 5. Air 3 in GC was fed through gas blower unit 8. To measure the speed of air movement in the characteristic planes of gas generator 2, the anemometer Testo 425 was used, whose sensor 9 was inserted into the GC through pipe 10. Pipe 10, through transition bushing 11, was attached to cover 1 of the gas generator with screws. Measurement data were displayed on monitor 12 of the anemometer. To position the sensor at a given point on the plane where measurements were performed, a plate (Fig. 2, *b*) was used, on the end of which a rubber ring was put on for reliable fixation in the gas generator.

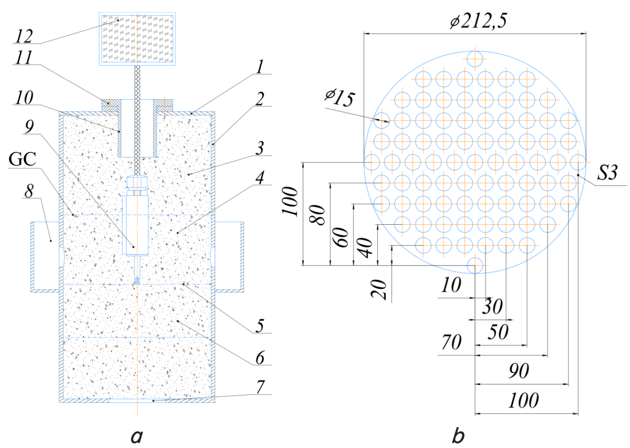


Fig. 2. Scheme for measuring the speed of air flows at the boundary of the oxidation zone and reduction zone in a gasification chamber: *a* – scheme for installing the anemometer Testo 425; *b* – plate for positioning the anemometer in the gas generator, GC – gasification chamber, 1 – gas generator cover, 2 – gas generator; 3 – air; 4 – oxidation zone of the gasification chamber; 5 – conditional boundary of oxidation and reduction zones; 6 – reduction zone of the gasification chamber; 7 – gas and ash weaning hatch, 8 – gas blower unit; 9 – Testo 425 anemometer sensor; 10 – steel pipe; 11 – bushing; 14 – anemometer monitor

The air velocity was measured in the horizontal cross-section that passes through the central air hole ∅10 mm in the gasification chamber (oxidation zone 4) and in the cross-section at the inlet to reduction zone 6 of the gasification chamber.

To compare the results of simulation modeling and experimental research, the procedure from [33] was applied. The hypothesis of the adequacy of the model to the object under study was tested by the coefficient of determination.

5. Results of studying the uniformity of filling the working volume of the gas generator with air jets

5. 1. Simulation results of the process of air flow movement in the working volume of the gas generator

Modeling of the movement of air jets in the gas generator was performed for seven variants of the design of the gas blower unit of the gas generator (Fig. 3–9). In the structure, we changed the number of blow holes and the technique of their placement on the surface of the gasification chamber:

1) holes ∅23.12 mm cut into one row (Fig. 3);

2) holes with diameters ∅7.97 mm, ∅9 mm, ∅10 mm, ∅11 mm, and ∅13 mm are arranged in five rows (Fig. 4);

3) holes with diameters ∅7.97 mm, ∅9 mm, ∅10 mm, ∅11 mm, and ∅13 mm are arranged in five rows with an offset of 45° (Fig. 5);

4) the holes (∅9.97 mm and ∅11 mm) and (∅13 mm and ∅15 mm) are arranged in pairs in four rows at an angle of 45° to the radius of the chamber with an offset of 45°. The holes of the fifth (middle) row ∅12 mm are cut radially (Fig. 6);

5) two holes with diameters ∅9.97 mm, ∅11 mm, ∅13 mm; and ∅15 mm are arranged in four rows at an angle of 45° to the radius of the chamber in opposite directions and shifted in pairs by 45°. The holes of the fifth (middle) row ∅12 mm are cut radially (Fig. 7);

6) the holes with diameters ∅7.97 mm, ∅9 mm, ∅10 mm, ∅11 mm; and ∅13 mm are arranged in five rows at an angle of 45° to a radius with an offset of 90° (Fig. 8);

7) the holes with diameters ∅7.97 mm, ∅9 mm, ∅10 mm, ∅11 mm, and ∅13 mm are cut into five rows at an angle of 45° to a radius with an offset of 90° (Fig. 9). Lances are installed in the holes in order to direct the air flow in a given direction.

According to [1, 8, 13, 14], a properly organized gas-blow regime has a primary impact on the gasification process. It makes it possible to ensure high temperature conditions of the gasification process and, as a result, high quality composition and calorific value of the produced gas. According to studies [14], the linear velocities of gas masses during gasification in the chambers of a straight cylindrical shape are almost the same in height of the chamber. Consequently, the factor of air flow rate, especially at the time of its contact with the fuel surface, depends on the diameter of the chamber selected, which they try to reduce to improve gasification conditions. The presence of blow holes with a constant diameter and height of the chamber provides a high speed of air flow. And their radial arrangement is possible even in several rows to ensure uniform overlap by air flows of the most important cross-section on the border of the oxidation and reduction zones.

In accordance with the purpose and objectives of the study, to eliminate the influence of the diameter of the gasification chamber, the speed, and volumetric air flow on the distribution of air flows in the gas generator, these parameters were stable. The influence of only the structural and technological parameters of the gas blower unit on the movement of air jets in the working volume of the gas generator and the uniformity of overlapping by air flows of the cross-section of the gasification chamber at the boundary of the oxidation and reduction zones were investigated. The simulation results are shown in Fig. 3–9. The effectiveness of the design of the gas blower unit was estimated by the coefficient of variation (Fig. 10).

The lowest uniformity of distribution of air flows in the gas generator is inherent in the design of unit No. 1 (Fig. 3), the coefficient of variation of which was 258 %.

Fig. 3 demonstrates that air masses with the highest speed (V=15.29 m/s) are concentrated in close proximity to the air holes.

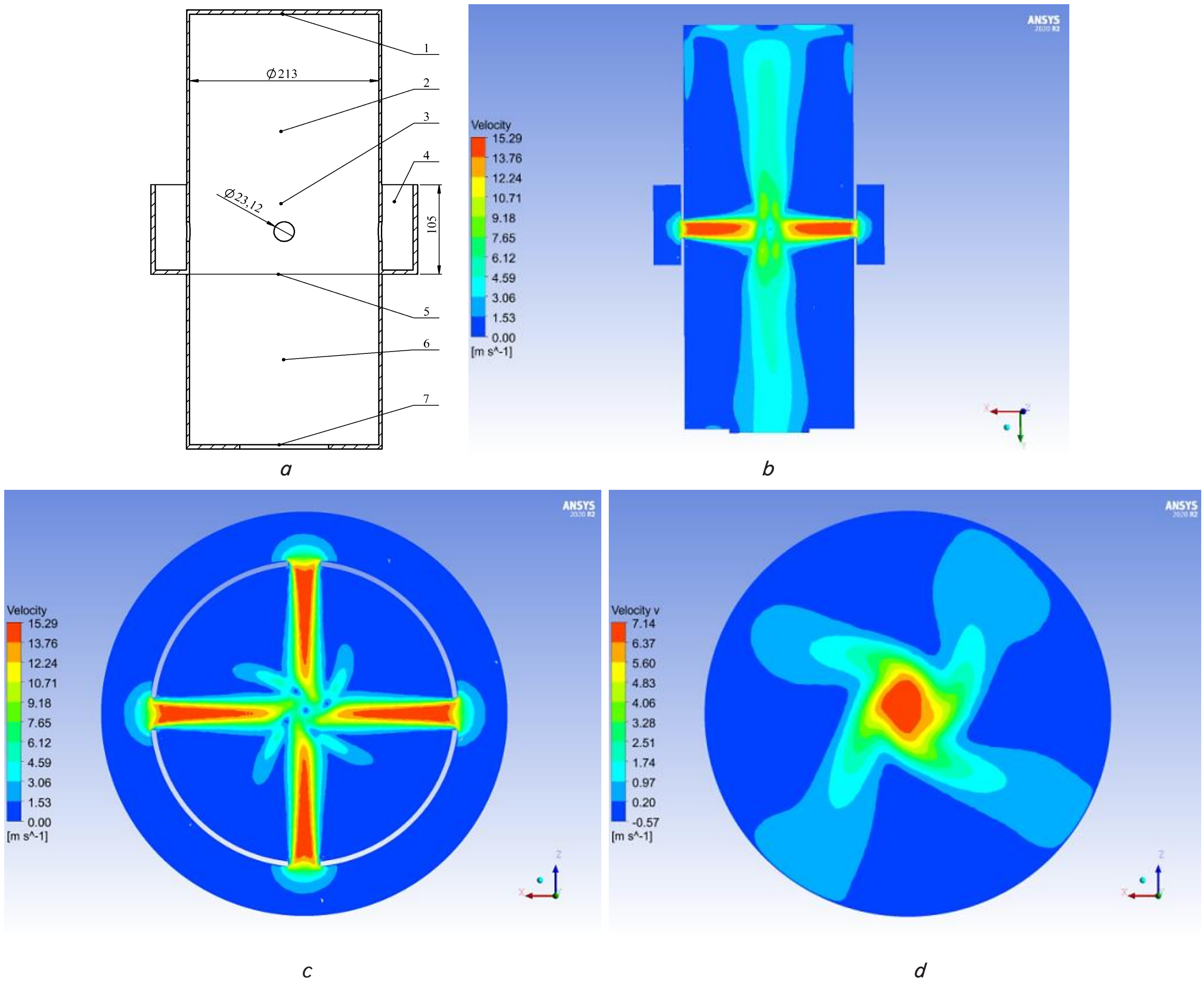


Fig. 3. Simulation results of air flow distribution in a gas generator equipped with a gas blower unit of design No. 1: *a* – gas generator; *b* – vertical cross-section of the gas generator; *c* – horizontal cross-section that passes through the central opening of the oxidation zone of the gasification chamber; *g* – cross-section at the inlet to the reduction zone of the gasification chamber

At the boundary of the oxidation and reduction zones of the gasification chamber, the vertical component of the air velocity (Fig. 3, *d*) is the highest in the center of the chamber (V=7.17 m/s), gradually falling in the direction of the gas generator housing. With such a design of a gas blower unit, active fuel combustion will occur directly in front of the fuel holes, at some, small distance from them, where almost all the oxygen in the air and the majority of the fuel are consumed. This zone in the transverse direction is limited by the contour of the air jet that leaves the mouth of the hole, creating a vertical air channel concentrated in the central part of the gas generator with an average air mass velocity of V=6.7 m/s. The movement of air masses along the height of the gas generator will provide the double passage of the produced synthesis gas through the zone of high temperatures in the oxidation and reduction zones. This will rid the gas of harmful mechanical impurities, resins, acids, and heavy hydrocarbons.

In addition, the structure of gas blower unit No. 1 is characterized by the presence of zones of considerable area and length in which the air velocity is V=0 m/s (Fig. 3, *b, d*). Filling the gas generator with fuel can help increase the size of these zones. During the operation of the gas generator, hot, unreacted fuel with oxygen is concentrated in these zones, which hangs and, under conditions of low ash melting temperature (for example, straw pellets), turns into ash-slag agglomerates. In general, over time, this phenomenon will lead to a gradual increase in pressure in the system and, as a result, to a complete stop of the gas generator.

In addition, our simulation has made it possible to investigate the aerodynamics of the free jet of air that came out of the blow hole. According to [14], a free jet is a gas flow that moves in an environment of the same physical properties as the substance of a jet. In a gas generator, even an empty one, there can be no free jet in the strict sense of this concept. The airflow that comes out of the blow hole meets, on the way, an oncoming stream of air, the walls of the chamber or gas generator, and in the case of a working gas generator, pieces of fuel. However, in order to obtain a rough understanding of the limits of the air jet that cover any zone of the gas generator, depending on the size and location of the blow hole, one should refer by analogy to the properties of the free jet. In this case, it is possible to transfer the results obtained from an empty gas generator to a filled one with fuel, since in the gas-blowing belt of the gas generator the gaps formed by pieces of fuel are quite large.

The designs of draft blower assemblies No. 2 to No. 4, which were considered, are shown, respectively, in Fig. 4–6. The structures of these units have similar values of variation coefficients, which are 215 %, 219 %, and 207 %, respectively. The difference is only in the different length of vertical air channels along the height of the gas generator and the overlap patterns of the air jets of the cross-section of the gasification chamber at the boundary of the oxidation and reduction zones. That is, a separate jet is characterized by a change in speed along the axis and at an angle of deviation at the same distance from the mouth of the blow hole.

The installation of five rows of holes reduced the size of the zones with air velocity V=0 m/s, which in practice will improve the conditions of the gasification process. The highest speed of air masses, as in option No. 1, is observed at the mouth of the air holes. Depending on the structure of the assembly, it varies in the range from $V \approx 14.5$ m/s (designs of units No. 2 and No. 3) to $V \approx 9.74$ m/s (design of unit No. 4). The vertical component of the speed of air masses at the inlet to the reduction zone of the gasification chamber is also the highest in the center of the chamber. However, for structures of units No. 2–4 (Fig. 3–5, *d*), compared to design No. 1 (Fig. 3, *d*), it has almost halved (node No. 2 – V=3.96 m/s; node No. 3 – V=4.38 m/s; node No. 4 – V=3.98 m/s).

In Fig. 4, *c*, we observed the phenomenon of the imposition of individual jets of air that come out of neighboring lances located vertically, one on the other, merging at the same time into a common airflow. In the central part of the chamber, oncoming air flows during a collision exert mutual resistance to further advancement to each other, mixing, changing the further trajectory of movement. The nature of the movement of air masses becomes laminar-turbulent. The speed of movement of air masses in the vertical section of the gas generator decreases (V=1.45 m/s, Fig. 4, *b* compared to V=4.59 m/s in Fig. 3, *b*). The length of the air channel along the height of the gas generator also decreases.

The location of the blow holes in pairs with an offset of 45° relative to one another (Fig. 5, 6) increased the turbulence of air flow and increased the level of turbulence. In this case, greater longitudinal velocities characterize the air masses that are directed from the central part of the chamber to the periphery, unlike those that have the opposite direction. This is explained by the fact that the average local flow rate is always higher in its central part.

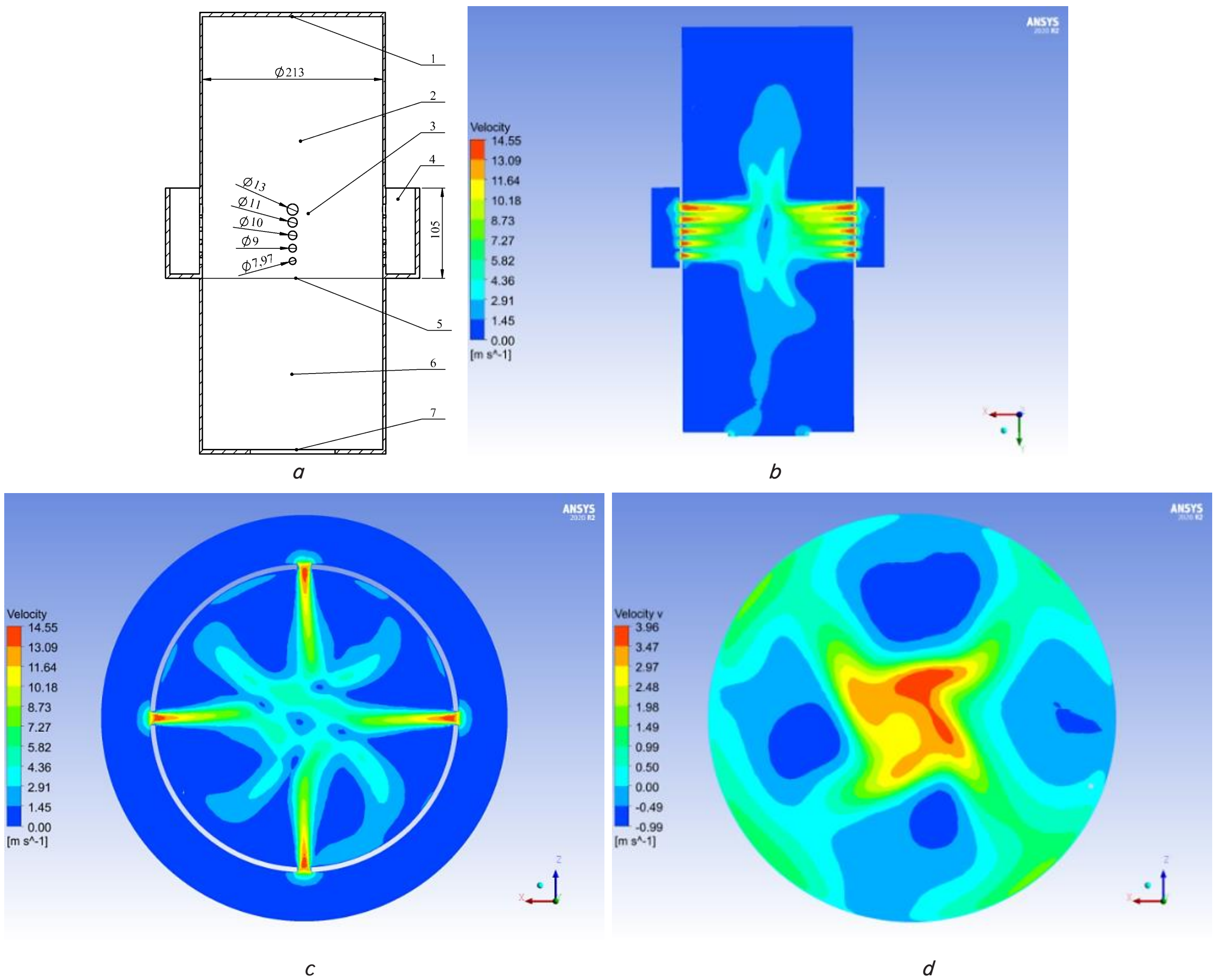


Fig. 4. Simulation results of airflow distribution in a gas generator equipped with a gas blower unit of design No. 2: *a* – gas generator; *b* – vertical cross-section of the gas generator; *c* – horizontal cross-section that passes through the central opening of the oxidation zone of the gasification chamber; *d* – cross-section at the inlet to the reduction zone of the gasification chamber

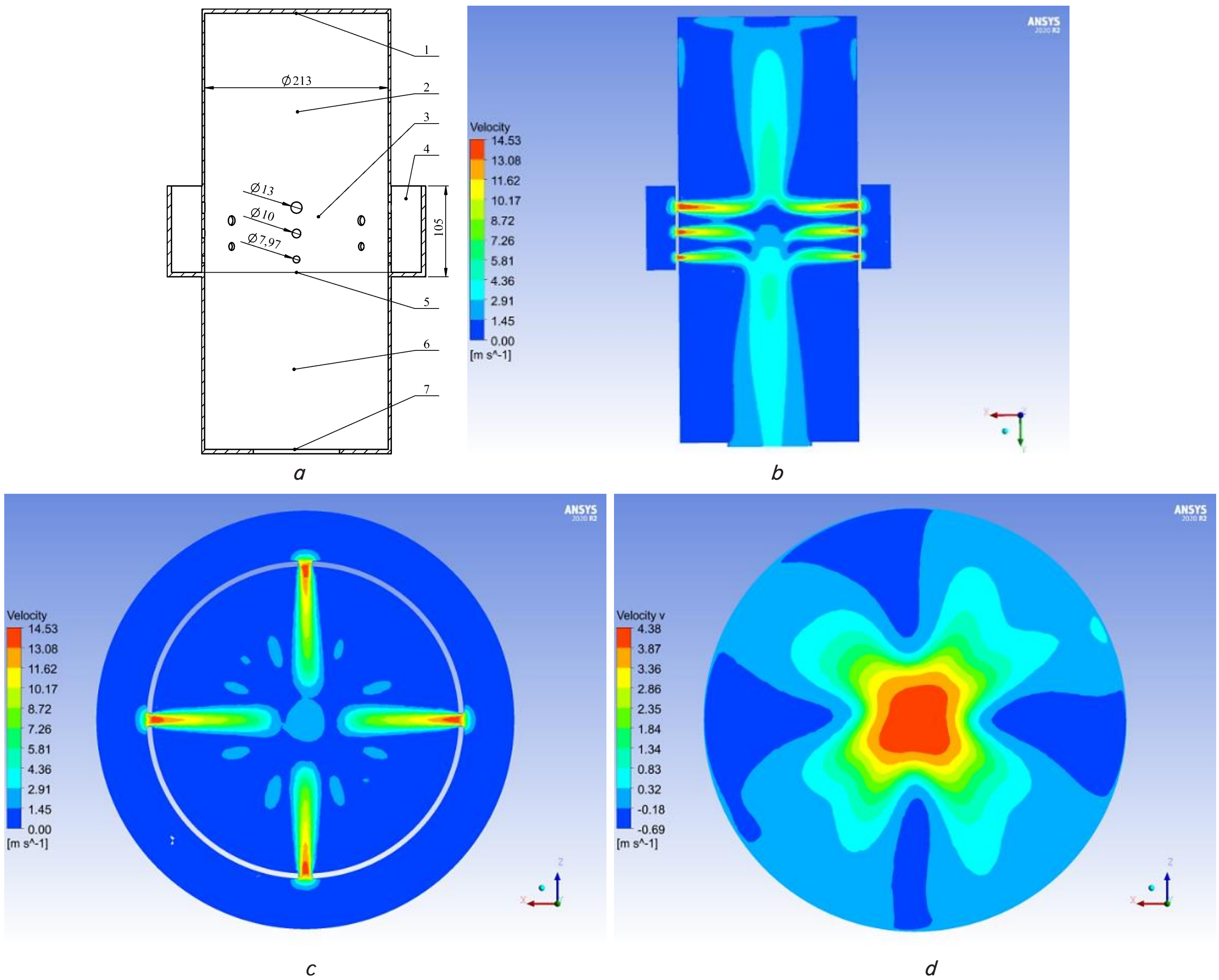


Fig. 5. Simulation results of airflow distribution in a gas generator equipped with a gas blower unit of design No. 3: *a* – gas generator; *b* – vertical cross-section of the gas generator; *c* – horizontal cross-section that passes through the central opening of the oxidation zone of the gasification chamber; *d* – cross-section at the inlet to the reduction zone of the gasification chamber

Subject to the entry into the environment of higher averaged speeds of air masses with lower speeds, the process of braking the movement of air flows in this environment takes place. The exchange of air masses in the transverse direction leads to the exchange of the amount of movement in the stream.

The turbulent nature of the flow contributed to a more uniform distribution of air flows in the cross-section of the chamber at the boundary of the oxidation and reduction zones (Fig. 6, *d*), as well as an increase in the area of the chamber itself, which is covered with jets.

In the peripheral zone of the chamber near the walls, there is no air movement, and the length of the flow along the height of the gas generator has also decreased. Such distribution of air masses during the operation of the gas generator on biomass will contribute to the completeness of the oxidation and reduction processes. However, the absence of air movement from the center of the chamber to the cover of the gas generator (according to the height of the gas generator) will indicate a low quality of the gas produced. The gas, without passing the pyrolysis and drying zone, will contain a high percentage of mechanical impurities, resins, complex hydrocarbons, and acids.

Design No. 5 (Fig. 7), when compared to previous versions of draft blower assemblies, has a higher efficiency (according to Fig. 10, the coefficient of variation is 184 %).

The location of the blow holes implemented in the chamber enabled a uniform distribution of air masses not only in the cross-section at the boundary of the oxidation and reduction zones but also in the vertical direction along the height of the gas generator. The dimensions of the air channel in terms of the height of the gas generator have increased significantly (compared to designs No. 1–4). The number of zones with no air movement is very small. The periphery of the chamber is dominated by zones, albeit with low-intensity but sufficient for the process of gasification [14] movement of air masses. The value of the vertical component of the speed of air masses in the center of the chamber (V=3.62 m/s) also increased.

Shown in Fig. 7, the structure of the blow unit of the gas generator is satisfactory for the implementation of the blowing mode necessary for the synthesis gas production process. The produced gas will not contain harmful impurities but will have a low calorific value.

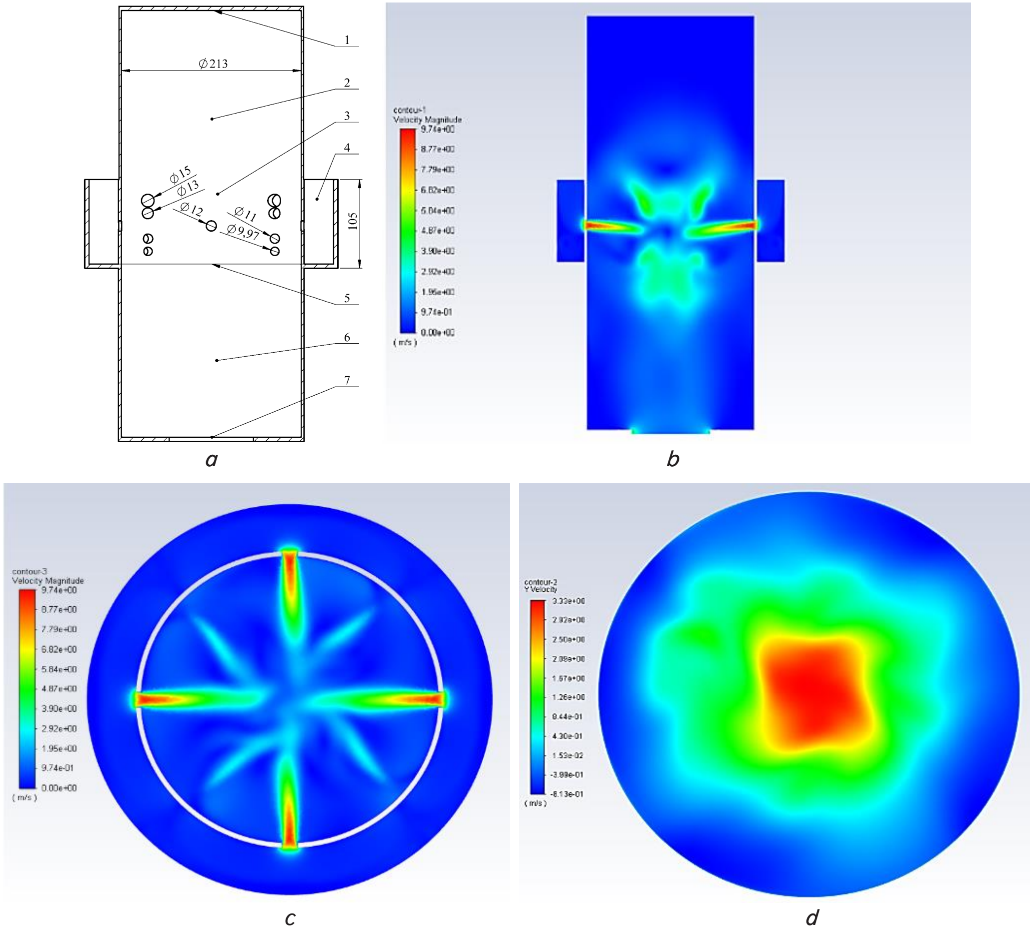


Fig. 6. Simulation results of airflow distribution in a gas generator equipped with a gas blower unit of design No. 4: *a* — gas generator; *b* — vertical cross-section of the gas generator; *c* — horizontal cross-section that passes through the central opening of the oxidation zone of the gasification chamber; *d* — cross-section at the inlet to the reduction zone of the gasification chamber

The best, for reasons of ensuring uniform overlap by air flows of the cross-section of the chamber at the boundary of the zones of oxidation and reduction and filling of the volume of the gas generator, are the structures of units No. 6 (Fig. 8) and No. 7 (Fig. 9). The coefficients of variation (Fig. 10) for these node structures were 93 % and 90 %, respectively.

For both variants of draft blower assemblies, there are only insignificant areas (only up to 12 % of the total cross-sectional area of the gas generator) of zones with no movement of air masses. In Fig. 8, *c* (node No. 6), these are the zones in the center of the chamber and near the wall of the chamber between the blow holes, in Fig. 9, *c* – in the center of the chamber. The speed of air masses on the border of the oxidation and reduction zones of the chamber is aligned throughout the cross-section and is $V \approx 4.5$ m/s (Fig. 8, 9, *c*).

The average value of the vertical component of the speed of air masses in the cross-section at the inlet to the reduction zone of the gasification chamber is $V \approx 0.6$ m/s for node No. 6 (Fig. 8, *d*) and $V \approx 0.5$ m/s for node No. 7 (Fig. 9, *d*).

Equipping the gas blower unit of the gas generator with lances (Fig. 9) did not significantly affect the quality indicators of the distribution of air flows in the gas generator. Only the nature of the distribution has changed. The authors of [1, 13, 14] note that the speed of the jet of air coming out of the lance is influenced by the geometric dimensions of the lance, the profile, its axial and radial characteristics, the compression coefficient of the jet, etc.

According to [14], near the mouth of the lance in a small area, the speed is maintained constant. This area is called the initial. The stability of the speed is explained, in this case, by the fact that the central part of the jet does not perceive the inhibitory effects of the environment in the specified area. The width of the cross-section of constant speeds at the mouth of the lance is equal to the diameter of the lance hole. According to the degree of distance from the mouth, this cross-section gradually evenly narrows to zero at the end of the initial cross-section. The width of the entire jet, on the contrary, is continuously expanding, starting from the mouth of the lance. This expansion takes place because the jet gradually captures previously fixed particles of the environment. Thus, according to the degree of distance from the mouth of the lance, the mass of moving air continuously increases, and the speed drops. In practice, a sharp decrease in the speed of the central particles of the jet occurs immediately after the initial cross-section. The intensity of this decrease gradually decreases, and the speed asymptotically tends to zero. In accordance with the above, Fig. 9, *c*, *d* clearly demonstrates a zone of high speeds ($V \approx 8.8$ m/s) near the mouth of the lance in the initial cross-section. From the end of the initial cross-section to the center of the chamber, there extends the zone of leveled speed $V \approx 2.93$ m/s, which covers almost 70 % of the total cross-section of the chamber at the boundary of the oxidation and reduction zones.

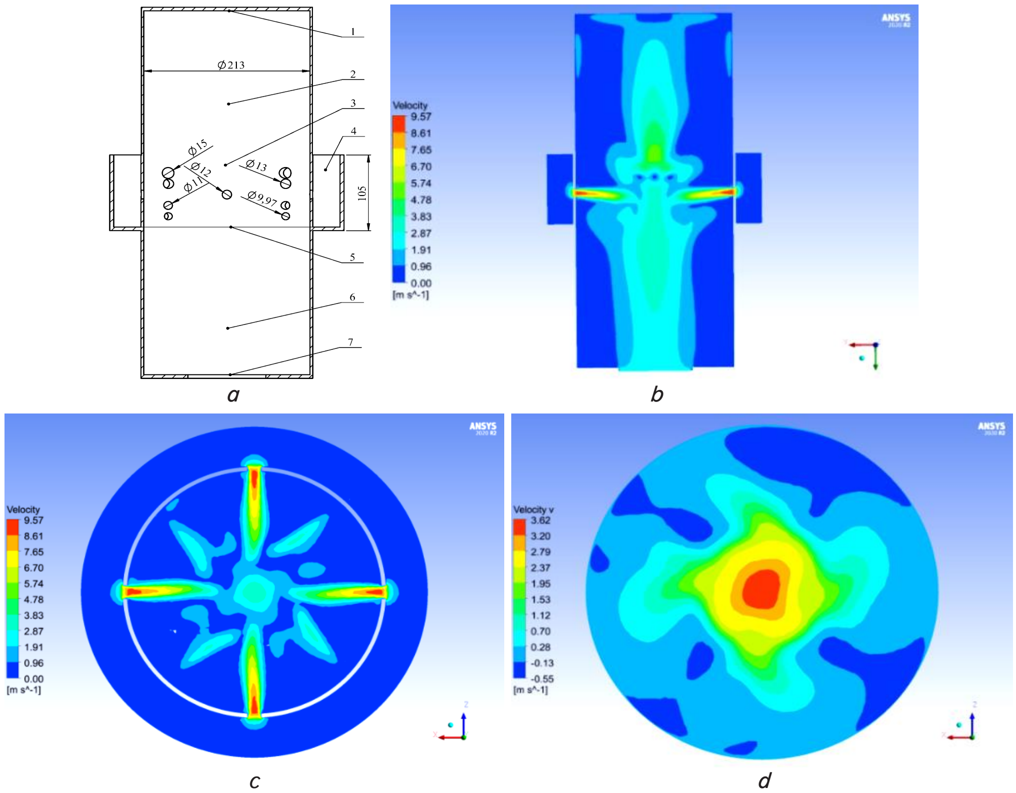


Fig. 7. Simulation results of airflow distribution in a gas generator equipped with a gas blower unit of design No. 5: *a* – gas generator; *b* – vertical cross-section of the gas generator; *c* – horizontal cross-section that passes through the central opening of the oxidation zone of the gasification chamber; *d* – cross-section at the inlet to the reduction zone of the gasification chamber

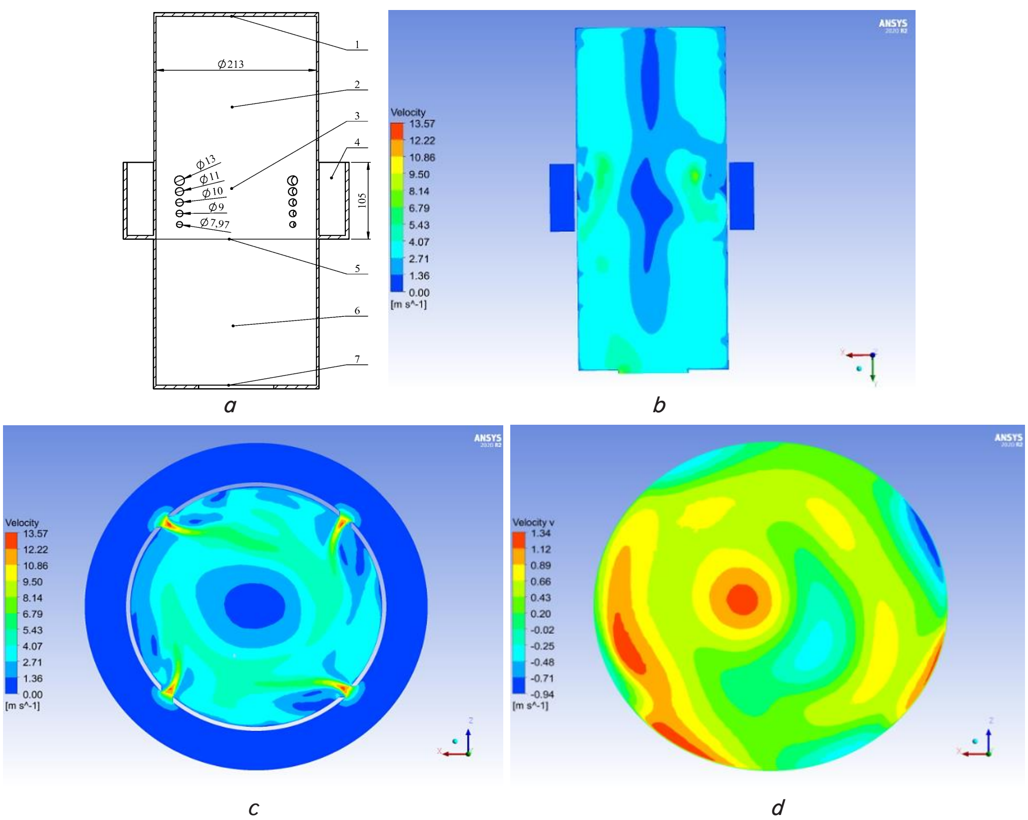


Fig. 8. Simulation results of airflow distribution in a gas generator equipped with a gas blower unit of design No. 6: *a* – gas generator; *b* – vertical cross-section of the gas generator; *c* – horizontal cross-section that passes through the central opening of the oxidation zone of the gasification chamber; *d* – cross-section at the inlet to the reduction zone of the gasification chamber

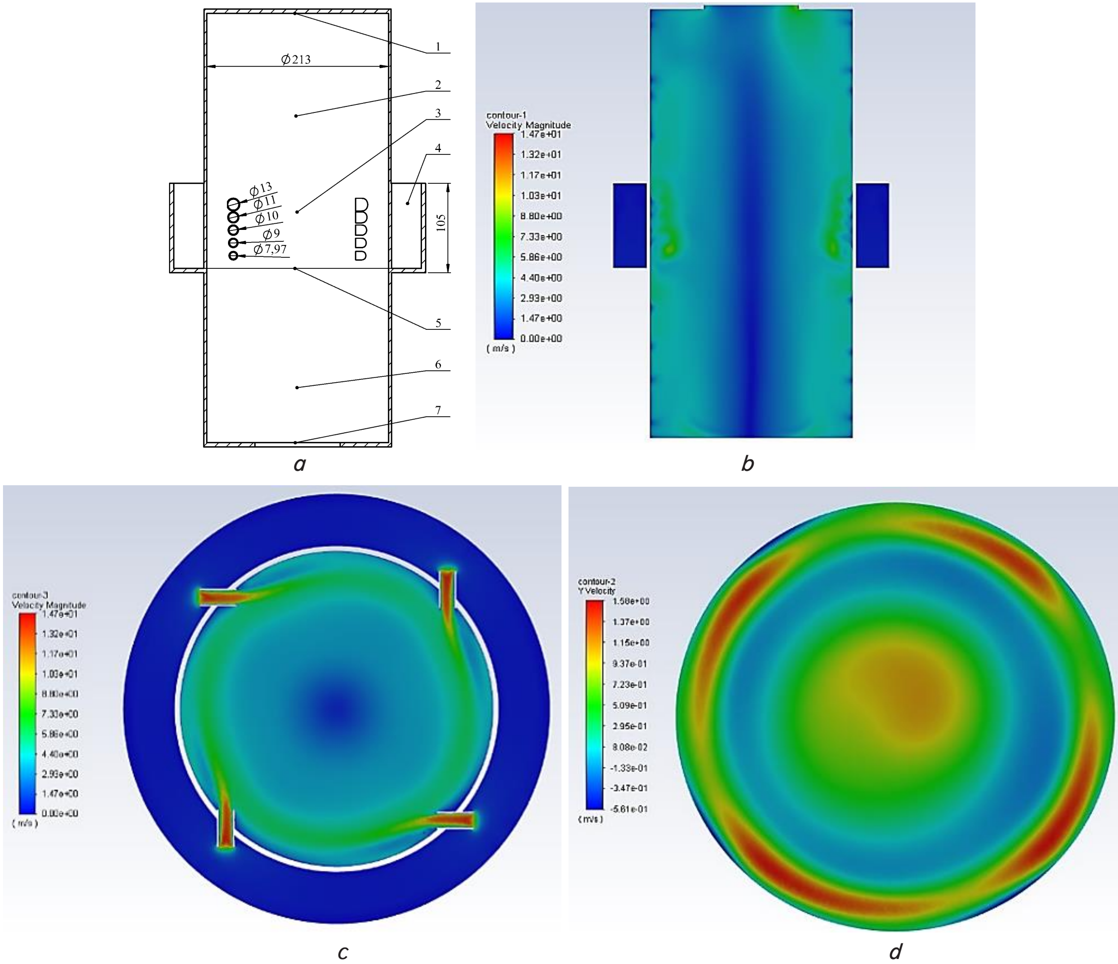


Fig. 9. Simulation results of airflow distribution in a gas generator equipped with a gas blower unit of design No. 7: *a* – gas generator; *b* – vertical cross-section of the gas generator; *c* – horizontal cross-section that passes through the central opening of the oxidation zone of the gasification chamber; *d* – cross-section at the inlet to the reduction zone of the gasification chamber

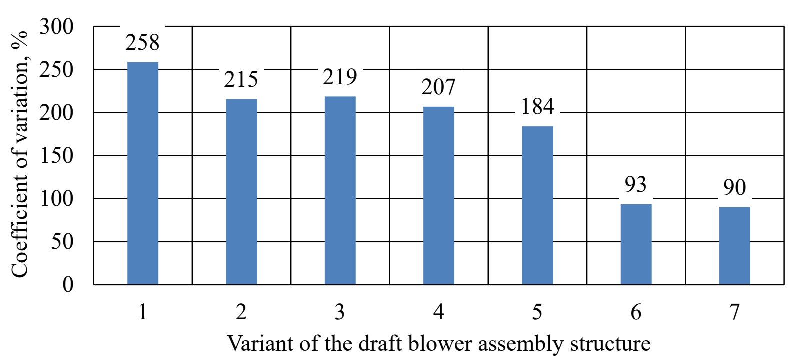


Fig. 10. Dependence of the coefficient of variation on the number of the draft blower assembly structure of the gas generator

The use of structures of draft blower assemblies No. 6 and No. 7 provides such a distribution of air flows, in which there will be a complete conversion of biomass into combustible gas. The produced synthesis gas will contain a high percentage of combustible components (CO and H_2), low content of mechanical impurities and complex hydrocarbons. However, there may be a phenomenon of incomplete burnout of resins in the composition of biomass. A zone with no air movement in the center of the chamber may be the reason for the low temperature in this part of the gas generator. However, in order to state this for sure, appropriate simulations should be carried out on a gas generator filled with fuel (pellets).

5. 2. Results of measuring the speed of air flow in the characteristic planes of the gas generator

Experimental studies were performed for the gas blower unit of design No. 6 (Fig. 8). The speed of movement of air jets in the cross-section, which passes through the boundary of the oxidation and reduction zones, was measured.

According to the results of our study, a graphic dependence of the speed of movement of air masses in the gasification chamber on the border of the oxidation and reduction zones (cross-section at the inlet to the reduction zone) was constructed; Fig. 11. To process the measurement results and build the dependence in Fig. 11, we applied the software Statistica 10 (StatSoft, USA).

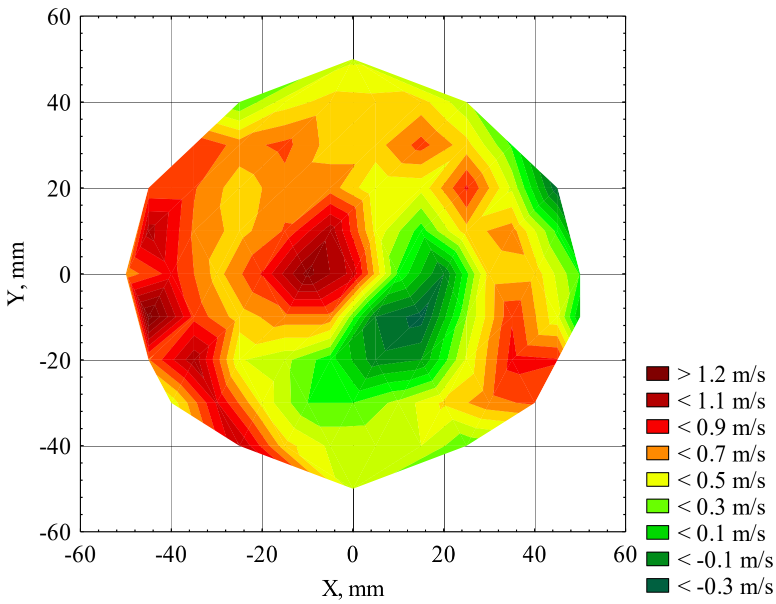


Fig. 11. Distribution of the speeds of movement of air masses in the gasification chamber at the boundary of the oxidation and reduction zones by coordinates from the center of the chamber to the location of the blow holes

Compliance of the simulation results (Fig. 8, *d*) with the results of the experimental study was checked by the coefficient of determination, which was $R^2=0.87$.

Analysis of Fig. 11 indicates some deviation of the data obtained experimentally from the simulation data. This is explained by the fact that both the plate (Fig. 2, *b*) and the telescopic probe and sensor with the Testo 425 anemometer during the experimental measurement were an obstacle to the propagation of air flows. Air jets, facing an obstacle, not only change the trajectory of movement but also the speed of their movement decreases. One should also take into account the measurement error of the device, its installation, the accuracy of the positioning of the plate, etc. Therefore, the schemes of overlap with air flows of the investigated section of the chamber (Fig. 8, *d*, 11) are different. However, this difference is negligible.

6. Discussion of results of studying the uniformity of filling the working area of the gas generator with air jets

The air blow mode, especially the speed of air when leaving the blow holes and the uniform distribution of air flows in the gas generator, are undoubtedly factors of paramount importance. It is these factors that actively influence the course of the entire gas-generating process.

By modeling, the influence of structural and technological parameters of the gas blower unit on the movement of air jets in the working volume of the gas generator was investigated (Fig. 3–9). In particular, special attention was paid to the uniformity of the overlapping by air jets of the cross-section of the gasification chamber at the boundaries of the oxidation and reduction zones (Fig. 3, 9, *d*). Among all the structures of the gas blower unit, the most effective are designs No. 6 and No. 7, which is also evidenced by the inherent lowest values of the coefficients of variation (Fig. 10). As noted, the equipment of the gas blower unit of the gas generator with lances (Fig. 9) did not significantly affect the qualitative indicators of the distribution of air flows in the gas generator. However, the conclusions on the efficiency of the structure of unit No. 7 (Fig. 9) without additional research are not reliable. It is imperative to study the influence of the geometric dimensions of the lances, profile, axial and radial characteristics on the jet compression ratio. Their speed characteristics and nature of distribution in the working volume of the gas generator depend on the degree of compression of the air jets.

Thus, among the structures of units No. 1–6, the most effective is the design of node No. 6. The above is justified by the highest uniformity of distribution of air flows at the boundary of the oxidation and reduction zones of the gasification chamber in the gas generator (Fig. 8, *d*). In this case, there are only small areas with no movement of air masses (up to 12 %).

In accordance with the task of our study, the simulation results were confirmed experimentally. Some deviations of the modeling data (Fig. 8, *d*) from the experimental ones (Fig. 11) are explained by the influence of obstacles (plate, anemometer) on the path of airflow propagation. Given this, the trajectory of the jets and the speed of their movement are somewhat different.

The use of modern modeling methods, in contrast to the procedures reported in [13, 14, 18, 19, 22, 23], has made it possible to consider the aerodynamics of the movement of air flows with high accuracy for engineering practice.

In particular, in contrast to the results discussed in [13, 14], the use of ANSYS Fluent made it possible to obtain more accurate results in studying the influence of the parameters of the gas blower unit on the efficiency of the gasification process. The author of [14], for the analytical description of aerodynamic processes that occurred during the movement of air flows in the gasification chamber, and due to the lack of proper technical means, introduced a number of empirical coefficients. Specifically, coefficients of speed, contraction, outflow, and resistance were introduced, which depend on the profile of the output nozzle, hydrostatic pressure, and speed mode of blowing. That had a significant impact on the accuracy of the results since the ranges of values of empirical coefficients were limited by a number of factors inherent in a certain design and type of gas generator, gas blower unit, biomass characteristics, etc. Studies [14] are complemented by the results reported in work [13].

The author of [13] studied the influence of air blow speed and hydraulic resistance of lances on the calorific value of gas, engine power under the predefined mode, adaptability of the engine to a sudden increase in gas consumption, flexibility of the gasification process. The research concerned the operation of gas generators on several types of biomass with different physicochemical properties and fractional composition.

Although the authors of [13, 14] performed a significant amount of work, nevertheless, in each of these cases, the influence of the air blow mode on the efficiency of the installation was studied on a gas generator filled with fuel. Therefore, the results of the study are generalized and reliable only for certain designs of gas generators operating on biomass with similar physical and technical properties. In addition, a disadvantage is the significant value of the error between the results of analytical and experimental studies, which is explained by the inability, at that time, to conduct a qualitative and quantitative assessment of physical phenomena with proper accuracy.

Owing to the use of ANSYS Fluent, an image of air jet overlapping was obtained of the most important, from the point of view of the gasification process, cross-section of the gasification chamber at the boundary of the oxidation and reduction zones. The conditions under which the distribution of air masses in the characteristic cross-sections of the gas generator will be as uniform as possible have been identified (Fig. 8). This will ensure high temperature conditions in the oxidation and reduction zones and in the gas generator in general, contributing to the production of synthesis gas with high calorific value and the absence of resins, acids, heavy hydrocarbons, and mechanical impurities.

Partially, the influence of the blowing mode and the dependence of the distribution of air flows in gas generators on the design of the blow assembly and the gas generator are presented, as already noted, in more recent studies [18, 19, 22, 23]. However, for example, in [18, 19], despite the high accuracy of the applied modeling by the method of finite elements, only a significant influence of the rational air blow regime on the temperature in the reaction zone and the composition of the gas are emphasized.

The results obtained by modeling (Fig. 3–9) are the basis for the study of the above-mentioned hydro-gas-dynamic processes, and the further use of ANSYS Fluent will ensure the high accuracy of research.

In works [22, 23], with the help of the modern software environment ASPEN Plus, along with other issues, the influence of the blowing regime on the efficiency of the gasification process was studied. However, the focus of these works is on the influence of the selected blowing mode on ensuring high temperatures, in particular in the oxidation zone. The course of heat and mass exchange processes during the gasification of coal [23] and biomass in a fluidized bed [22] is described in detail. Supplementing materials [22, 23] by the studies carried out in ANSYS Fluent (Fig. 3–9) will explain the presence of a gas generator zone where the intensity of the process is low or absent at all. That also makes it possible to determine with which processes it is associated and how the efficiency of the gasification process changes as a whole.

The results obtained owing to ANSYS Fluent (Fig. 3–9) should be used to select the optimal blowing mode for any designs of gas generators with a continuous layer operating on biomass. The exception is gas generators with circulating and pseudo-fluidized beds, in which the biomass gasification process has a significantly different character. Also, a limitation to the application of our results (Fig. 3–9) is the porosity of the fuel material layer, the value of which should not be less than 0.3. The exceptions are gas generators with circulating and pseudo-liquefied layers, in which the process of biomass gasification is significantly different. In addition, a limitation on the use of the obtained results (Fig. 3–9) is the size of the threshold of the fuel material layer, the value of which should not be less than 0.3. During the gasification of finely dispersed fuel with a layer threshold of 0.3 due to the small size of the inter-lumpy channels and, as a result, significant resistance to the fuel layer, the range of air jets will be quite insignificant. Air masses will be concentrated at the mouth of the lances, where, directly, the process of gasification of fuel will take place. In other parts of the gas generator, the gasification process will not occur. The results of this negative phenomenon can be partially leveled by increasing the air blow speed, the volume of which must be consistent with the parameters of the gasification chamber and the physicochemical characteristics of the fuel. However, at significant blow velocities, there will be phenomena of blowing fuel from the gasification core and its intensive cooling. For example, according to [14], for cylindrical gasification chambers with diameters of 200–600 mm, the limit value is the blow rate of 90 m/s. Consequently, the results obtained are reproducible during the gasification of plant biomass with a layer threshold based on it of 0.3–07 in gas generators with a continuous layer. The speed of air blow, depending on the design of the gas generator (diameter of the gasification chamber and neck) should not exceed the limit value.

Further research will be carried out towards modeling the influence of structural and technological parameters of blow lances on the range of air jet propagation in the gas generator. It is also planned to study the dependence of the distribution of air flows in a gas generator filled with fuel on the design of the selected gas blower unit equipped with lances.

7. Conclusions

1. Simulation of the process of movement of air flows in the gas generator depending on the design of the gas blower unit was performed. By the method of simulation, it was established that the structure of gas blower unit No. 6 provides the most uniform movement of air jets in the working volume of the gas generator ∅213 mm. The speed of air masses at the boundary of the oxidation and reduction zones of the chamber is aligned in the entire cross-section and is $V \approx 4.5$ m/s. The highest uniformity of overlapping by air jets of the cross-section of the gasification chamber at the boundary of the oxidation and reduction zones is also achieved. In practice, this type of distribution of air masses will ensure the highest efficiency of synthesis gas production from biomass, high content of combustible components (CO, H_2) in the gas and, accordingly, a high calorific value of the gas.

2. It was experimentally confirmed that the design of gas blower unit No. 6 provided the highest uniformity of overlapping with air jets of the cross-section of the gasification chamber at the boundary of the oxidation and reduction zones. The conformity assessment of simulation data to the experimental was estimated by the coefficient of determination, which was 0.87. The results of our study are recommended for further investigation of the distribution of air flows in a gas generator filled with fuel and thermal processes that take place during the process of gasification of plant biomass. This will ensure the high efficiency of the synthesis gas production process with a high content of combustible components and calorific value.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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