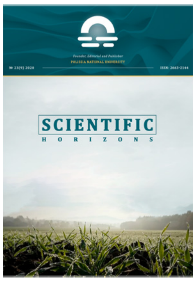
SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua
Scientific Horizons, 24(6), 9-23



UDC 631.2:658.264; 631.172
DOI: 10.48077/scihor.24(6).2021.9-23

Experimental Studies of Structural and Technological Parameters of a Downdraft Gasifier Based on Plant Biomass

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Article's History:
Received: 28.07.2021
Revised: 25.08.2021
Accepted: 30.09.2021

Suggested Citation:
Tregub, M., Holubenko, A., & Tsyvenkova, N. (2021). Experimental studies of structural and technological parameters of a downdraft gasifier based on plant biomass. *Scientific Horizons*, 24(6), 9-23.

Abstract. The relevance of the study is conditioned upon the need to develop and implement structural and technological solutions to improve the efficiency of the chemical and thermal conversion of biomass into combustible gas. Within the framework of the above, the authors of this paper have designed a downdraft gasifier running on plant biomass. The presented research links the heat quantity received from the utilisation of syngas produced during the gasifier operation cycle with the parameters of the gas blow regime and the physico-chemical properties of biomass. For an in-depth study of the influence of the gas blow regime on the yield and calorific value of syngas produced from biomass, the authors introduce the concept of the blow coverage quality coefficient. This coefficient describes the quality of the cross-section coverage of the gasification chamber neck with gas currents of the tuyere zone. The purpose of this study is to establish the influence of the blow coverage quality coefficient, the volume of blow gases and the void ratio of the bulk biomass layer on the heat quantity received from syngas produced during the gasifier operation cycle. A multi-factor experiment was planned and performed, which relates the dependent factor to variables, and the corresponding response surfaces were constructed. The research findings are that the maximum value of the heat quantity received from the utilisation of syngas produced during the one-hour gasifier operation cycle was 519 MJ. This value is achieved with 0.8 blow coverage quality coefficient and a blow gas volume of 47.4 m^3/h and 46.75% void ratio of the bulk biomass layer. The measurement results are highly consistent with the calculated data. The coefficient of determination was R^2=0.983. The practical value of this study is to substantiate the rational design and technological parameters of the downdraft biomass gasifier operation, which will increase the efficiency of biomass energy production. The findings presented in this study can be used both to design new gasifiers and to improve the efficiency of the available ones

Keywords: downdraft gasifier, gasification chamber, syngas, tuyere belt, void ratio, blow coverage quality coefficient

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INTRODUCTION

Successful technical solutions in the context of creating new samples of gasifier equipment and a thorough analytical study of the production processes of combustible syngas from carbon-containing raw materials indicate the modernity and relevance of the subject under study. Studies [1; 2] analyse global trends in the successful introduction of technologies and present means of producing combustible syngas from biomass, both for scientific and commercial purposes. Depending on the energy needs and availability of raw materials, gasifier designs with fixed bed, fluidised bed and entrained flow layers of different capacities are intensively developing. For example, in the USA, Austria, Germany, and Denmark, fluidised bed and entrained flow gasifiers are commonplace, producing over 80% of syngas, the calorific value of which reaches 18...20 MJ/nm^3 [3]. In the Philippines, Latvia, Lithuania, Estonia and Ukraine, fixed bed gasifiers are most commonly operated [4]. Such types of gasifiers have a capacity of 10 kW–1 MW and are more suitable for small-scale applications [4; 5]. The calorific value of syngas produced in fixed bed gasifier is low and amounts to only 5...7.5 MJ/nm^3. However, the substantial advantages of gasifiers of this type are the simplicity of design and operation, the possibility of efficient operation on plant biomass, and the low content of resins in the produced gas (20-30 mg/m^3) [5]. Therefore, for countries where agriculture develops at the level of farming, it is more typical to develop fixed bed gasifiers, namely downdraft gasifiers.

However, despite the advantages, the use of fixed bed gasifiers does not always allow getting the expected results. The reason is a number of technical difficulties relating to the lack of practical data [3-5]. Such issues are methods for improving the efficiency of production of combustible gases from non-condensing raw materials (grain straw, sunflower husk, corn stalks) and methods for ensuring the quality of the gas produced (chemical composition, calorific value, absence of particulate matter and resins) [6]. There are technological and constructive ways to solve these difficulties. In particular, structural ways include modernisation of the gasifier design (hopper, gasification chamber, grate, ash pan, etc.) [5; 7]. Technological ways provide for the development of a gas blow regime [8]; maintenance of high temperatures in the gasification zone [9]; ensuring stable pressure [10]; increasing the reactive surface of fuel [11].

However, despite a considerable number of published scientific papers, the issue of improving the efficiency of fixed bed gasifiers was considered mainly in terms of increasing the calorific value of the generated syngas by increasing the content of the main combustible components in the gas composition (CO and H_2). The amount of gas produced per cycle (or unit of time) is almost not covered. The total heat quantity received from the utilisation of syngas produced during the gasifier operation cycle depends not only on its qualitative chemical composition, but also on the quantity. An increase in both each component separately and two simultaneously will lead to an increase in the total heat quantity received from the utilisation of syngas produced during the gasifier operation cycle in the corresponding heat engineering equipment. Therefore, a slight deterioration in the quality of syngas is acceptable if this is compensated by an increase in its volume produced per unit time. Since the quality and quantity of syngas produced are largely related to the gas blow regime of gasifier operation, this allows adjusting the supply of blow gases necessary for the gasification within a wider range.

Therefore, the issue of improving the efficiency of a gasifier, which is determined by a complex indicator of the heat quantity received from the utilisation of syngas produced during the one-hour gasifier operation cycle, is relevant and needs to be studied.

Given the above, the purpose of this study is to establish the influence of the blow coverage quality coefficient, the volume of blow gases and the void ratio of the bulk layer of biomass on the heat quantity received from the utilisation of syngas produced during the gasifier operation cycle.

The concept of the blow coverage quality coefficient *k* is introduced, which describes the degree of coverage of the chamber neck by tuyere zones created by air currents.

To achieve *this purpose*, the following tasks required solving:

– to design a downdraft gasifier running on plant biomass and a blow gas preparation and supply unit;

– to determine the dependence of heat quantity received from syngas, that was produced during one-hour cycle of gasifier operation, from the blow coverage quality coefficient, blow gases volume and the void ratio of bulk biomass layer.

LITERATURE REVIEW

In the process of chemical and thermal conversion of solid fuel to gaseous fuel, numerous intermediates are formed in fixed bed gasifiers, which have a substantial impact on the quality and quantity of the final gasification product – syngas [12]. These intermediates are water vapor of chemical and hygroscopic moisture of the fuel and gases, various distillates developed during the dry distillation of fuel [13].

The chemical composition and caloric content of syngas, which describe the degree of perfection of the gasification process in general, depend on the conditions that are maintained in the gasification chamber, namely: the temperature of the reaction layer of fuel, i.e., the zone of the chamber where the reactions of the formation of water and air gases occur and where distillates coming from the hopper burn and are subject to cracking; the physical and chemical properties of fuel (density, grain, void ratio, reactivity); the uniformity of fuel intake into the chamber; the load mode of the gasifier, which determines for a certain geometric shape of the gasification chamber the speed of movement of gas masses in the and the time of their contact with the fuel surface [14].

Changes in the above-mentioned intermediates and physico-chemical conditions of the operation depend on the gasifier design features: the geometric shape of the chamber; the profile, dimensions, quantity and method of installing tuyeres that supply blow gases to the gasification zone; the angle of inclination of the hopper cone and the degree of its heating; as well as on external influences (movement of the grate, fuel stoking, gasifier vibrations) [7; 15]. The above list of factors that affect the gasification flow indicates the difficulty of considering the impact of each of them separately. In addition, numerous studies [1; 3-5; 14; 15] have proved that most of these factors are variables, which determines the variability of the gasification and, consequently, the low quality of gas.

According to [15; 16], one of the main factors that controls the thermodynamics of the gasification is the temperature in the gasification chamber, the value of which also determines the cracking of resins and other dry distillation products. The numerical value of the temperature depends on many factors, the main of which are as follows: the speed of blow gases coming out of the tuyeres and their temperature; the number and location of tuyeres; the configuration of the chamber; combustion intensity; humidity and void ratio of the fuel; thermal insulation quality of the hopper. The study [17] notes that the main reason for fluctuations in the temperature of the reaction layer during gasification is the uneven deposition of fuel near tuyeres. The reason for this phenomenon is the ability of fuel to hang and form arches. As a result, the combustion intensity decreases, which is expressed by the value of the hourly consumption of conditionally burned fuel per 1 m^2 cross-sectional areas along the tuyere belt. This worsens the flexibility of the gasification and the quality of syngas.

The influence of combustion intensity on the flexibility of the gasification is also noted in the study [18]. The authors note that as the diameter of the tuyere belt increases, the area of the combustion mirror and the mass of fuel that creates the reaction layer increase. A sharp increase in gas consumption by consumer equipment leads to the fact that the increase in the temperature of the reaction layer lags behind the growth of gas masses. The greater the mass of charred fuel that reacts, the longer it takes to increase its temperature with the same heat released. The issue of ensuring a stable combustion intensity in downdraft gasifiers that run on plant biomass requires an in-depth experimental study with the subsequent development of mathematical models that will link the design parameters of the gasification chamber with the physical and chemical properties of the fuel and the needs for syngas of the heat engineering equipment that runs on it.

The authors of [19] note that it is the high speed of blow gases at the exit of tuyeres that is the main factor that improves the flexibility of the gasification and the quality of the produced syngas. However, the study [19] also indicates that an increase in this velocity contributes to an increase in the resistance in the gasifier and attenuation of the gasification. When an internal combustion engine runs on such a gas, there is a deterioration in its filling and a drop in power, which is also confirmed by research carried out in [15]. Therefore, for each type of fuel, there is a certain limit to the appropriate increase in the speed of blow gases, which must be determined accordingly.

A promising method for increasing the calorific value of syngas to 9-13 MJ/nm^3 is the use of air-steam blow upon gasification [20]. However, research on the use of steam in the syngas production is performed mainly in gasifiers with updraft gasification and in pseudofluidised bed gasifiers running on coal. The disadvantage of this technology is the need for preliminary pair formation, which in turn is accompanied by additional capital expenditures for the purchase of appropriate equipment.

The study [21] notes that it is more expedient to intensify the gasification in a downdraft gasifier by supplying air to the gasification zone in two stages. The authors investigated the chemical composition and calorific value of syngas produced from biomass by changing the air flow rate during the gasification from 18 nm^3/h up to 22 nm^3/h and the air flow ratio in the two stages between 0% and 80%. According to the results of the study, syngas with a low resin content of 54.25±0.66 mg/nm^3 and particulate matter 102.4±1.09 mg/nm^3 were obtained, for a total air flow rate of 20±0.45 mg/nm^3 and an air ratio, between the two stages, of 80%. Thanks to the use of two-stage air supply to the gasification zone, the resin content in the produced syngas decreased by almost 87%. The results obtained in [21] should be considered upon designing the unit for preliminary preparation and supply of blow gases to the gasifier. The authors of [22] propose to use oxygen blow, which allows increasing the calorific value of syngas produced in downdraft gasifier to 11…15 MJ/nm^3. However, this technique has not been widely used commercially due to the high cost of equipment for preliminary preparation and storage of oxygen.

The influence of the air injection rate on the syngas production process is studied in the paper [23]. The gasification conditions of solid waste and wheat straw in a laboratory-scale continuous fluidised bed reactor in a high-oxygen environment are presented. The equivalence coefficient was 0.2…0.5, and the operating temperature in the gasification zone was 600…90^{0}C. To control the distribution of temperature fields in the gas reactor and the composition of the gaseous product yielded, the fuel supply and the amount of air required for gasification were modified. The study proves that the temperature distribution in the reaction zones is controlled by the air supply, and the composition of the gas yielded is controlled by the equivalence coefficient of reagents (biomass and air). The results of this study are generalised and can be used to develop the gas-air regime of the gasification and the tuyere belt design.

There are several studies described in [5; 7; 15; 22], which note the influence of the chamber design on the gasification conditions, as well as features of the tuyere belt design to ensure proper gas blow regime. In particular, the optimal ratio of the diameter of the gasification chamber to the neck; rational geometry of tuyeres (profile, diameter, length) and their number are presented. The axial and radial characteristics of the tuyeres, the hydraulic resistance created by the tuyeres, the aerodynamics of the air current coming out of the tuyere, etc. are studied as well. Even though the presented studies provide an in-depth analysis of the influence of the gas blow regime on the nature of the gasification, the question of the dependence of the produced syngas quality on the coverage of the chamber neck with tuyere zones created by blow gas currents and the dependence of the geometry of tuyere zones on the design of the chamber has not been considered.

One of the essential features of a fuel (along with humidity, reactivity, chemical composition), which determines the chemical composition, calorific value and final application of syngas, is the size of its particles. The authors of the study [24] experimentally confirmed that the size of fuel particles substantially affects the duration of gasification, and, consequently, the size and geometry of the main components of the gasifier – hopper, chamber, etc. However, the published studies did not consider the effect of void ratio of the bulk biomass layer on the gasification. A clear understanding of the degree of influence of this parameter will allow determining as accurately as possible, depending on the volume of fractional voids of fuel, the amount of blow gases required for the gasification and the rational correlation between the amount of air and fuel.

The efficiency of syngas production from biomass in the presented studies has been investigated separately for each of the indicators – according to the calorific value of syngas, and, less frequently, according to its quantity. Studies that determine the efficiency of syngas production from biomass according to the heat quantity received from the utilisation of this gas produced during the gasifier operation cycle have not been conducted. The dependence of this indicator on the design and technological parameters of the gasifier and the properties of biomass also received no prior coverage. Therefore, to increase the efficiency of the chemical and thermal conversion of plant biomass into combustible gas, a complex of studies should be carried out using the achievements of modern scientific thought and methodology.

MATERIALS AND METHODS

The working hypothesis of this study notes that with a certain increase in the amount of blow gases entering the gasifier, the calorific value of syngas may slightly decrease, but the total amount of gas produced during the gasifier operation cycle increases. This leads to an increase in the total heat quantity received from the utilisation of such syngas, namely by its direct combustion.

Crushed wheat straw was used as the test material. The chemical composition of wheat straw per its dry weight is as follows: N=0.54%, C=43.43%, H=5.86%, O=44.26%, S=0.11%, ash content 5.8%. A polyfraction mixture is made from straw-sections as follows: small split stems with a length l=9-27 mm, wall thickness δ=0.16-0.26 mm; flattened stems – l=18-38 mm, δ=0.32-0.48 mm; cylindrical smooth stems – l=22-40 mm, δ=0.22-0.34 mm, outer diameter Ø2-4 mm; cylindrical stems – $l \approx 38$ mm with thickenings, δ=0.45-1.2 mm; small split stems – $l \approx 9$ mm, δ=0.15 mm; the content of other fractions in the mixture does not exceed 4%. The humidity of the straw based on which the polyfraction composition was created was 12%.

The composition of the mixture is expressed by the percentage of fractions: coarse (l>32 mm), medium ($27 \le l \le 32$ mm), and fine (l<27 mm). Mixture I contains 60% coarse, 25% medium, and 15% fine fractions and has a void ratio ε=50%. Mixture II contains 40% coarse, 45% medium, and 15% fine fractions and has a void ratio ε=43.5%. Mixture III contains 25% coarse, 60% medium, and 15% fine fractions and has a void ratio ε=30%. The content of fractions in the mixture was selected according to the reduction theory and filtration theory [15] to ensure the flow of all reactions of the gasification in the appropriate time intervals and at the specified speed. Void ratio ε of the bulk biomass layer was determined according to the method [25].

To run experiments, a pilot plant with a downdraft gasifier was designed, the flow chart of which is presented in Figure 1. The productivity of downdraft gasifier is 60-68 $m^3 \cdot h^{-1}$. The prototype for this unit was the design of the gasifier presented in [7]. According to Figure 1, the plant contained a gasifier; a unit for preparing and supplying blow gases to the gasification chamber; a unit for preparing syngas for utilisation; a unit for collecting, analysing, and accumulating data on the parameters of the syngas produced; syngas utilisation unit.

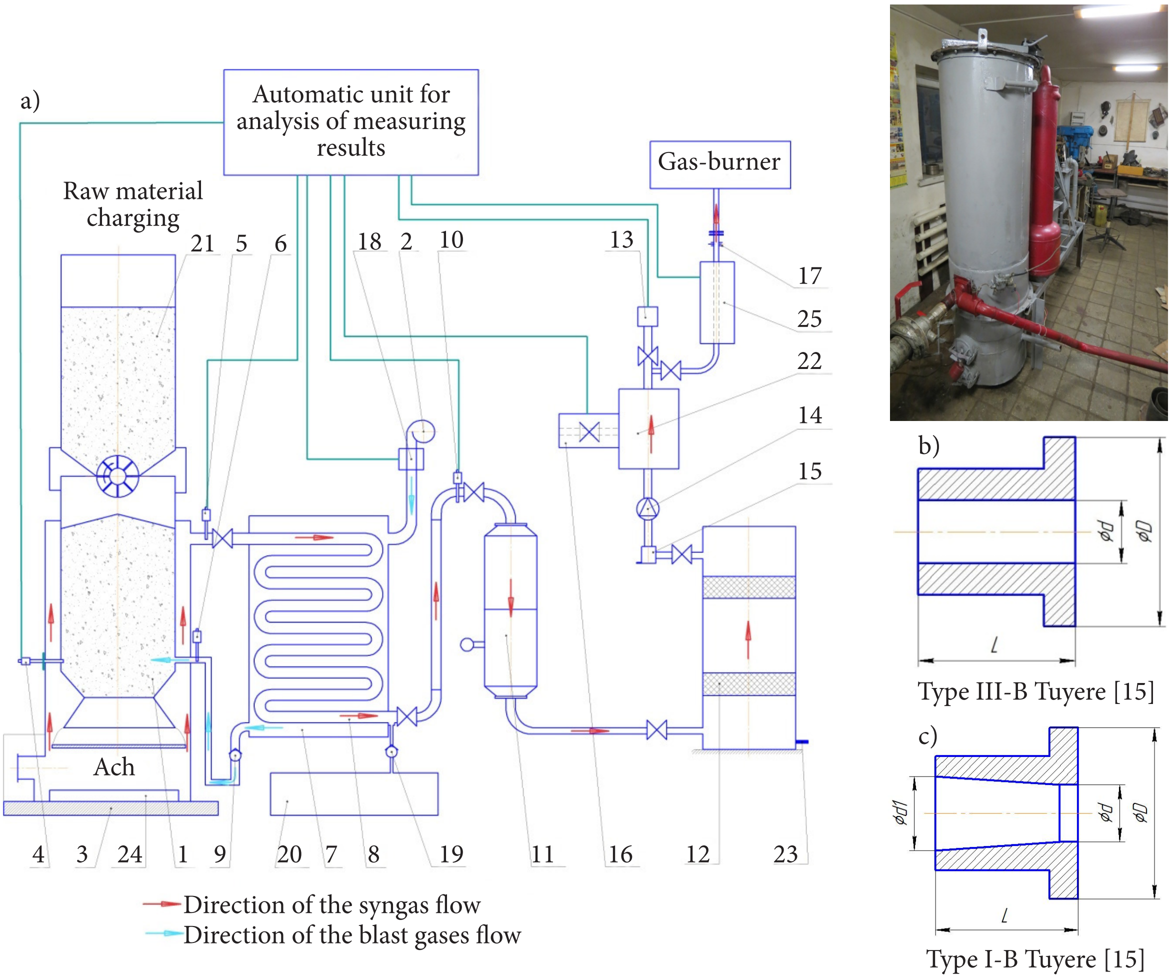

***Figure 1**. A pilot plant with a downdraft gasifier: a – the flow chart; b – downdraft gasifier; c – blowing tuyeres*

Gasification unit included a downdraft gasifier 1 equipped with a hopper with a continuous fuel supply system 21. The gasifier is installed on scales 3 (TVE 500-10 "Tekhnovahy" under DSTU EN 45501), which were used to control fuel consumption. The ash residue was weighed using laboratory scales 24 (TVE 150-5 under DSTU EN 45501). Continuous measurement of the weight of the gasifier allowed monitoring the degree of fuel burnout and coordinating the operation of the gasifier with fuel metering equipment. The temperature in the gasification zone was controlled by thermocouples 4 and 6 (tungsten-ranium thermocouples, TVR-251).

Unit for preparation and supply of blow gases to the gasification chamber. The volume of air supplied to the chamber was regulated by changing the fan rotor 2 rotation speed. The air, before being fed to the tuyere belt of the gasification chamber mounted on the gasifier 1, had been preheated to a temperature of 270…320^{0}C. Heating was carried out in the heat exchanger 7 due to the heat of the produced syngas, which, in turn, was cooled to a temperature of 40^{0}C. The temperature of the heated air was monitored by a thermocouple 6 and recorded in real time by *a block for collecting, analysing, and accumulating data*. To prevent the return of air from the tuyere zone to the heat exchanger, a non-return valve 9 is installed. The volume of air that was supplied to the gasification chamber was calculated using the meter 18.

The preparation unit for syngas utilisation was used for cleaning, cooling, and normalising the parameters of the syngas produced before utilisation in the appropriate heat engineering equipment. The unit contained a heat exchanger 7 with a coil 8, through which syngas was passed. To remove condensate developed during cooling of the syngas upon passage through the coil 8, the heat exchanger 7 was equipped with a branch pipe 19 for discharge and a tank 20 for collecting condensate. The temperature of the syngas at the inlet and outlet of the heat exchanger 7 was controlled by thermocouples 5 and 10 (chromel-aluminum, TXA-XA-2388 065-16).

The preparation unit for syngas utilisation included filters for gas purification: coarse 11 and fine 12. The branch pipe 23 in the design of the fine filter 12 served to remove condensate. The purified syngas, passing through an additional moisture separator 15, entered the receiver 22, where the gas composition was averaged within the volume of the receiver. Through the branch pipe 16, the gas was sampled to analyse the content of resins and particulate matter. To overcome the aerodynamic drag exerted by the filter equipment, a suction-type vacuum pump 14 is provided in the gasifier design. The duration of experiments was recorded using an electronic clock with a timer. The data collection, analysis, and accumulation unit, apart from thermocouples 4, 5, 6, 10, and meter 18, included a gas calorimeter 13 (model CM6G, margin of error 1%) and a gas rotary meter 25 (RG-100 TU U 3.48-05782912-048-97, margin of error 1%).

Syngas utilisation unit contained a burner with a throttle valve 17 to control the amount of syngas supplied for utilisation. According to the task of the study, the heat quantity Q_V was measured, which can be received by recycling syngas produced during the gasifier operation cycle, and Q_V depends on the blow coverage quality coefficient k, the void ratio of the bulk biomass layer ε and the amount of air V_{air} necessary for the gasification. To link the independent (k, ε, V_{air}) and dependent (Q_V) factors, determine the nature of this link and find a mathematical equation to describe it, a multi-factor experiment was conducted using the methodology described in [26].

The total air consumption for the gasification was calculated according to [15], based on the nominal gasifier capacity for gas of 60...68 m^3/h and they were 34...46 m^3/h. Since the plan of the multi-factor experiment provided for three levels of variation and the intervals between levels should be the same, the values of total air flow were adopted as follows: V_{air} 30, 40, and 50 m^3/h. The values of the void ratio ε of the bulk biomass layers were 35%, 43.5%, and 50%.

Coefficient k of the blow coverage quality was established analytically according to the methodology developed by the authors. Calculations were performed using the Statistica 11.0 software package (StatSoft, USA). Coefficient k was established based on the condition that the radius $\rho(S)$ of the tuyere zone may vary. The main control parameters are as follows: the speed of blow gases (air) V_{air}; tuyere specifications defined by the tuyere diameter d_t and coefficients α and a; geometric parameters of the chamber – diameter of the tuyere installation D_{ti}, neck diameter d_n, distance from tuyere belt to neck h_n. Of particular importance is ρ_{max} — the radius of the tuyere zone in the neck plane, m.

According to the theory of a turbulent source [15] applied to a current symmetric relating to the axis, the velocity of the main part of the current of blow gases will be equal to:

$$V_x = \frac{0.96 \cdot V_0}{\dfrac{2 \cdot a \cdot S_x}{d_t} + 0.29} = \frac{0.96 \cdot V_0 \cdot d_t}{2 \cdot a \cdot S_x + 0.29 \cdot d_t} \qquad (1)$$

where V_x is the particle velocity of the blow gas current at a given point at a distance X from the tuyere nose, m/s; V_0 is the initial velocity of a current particle of blow gases at the time of exit from the tuyere nose, m/s; S_x is the distance travelled by a particle of the blow gas current from the tuyere nose to a given point on the x axis, m; d_t is the tuyere diameter, m; a is the experimental coefficient that depends on the flow structure in the initial section of the current (for a current with a circular cross-section a=0.07-0.08) [15].

When the tuyere diameter d_t decreases, the denominator of expression (1) increases, and the velocity V_x, accordingly, decreases, provided that V_0=*const*. Consequently, as the tuyere diameter increases, the range of the current increases. According to the aerodynamics of blowing in the gasification chamber, it is preferable to use a small number of tuyeres of a larger diameter. Since there is a tendency to a sharp decrease in the speed of the blow gas current V_x along the x-axis, the limit values of the parameter V_x, are set, upon reaching which the movement of the gas flow towards the x axis stops. Evidently, $V_X \ll V_0$, and $V_X \ll V_Z$.

The initial velocity of blow gases in the tuyere nose is as follows:

$$V_0 = \frac{4 \cdot V_{air}}{\pi \cdot \alpha \cdot n \cdot d_t^2} = \frac{5.06 \cdot N_2^{г} \cdot V_{gas}}{\pi \cdot \alpha \cdot n \cdot d_t^2} \qquad (2)$$

where α is the current compression coefficient, which determines the ratio of the area of the smallest cross-section of the current to the area of the tuyere opening in its smallest cross-section (α=0.7-1.3) [15]; n is the number of tuyeres; V_{air} is the air consumption for the gasification, m^3/h; V_{gas} is the volume of syngas produced, m^3/h; N_2^{gas} is the nitrogen content in syngas, which depends on its content in straw and in blow gases supplied to ensure the gasification (N_2^{gas}=0.38...0.53 of mass fraction).

Therefore, considering (2), the velocity of the main part of the blow gas current is as follows:

$$V_x = \frac{1.54 \cdot N_2^{г} \cdot V_{gas}}{\alpha \cdot n \cdot d_t \cdot (2 \cdot a \cdot S_x + 0.29 \cdot d_t)} \qquad (3)$$

Under different conditions, the tuyere zones created by blow gas currents in the chamber neck may undergo coverage to varying degrees. As an example, three variants of schemes for tuyere zones coverage in the neck of the gasification chamber with the number of tuyeres n=8 are considered (Fig. 2). According to Figure 2, three main zones of fuel coverage with a gas current are formed in the cross-section of the neck: Zone 1 – a single coverage; Zone 2 – the zone that is not covered by any of the currents (phenomena of insufficient CO$_2$ content in the gas mixture are observed, or low recovery intensity); zone 3 – a zone where two or more gas currents undergo coverage. Consequently, on the one hand, there is a more intense mixing of gas, and on the other hand, there may be a lack of carbon in the fuel, which affects the quality of syngas. The key factor for justifying rational blow parameters is to plan a coverage scheme that will provide the highest calorific value of syngas at a given gas chamber capacity. Therewith, the values of the neck diameter and the radius of the tuyere zone are not important, only their ratio affects the gasification conditions.

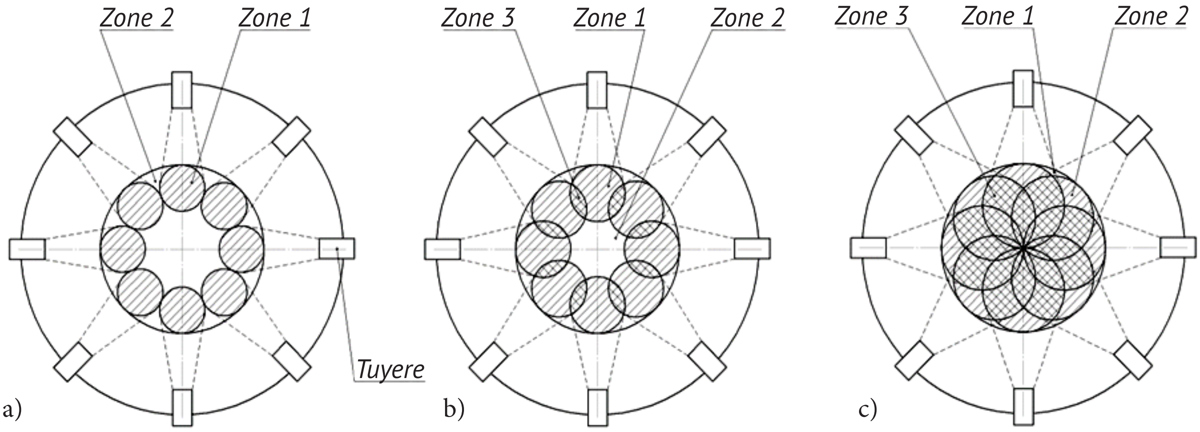

***Figure 2**. Schemes for tuyere zones coverage created by blow gas currents in the neck of the gasification chamber depending on their radii $\rho(S)$ with the number of tuyeres n=8:*
a) coverage of cross-sections of tuyere zones in the chamber neck at $(d_n / 2\cdot\rho_{max}) = 3.6$;
b) coverage of cross-sections of tuyere zones in the chamber neck at $(d_n / 2\cdot\rho_{max}) = 2.75$;
c) coverage of cross-sections of tuyere zones in the chamber neck at $(d_n / 2\cdot\rho_{max}) = 2$

To compare the gasification conditions, the specific area of the coverage calculated for the number of tuyeres n=8-12 was investigated. The specific area of the coverage is determined considering the coefficient k, which for Zone 1 is k=1, for Zone 2 – k=0.2, for Zone 3 – k=0.6. Based on the research results, graphical dependencies were constructed (Fig. 3).

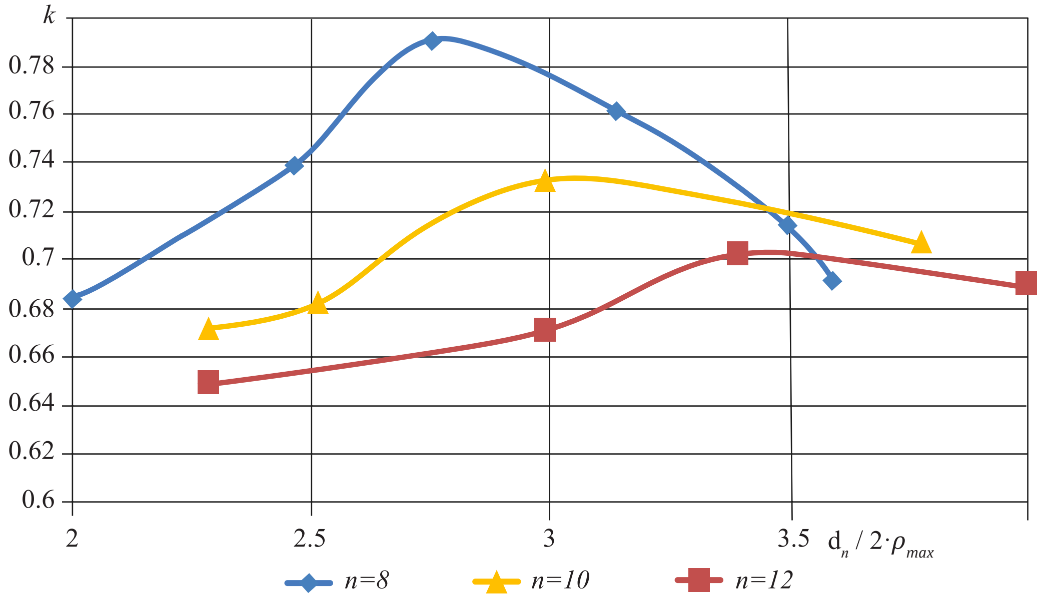

***Figure 3**. Dependence of the coverage quality coefficient k from the number of tuyeres n and the correlation* $(d_n / 2\cdot\rho_{max})$

The result of the study (Fig. 3) is the establishment of the conditions that are most favourable for the gasification, with certain correlations between the neck diameter d_n and the opening radius of the tuyere zone in the neck section ρ_{max}. Thus, with the number of tuyeres n=8, the best conditions for the gasification are achieved when $d_n / 2\cdot\rho_{max}$=2.75 (while k = 78%). With the number of tuyeres n = 12, these conditions are achieved when $d_n / 2\cdot\rho_{max}$=3.39 (k=70.5%).

These findings suggest that it is more appropriate to use a smaller number of tuyeres, while providing the ability to control the path that the blow gas currents pass in the chamber. The justified correlations $(d_n / 2\cdot\rho_{max})$ are summarised in Table 1.

***Table 1**. Influence of the number of tuyeres and the radius of the tuyere zone in the neck section on the path of the blow gas current along the x axis*

No.	Number of tuyeres n, pcs.	Radius of the tuyere zone in the neck plane ρ_{max}, m	Coefficient of the blow coverage quality in the chamber neck by tuyere zones created by air currents k
1	8	$\rho_{max}=d_g/5.5$	0.68...0.78
2	10	$\rho_{max}=d_g/5.98$	0.67...0.73
3	12	$\rho_{max}=d_g/6.78$	0.65...0.71

To conduct the experiment, a five-level second-order plan was implemented according to the methodology described in [26]. The plan for conducting experiments made provision for a variation of three independent factors k, V_{air} and ε, which affect the heat quantity Q_V, which can be received from the utilisation of syngas. Factors encoding: $X_1=k$, $x_2=V_{air}$, $X_3=\varepsilon$.

Variation levels of abovementioned factors are presented in Table 2.

***Table 2**. Variable factors and limits of their variation for definition of heat quantity that can be received from syngas burning, which was produced during one-hour gasifier operation cycle*

Factor variation level	Coefficient of blow coverage quality k	Blow gases volume V_{air}, $m^3 \cdot h^{-1}$	Void ratio of bulk biomass layer ε, %
Lower level (-)	0.68	30	35
Middle level (0)	0.74	40	42.5
Upper level (+)	0.8	50	50

The first step of the study (Table 3) investigated the polyfraction mixture II, with void ratio of the bulk biomass layer ε 43.5%. The tuyere belt contained 8 tuyeres Ø10.6 mm each with a nozzle of the corresponding design (Type I-B). According to the design of the tuyere belt and the void ratio of the bulk biomass, the coefficient k was 0.8. Through the tuyeres, air was supplied to the gasification zone with a volume of V_{air}=50 m^3/h and the amount of syngas produced and its calorific value were measured. The heat that can be obtained by burning the produced syngas was calculated as follows. The experimental interval, which was one hour, was divided into elementary intervals of 4 minutes. Time intervals were recorded by an electronic clock with a timer integrated into the data collection, analysis and accumulation unit. At the specified time intervals, the indicators of the gas meter 18 and the indicators of the gas calorimeter 13 were recorded. The heat was defined as the sum of the products of the volumes of gas produced in an elementary time interval and the calorific value of this gas.

The implementation of a multi-factor experiment involved the following actions: encoding factors; randomisation; developing a sequence of experimental stages; establishing the degree of reproducibility of the experiment; determining and evaluating the significance of regression coefficients; establishing the adequacy of the model. A series of 15 original experiments was performed according to the planning matrix and the coefficients of the linear part of the polynomial were calculated using the methodology described in [26]. For the reliability of experimental data, it is assumed that the number of parallel experiments conducted under the same conditions is equal to three.

***Table 3**. Diameters and types of tuyeres that provide the volume of air for gasification and the blow coverage quality coefficient for the corresponding values of void ratio of the bulk biomass layer*

	Experiment planning method			Values of experimental factors			Tuyere diameter d_t, mm	Tuyere type [15] (Fig. 1)
	X_1	X_2	X_3	X_1	X_2	X_3		
1	+	+	0	0.8	50	43.5	10.6	I-B
2	+	–	0	0.8	30	43.5	7.4	III-B
3	–	+	0	0.68	50	43.5	10.4	III-B
4	–	–	0	0.68	30	43.5	9	I-B

Table 3, Continued

	Experiment planning method			Values of experimental factors			Tuyere diameter d_t, mm	Tuyere type [15] (Fig. 1)
	X_1	X_2	X_3	X_1	X_2	X_3		
5	0	0	0	0.74	40	43.5	8.8	III-B
6	+	0	+	0.8	40	50	9.2	III-B
7	+	0	–	0.8	40	35	7.8	III-B
8	–	0	+	0.68	40	50	10	III-B
9	–	0	–	0.68	40	35	9.4	I-B
10	0	0	0	0.74	40	43.5	8.8	III-B
11	0	+	+	0.74	50	50	10.6	III-B
12	0	+	–	0.74	50	35	9	III-B
13	0	–	+	0.74	30	50	9.2	I-B
14	0	–	–	0.74	30	35	7.8	I-B
15	0	0	0	0.74	40	43.5	8.8	III-B

According to the plan of multifactor experiment, the values of the model's relative error are lower than 1.64%. This is the case for all experiments. The values of mean relative deviation are lower than 1.2%. Thus, the relative error value is less than 5%. Such relative error value is considered acceptable in modelling [26].

Therefore, it can be concluded that presented model predicts the heat quantity (that can be received from syngas burning, which was produced during one-hour gasifier operation cycle) with high accuracy.

RESULTS AND DISCUSSION

The results of the experimental study were processed using the Statistica package. As a result of experimental research and statistical processing, an array of data values of the heat quantity Q_V was obtained, which is received from the utilisation of syngas produced during the gasifier operation cycle, which are presented in Table 4.

***Table 4**. Calculated matrix of the heat received from the utilisation of syngas produced during the gasifier operation cycle*

No.	Experiment planning method				Experiments results				Model adequacy check		
	X_0	X_1	X_2	X_3	Q_{V1}	Q_{V2}	Q_{V3}	$Q_{V\,med}$	$Q_{V\,med.com}$	$(Q_{V\,med} - Q_{V\,med.com})$	$(Q_{V\,med} - Q_{V\,med.com})^2$
1	+	+	+	0	516.9	512.0	512.0	513.6	508.9	4.7	22.129
2	+	+	–	0	411.0	409.0	407.0	409.0	400.9	8.1	64.870
3	+	–	+	0	474.0	474.0	473.0	473.7	481.7	-8.1	64.870
4	+	–	–	0	300.0	298.0	299.0	299.0	303.7	-4.7	22.129
5	+	0	0	0	468.0	471.0	467.0	468.7	470.6	-1.9	3.568
6	+	+	0	+	435.0	437.0	438.0	436.7	445.0	-8.4	69.931
7	+	+	0	–	399.0	399.0	393.0	397.0	402.7	-5.7	32.443
8	+	–	0	+	413.0	412.0	408.0	411.0	405.3	5.7	32.443
9	+	–	0	–	326.0	327.0	326.0	326.3	318.0	8.4	69.931
10	+	0	0	0	469.0	472.0	472.0	471.0	470.6	0.4	0.198
11	+	0	+	+	490.0	493.0	490.0	491.0	488.9	2.1	4.340
12	+	0	+	–	356.0	354.0	355.0	355.0	355.6	-0.6	0.340
13	+	0	–	+	279.0	277.0	278.0	278.0	277.4	0.6	0.340
14	+	0	–	–	281.0	277.0	279.0	279.0	281.1	-2.1	4.340
15	+	0	0	0	470.0	476.0	470.0	472.0	470.6	1.4	2.086

Regression coefficients: b_0=470.556; b_1=31.113; b_2=71.5; b_3=32.417; b_{12}=-17.508; b_{13}=-11.25; b_{23}=34.25; b_{11}=-2.365; b_{22}=-44.365; b_{33}=-75.44.

The Cochran's test was applied to verify the uniformity of variances. The tabular value of the Cochran's test criterion was G^{table}=0.4 at 5% significance levels for the number of degrees of freedom equal to f_2=2 and the number of experiments f_1=15. It was established that $G^{com}=0.21<G^{table}(0.05;\ 15;\ 2)=0.4$ [26]. Thus, the process is fully reproduced.

The significance of the coefficients of the regression equation is estimated according the Student's t-test. Tabular value of the Student's t-test at 5% significance level, f_2=2 and the number of experiments f_1=15 was t=4.3 [26; 27]. The coefficients of the regression equation were estimated by their significance and insignificant ones were excluded. Finally, the polynomial equation took the following form:

$$Q_V=470.556+31.113\cdot X_1+71.5\cdot X_2+32.417\cdot X_3-17.508\cdot X_1\cdot X_2-11.25\cdot X_1\cdot X_3+34.25\cdot X_2\cdot X_3-2.365\cdot X_1^2-44.365\cdot X_2^2-75.44\cdot X_3^2 \quad (4)$$

where Q_V is the heat quantity received from the utilisation of syngas produced during one hour gasifier operation cycle, MJ/h; X_1 is the encoded value of the coefficient of the blow coverage quality for the neck cross-section in the gasification chamber by air currents of the tuyere zone; X_2 is the encoded value of the air supply for gasification, m^3/h; X_3 is the encoded value of the void ratio of the bulk biomass layer.

The hypothesis on the adequacy of the model to the object under study was tested using the Fisher's test. Variance $S_y^2\{Q_V\}$ of the initial optimisation parameter was established based on the results of experiments in the centre of the plan (Table 4) and amounted to S_y^2=2.92. As a result of calculations, the value of the adequacy variance was obtained, which was equal to S^2_{inadeq}=2.77. The calculated value of the Fisher's test for the specified values of variances was equal to F^{com}=9.47. Since $F^{com}=9.47<F^{table}(0.05;\ 15;\ 2)=19.38$, then the hypothesis on the adequacy of the regression equation is confirmed [26; 27]. The value of the coefficient of determination was R^2=0.983. Thus, the mathematical model (4) of the parameter Q_V dependence obtained from variable factors adequately describes the results of the experiment at a 5% significance level.

After substituting the values of the obtained coefficients into canonical Equation (4), the regression equation of the process under study is written as follows:

$$Q_V=-4748.56+3720.53\cdot k+44.83\cdot V_{air}-118.55\cdot \varepsilon-29.18\cdot k\cdot V_{air}-25\cdot k\cdot \varepsilon+0.457\cdot V_{air}\cdot \varepsilon-656.944\cdot k^2-0.444\cdot V_{air}^2-1.341\cdot \varepsilon^2 \quad (5)$$

where: Q_V is the heat received from the utilisation of syngas in the volume produced by the gasifier during the one-hour operation cycle, MJ/h; k is the coefficient of the blow coverage quality; V_{air} is the air supply for gasification, m^3/h; ε is the void ratio of the bulk biomass layer, %.

Graphical representations of the abovementioned equation are presented in Figure 4-b.

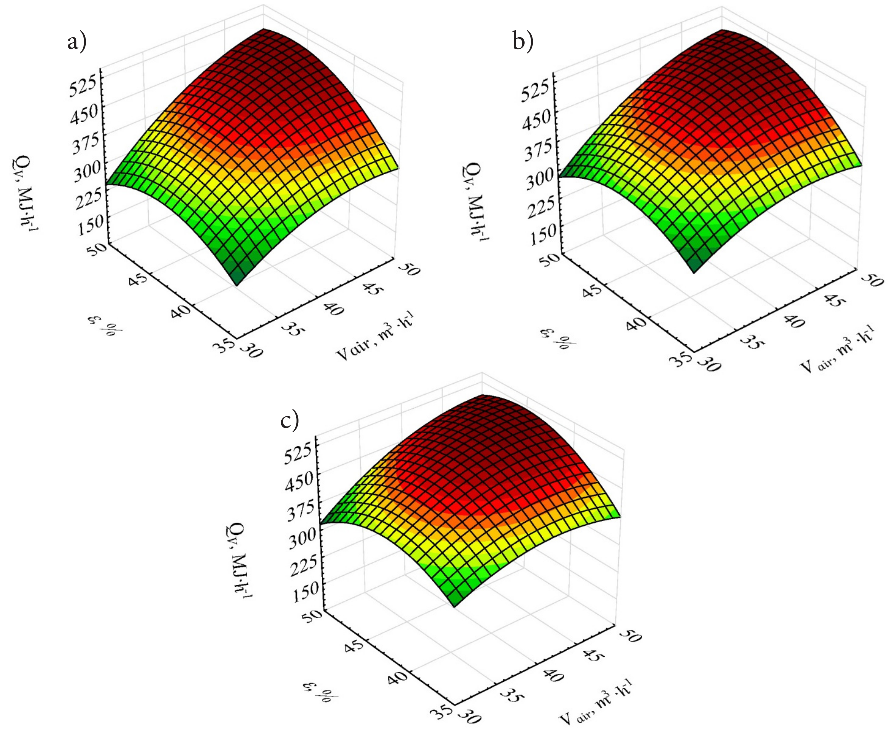

***Figure 4**. Dependence of the heat quantity Q_V on the void ratio of the bulk biomass layer ε and air supply for gasification V_{air}: a) – k=0.68, b) – k=0.74, c) – k=0.8*

According to Figure 4a, the dependence of the heat quantity Q_V from void ratio ε and the volume of air blow V_{air} is nonlinear and has a well-formed maximum observed for all values of the coefficient k. Thus, with the blow coverage quality coefficient k=0.68 and void ratio of the polyfraction mixture ε =46.7%, to reach the maximum parameter value Q_{Vmax}=502 MJ/h, it was necessary to bring 49.2 m^3/h of air into the chamber for the gasification. Considering the results obtained, for the coefficient k=0.68, the recommended air blow volume range is equal to V_{air}=45.2...53.2 m^3/h.

With increasing void ratio of the bulk biomass ε from 35% to 46.7%, the heat quantity Q_V also increases. This phenomenon is explained by the fact that the resistance of the fuel layer against the passage of air through it decreases. The degree of branching of the paths through which air currents pass through the bulk biomass layer also increases, which, in turn, increases the radius of opening of the currents in the cross-section of the neck of the gasification chamber. However, with a further increase in void ratio of the bulk biomass layer ε towards values above 46.7%, the heat quantity Q_V decreases. This phenomenon is explained, on the one hand, by a decrease in the contact area of the fuel surface with air, on the other hand, by the development of air currents of stable trajectories in a bulk biomass with a large void ratio. The latter, in turn, also helps reduce the contact area of the fuel surface with air. Additionally, the higher void ratio of the bulk biomass helps reduce the temperature in the core of the gasification chamber, which entails worse conditions for the main chemical reactions of the gasification and the predominance of CO_2 content over the CO content in the syngas produced.

According to Figure 4b, at the value of the coefficient k=0.74 the maximum heat quantity Q_V=514 MJ/h is achieved at a lower value of the air blow volume (V_{air}=48.3 m^3/h) compared to Figure 4a. The void ratio value remains almost unchanged and is ε=46.5%. As the coefficient k increases from 0.68 (Fig. 4a) to 0.74 (Fig. 4b), the value Q_V grows, reaching Q_V=512 MJ/h at V_{air}=50 m^3/h and ε=46.75%. In the above case, an increase in the heat quantity Q_V is explained by the improvement of the syngas quality. Chemical analysis of syngas demonstrated that the CO content in the gas increased from 16.25% to 19.01%. The measurements were performed at the Gas Institute of the National Academy of Sciences of Ukraine using a two-channel chromatograph model Agilent 6890 N.

The graphical dependency presented in Figure 4b, was built at the highest value of the blow coverage quality coefficient k=0.8. Under these conditions, the volume of air blow V_{air}, at which the maximum value is obtained Q_V=519 MJ/h, reduced to 47.4 m^3/h with the specified void ratio value of the bulk biomass layer ε=46.75%. The results obtained indicate that the higher values of the coefficient k, that is, the highest quality of coverage of the gasification chamber neck with air currents improves the conditions of gasification. This also contributes to an increase in the calorific value of syngas due to an increase in the CO content in the chemical composition of the produced gas.

Analysis of dependencies presented in Figure 4 indicates that the blow coverage quality coefficient k has a greater impact on changing the parameter Q_V compared to the volume of air blow $V_{air.}$ Thus, even at the lowest values of the air blow volume (V_{air} =30 m^3/h), with increasing coefficient k, the parameter Q_V is also rapidly growing, especially in the range of values of void ratio of the bulk biomass layer ε =45...47%.

The surfaces presented in Figure 5 illustrate the dependence of the parameter Q_V on the void ratio of the bulk biomass layer ε and the coefficient k at the values of the air blow volume V_{air}, which are equal to 30, 40, and 50 m^3/h, respectively.

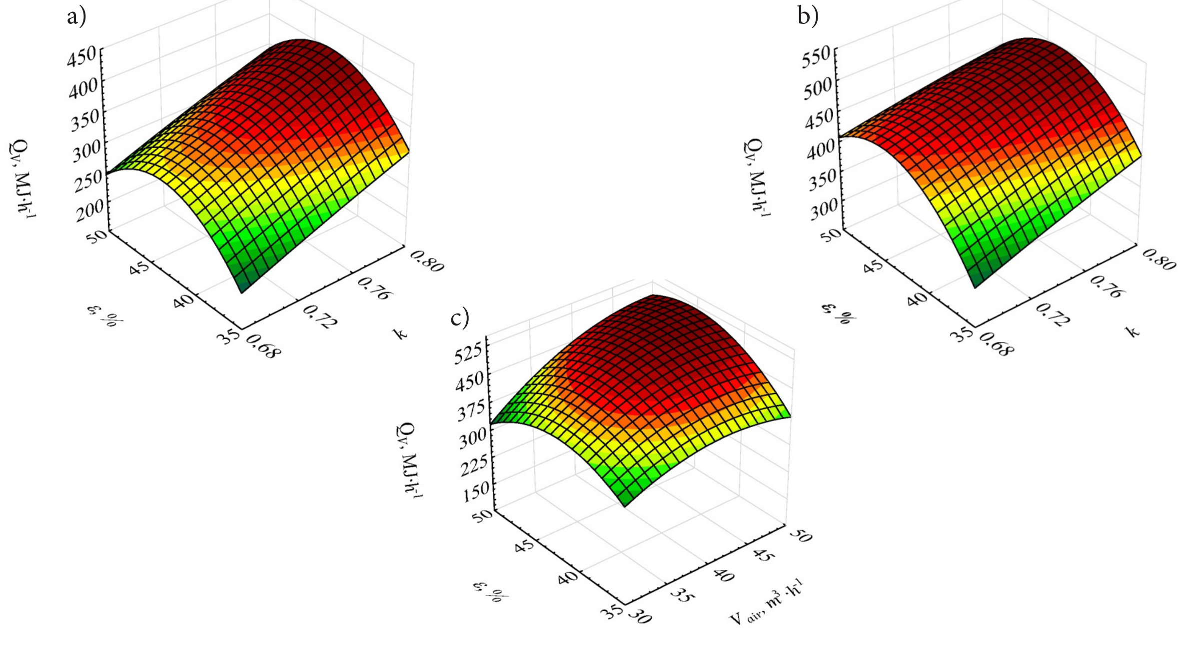

***Figure 5**. Dependence of the heat quantity Q_V on the void ratio of the bulk biomass layer ε and the blow coverage quality coefficient k: a) – V_{air}=30 m^3/h, b) – V_{air}=40 m^3/h, c) – V_{air}=50 m^3/h*

Analysis of the surfaces presented in Figure 5 indicates the existence of an optimal void ratio range for the bulk biomass layer ε, which is 45...47%. It is in this range that the highest values of the parameter Q_V are observed for all values k and V_{air}. In this case, between the heat quantity Q_V and the k coefficient there is a correlation close to linear. Increasing the value of the k coefficient leads to an increase in the Q_V parameter. In the range of optimal void ratio values ε=45...47% at k=0.68, the heat quantity Q_V is 303.7 MJ/h. When the coefficient k increases to a value of 0.8, the heat quantity reaches Q_V=401 MJ/h, i.e., increases by 65.7%. When the amount of air blow V_{air} increases in the process of gasification with a simultaneous increase in the k coefficient, the upward trend of the parameter Q_V is retained. However, with an increase in the amount of air blowing V_{air}, the growth in the heat quantity Q_V decreases.

According to Figure 5c, at the value k=0.68 in the range of the values of void ratio of the bulk biomass ε=45...47%, the maximum value of Q_V is 502 MJ/h. As the k coefficient increases up to 0.8, the heat quantity Q_V=518 MJ/h, i.e., increases by only 3.5%. This indicates a more substantial influence of the blow coverage quality coefficient k on the parameter Q_V with smaller volumes of air blow V_{air} and a reduction in the impact of this coefficient k under conditions of intensification of air blow. This can be explained by the fact that with an increase in the blow volume, the bulk biomass layer is more intensively mixed in the cross-section of the chamber neck, which, in turn, increases the contact area of air with the fuel surface.

Figure 6 demonstrates graphical dependencies that illustrate the correlation between the heat quantity Q_V, air blow volume V_{air}, and the blow coverage quality coefficient k at different values of void ratio of the bulk biomass layer ε. According to Figure 6, with an increase in the volume of air blow V_{air} up to 49 m^3/h, the parameter Q_V is growing. However, with further increase of V_{air}>49 m^3/h, the parameter Q_V starts to subside. Lower values of the heat quantity Q_V at V_{air}<45 m^3/h indicate a lack of oxygen, which leads to incomplete carbon oxidation of the fuel. At the volume of air blow V_{air}>53 m^3/h, the parameter Q_V decreases, and the fuel is cooled in the gasification zone by excess air. This process is accompanied by active carbon removal of fuel with the produced syngas, which leads to an increase in the volume of CO_2 content in syngas by reducing the CO content. According to Figure 6, the optimal parameter Q_V for the syngas production is a range of air blow volume within V_{air}=V_{air}=45.2...53.2 m^3/h.

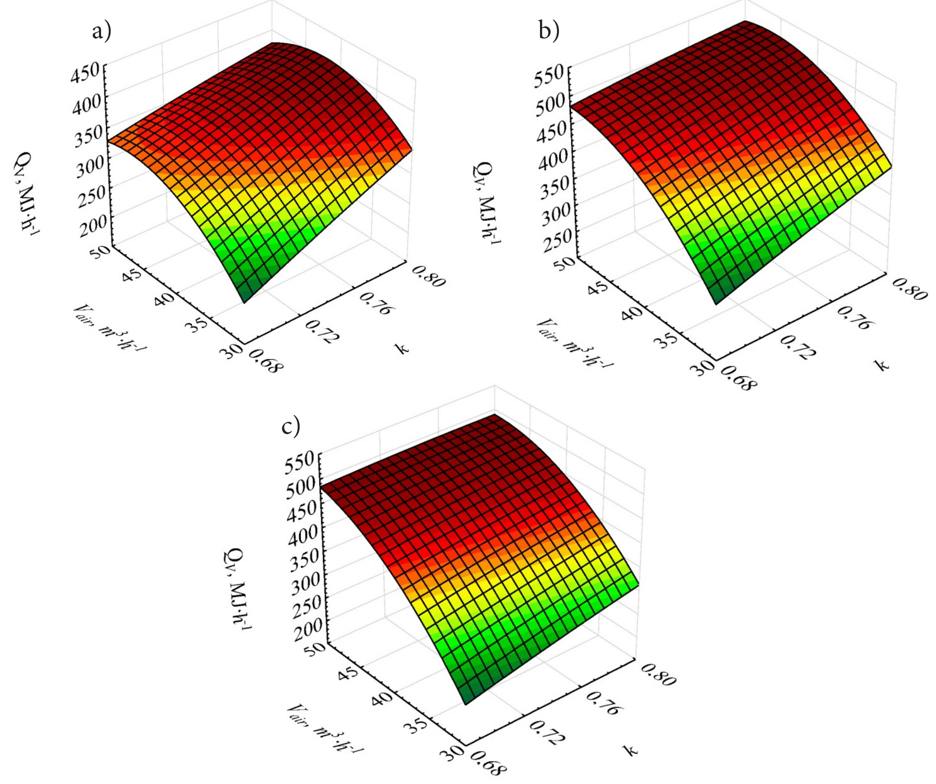

***Figure 6**. Dependence of the heat quantity Q_V from the blow coverage quality coefficient k and air supply for gasification V_{air}: a) – ε=35%, b) – ε=43.5%, c) – ε=50%*

Graphical dependencies presented in Figure 6 also indicate that with an increase in the blow coverage quality coefficient k, heat quantity Q_V of the generated syngas is also growing. In this case, the maximum value of the parameter Q_V=521 MJ/h corresponds to the void ratio of the bulk biomass layer ε=45%, air blow volume V_{air}=47.3 m^3/h and the blow coverage quality coefficient k=0.8. The resulting value of 521 MJ/h is greater than the heat equal to 505 MJ/m^3, which was received from the utilisation of the maximum amount of syngas produced (65 m^3) with the highest calorific value of 7.9 MJ/m^3.

The presence of optimal ranges of void ratio of the bulk biomass layer in the presented study ε and the volume of air blow V_{air} suggest that, under the condition of direct utilisation of the produced syngas, such an indicator as the HHV of the syngas produced is not decisive. A more defining indicator is the heat quantity Q_V received from the utilisation of the produced syngas in the appropriate heat engineering equipment. Optimal ranges of void ratio of the bulk biomass ε and the volume of air blow V_{air} at k=0.8, where the maximum heat quantity Q_V (500…521 MJ/h) can be received from the utilisation of syngas produced from the straw section during the one-hour gasifier operation cycle are ε=45…47% and V_{air}=45.2…53.2 m^3/h, respectively.

There are several studies aimed at high-tech improvements of gasification, the design of gasifiers, etc. These studies put forward extremely bold hypotheses, the implementation of which in real projects has a high cost and technical complexity. Scientific papers [21; 28] present research results similar to the level of constructive complexity of the above experiment. These works indicate the degree of influence of air blow on the calorific value of syngas produced in a fixed bed gasifier, but the design of the main components of the gasifier, namely the gasification chamber, and the type of raw materials that are gasified differ. In the study [21], eucalyptus wood was used as a raw material. Thanks to the two-stage air supply, syngas with a low calorific value of about 5 MJ/m^3 was obtained. Even though in the present study that syngas of the highest calorific value of about 7.9 MJ/m^3 was obtained, it is incorrect to compare the results of these studies, since in the present case the studies were performed with a section of wheat straw. In addition, a hypothesis similar to that put forward in the experiment presented herein has not yet been investigated. The comparison can be carried out exclusively according to the gasifier performance indicators in terms of gas yield and average calorific value.

CONCLUSIONS

1. The design of a downdraft gasifier running on plant biomass was developed and numerous studies were performed to establish the efficiency of the gasifier according to the total heat quantity received from the utilisation of syngas produced during the gasifier operation cycle.

2. The influence of the blow coverage quality coefficient of the chamber neck with tuyere zones created by air currents, the amount of air required for the gasification, and the void ratio of the bulk biomass layer on the total heat quantity received from the combustion of syngas produced during the gasifier operation cycle is experimentally studied. The findings of the present study are as follows:

– There is an optimal range of void ratio of the bulk biomass layer based on straw cross-section wherein high values of the heat quantity 502…519 MJ/m^3 are obtained and it amounts to 45…47%. If the void ratio values of the bulk biomass layer are less than 45%, the resistance that the fuel layer exerts against the passage of air through it increases. At void ratio values over 47%, the contact area of the fuel surface with air decreases, which also leads to a decrease in the heat quantity.

– With an increase in the volume of air required for the gasification from 30 to 45 m^3/h, the heat quantity received from the utilisation of syngas increases from 280 MJ/m^3 to 512 MJ/h in the range of void ratio of the bulk biomass layer of 45…47% with the blow coverage quality coefficient k=0.74. Therewith, the heat continues to increase due to an increase in the volume of syngas produced, even if the calorific value of the gas slightly decreases. The optimal range of blow volume values required for the gasification process is 45.2…53.2 m^3/h. The maximum value of the heat is 521 MJ/h and was obtained with a void ratio of the bulk biomass layer of 45%, an air blow volume of 47.3 m^3/h and the value of the blow coverage quality coefficient of the chamber neck section by air currents k equal to 0.8.

– As the quality factor of the blow coverage increases, the heat that can be obtained from burning the generated syngas also increases. With an increase in the blow coverage quality coefficient, a larger increase in heat quantity is inherent in smaller volumes of air blow. As the blow coverage quality coefficient increases, the effect of the blow volume on the heat quantity received from the utilisation of the produced syngas decreases. Dependencies (Fig. 4-6) indicate the achievement of close maximum values of the heat quantity, which vary in the range of 500…521 MJ/h. This indicates the need to adjust the blow within the optimal range and reduces the impact of the design of the tuyere belt of the chamber (diameter and shape of the tuyere), but does not eliminate the need for their correct selection.

3. Therefore, the results of the study confirm that with an increase in the blow volume, the volume of syngas increases faster than its calorific value decreases. Therefore, the heat has a maximum shifted relative to the maximum calorific value towards increasing the blow volume. At optimal gasification modes (blow volume 47.3 m^3/h, void ratio of the bulk biomass 45%, blow coverage quality coefficient 0.8) 521 MJ/h heat was obtained from syngas utilisation. This is more than the heat quantity equal to 505 MJ/h, which was received from the utilisation of the maximum amount of syngas produced (65 m^3), the highest calorific value of which was 7.9 MJ/m^3.

REFERENCES

[1] Heidenreich, St., Müller, M., & Foscolo, P.U. (2016). *Advanced biomass gasification new concepts for efficiency increase and product flexibility* (1st ed.). New York: Academic Press.

[2] Devi, G.S., Vaishnavi, S., Srinath, S., Dutt, B., & Rajmohan, K.S. (2020). Energy recovery from biomass using gasification. In *Current developments in biotechnology and bioengineering: Resource recovery from wastes* (pp. 363-382). Amsterdam: Elsevier.

[3] Mirmoshtaghi, G. (2016). *Biomass gasification in fluidized bed gasifiers*. Sweden: School of Business, Society and Engineering.

[4] Basu, P. (2018). *Biomass gasification, pyrolysis and torrefaction: Practical design and theory* (3rd ed.). San Diego: Elsevier Science Publishing Co Inc.

[5] Susastriawana, A.A.P., Saptoadi, H., & Purnomo. (2017). Small-scale downdraft gasifiers for biomass gasification: A review. *Renewable and Sustainable Energy Reviews,* 76, 989-1003. doi: 10.1016/j.rser.2017.03.112.

[6] Pavlenko, M., Chuba, V., Tsyvenkova, N., & Tereshchuk, M. (2020). An experimental study on biomass air-steam gasification effectiveness in a downdraft gasifier. *Engineering for Rural Development*, 19, 1831-1839. doi: 10.22616/ERDev.2020.19.TF495.

[7] Tsyvenkova, N., Kukharets, S., Kukharets, V., & Savchenko, N. (2020). Experimental study of influence of tuyere belt design on thermal conditions of gasification chamber operation. *Engineering for Rural Development,* 19, 1248-1254. doi: 10.22616/ERDev2020.19.TF302.

[8] Jaojaruek, K., Jarungthammachote, S., Gratuito, M.K.B., Wongsuwan, H., & Homhual, S. (2011). Experimental study of wood downdraft gasification for an improved producer gas quality through an innovative two-stage air and premixed air/gas supply approach. *Bioresource Technology,* 102(7), 4834-4840. doi: 10.1016/j.biortech.2010.12.024.

[9] Pio, D.T., Gomes, H.G.M.F., Tarelho, L.A.C., Vilas-Boas, A.C.M., Matos, M.A.A., & Lemos, F.M.S. (2022). Superheated steam injection as primary measure to improve producer gas quality from biomass air gasification in an autothermal pilot-scale gasifier. *Renewable Energy*, 181, 1223-1236. doi: 10.1016/j.renene.2021.09.083.

[10] Motta, I.L., Miranda, N.T., Maciel Filho, R., & Wolf Maciel, M.R. (2018). Biomass gasification in fluidized beds: A review of biomass moisture content and operating pressure effects. *Renewable and Sustainable Energy Reviews*, 94, 998-1023. doi: 10.1016/j.rser.2018.06.042.

[11] Liao, L., Zheng, J., Zhang, Bo, Wang, Z., & Zhang, Y. (2021). High-temperature gasification of woody biomass in a drop tube reactor: A special focus on the particle size and axial temperature gradient. *Journal of the Energy Institute*, 99, 266-272. doi: 10.1016/j.joei.2021.10.003.

[12] Caglar, B., Tavsanci, D., & Biyik, E. (2021). Multiparameter-based product, energy and exergy optimizations for biomass gasification. *Fuel*, 303, article number 121208. doi: 10.1016/j.fuel.2021.121208.

[13] Bassil, G., Saab, J., Goutaudier, C., Negadi, L., Jose, J., & Mokbel, I. (2022). Experimental measurements for the liquid-liquid equilibrium of ternary systems [(water + methyl oleate + model mixtures of tar (naphthalene, phenanthrene and anthracene)] issued from the biomass gasification process. *The Journal of Chemical Thermodynamics*, 164, article number 106613. doi: 10.1016/j.jct.2021.106613.

[14] Jenkins, R.G. (2020). Thermal gasification of biomass – a primer. In *Bioenergy (2nd ed.): Biomass to biofuels and waste to energy* (pp. 293-324). New York: Academic Press. doi: 10.1016/B978-0-12-815497-7.00015-4.

[15] Mezin, I.S. (1948). *Transport gas generators*. Moscow: OGIZ SELHOZGIZ.

[16] Leiva Butti, J.M., Núñez Mc Leod, J.E., & Rivera, S.S. (2020). Solar gasification of grape marc for syngas production: Solar-dish-coupled reactor basic engineering and optimization. *Chemical Engineering and Processing – Process Intensification,* 156, article number 108050. doi: 10.1016/j.cep.2020.108050.

[17] Tan, J., He, Y., Yuan, Y., Wang, Z., Liu, J., & Cen, K. (2021). Structure and combustion characteristics of semi-cokes from a pilot-scale entrained flow gasifier using oxygen-enriched air. *Journal of the Energy Institute*, 97, 80-91. doi: 10.1016/j.joei.2021.04.006.

[18] Guo, Y., Guo, F., Zhou, L., Guo, Z., Miao, Z., Liu, H., Zhang, X., Wu, J., & Zhang, Y. (2021). Investigation on co-combustion of coal gasification fine slag residual carbon and sawdust char blends: Physiochemical properties, combustion characteristic and kinetic behavior. *Fuel*, 292, 120387. doi: 10.1016/j.fuel.2021.120387.

[19] Faraji, M., & Saidi, M. (2021). Hydrogen-rich syngas production via integrated configuration of pyrolysis and air gasification processes of various algal biomass: Process simulation and evaluation using Aspen Plus software. *International Journal of Hydrogen Energy*, 46(36), 18844-18856. doi: 10.1016/j.ijhydene.2021.03.047.

[20] Nam, H., Wang, S., Sanjeev, K.C., Seo, M.W., Adhikari, S., Shakya, R., Lee, D., & Shanmugam, S.R. (2020). Enriched hydrogen production over air and air-steam fluidized bed gasification in a bubbling fluidized bed reactor with CaO: Effects of biomass and bed material catalyst. *Energy Conversion and Management,* 225, article number 113408. doi: 10.1016/j.enconman.2020.113408.

[21] Galindo, A.L., Lora, E.S., Andrade, R.V., Giraldo, S.Y., Jaén, R.L., & Cobas, V.M. (2014). Biomass gasification in a downdraft gasifier with a two-stage air supply: Effect of operating conditions on gas quality. *Biomass and Bioenergy*, 61, 236-244. doi: 10.1016/j.biombioe.2013.12.017.

[22] Wang, L., Du, X., Chen, J., & Wu, Z. (2021). Numerical study on characteristics of biomass oxygen enriched gasification in the new gasifier on an experimental basis. *Renewable Energy*, 179, 815-827. doi: 10.1016/j.renene.2021.07.098.

[23] Zhao, J., Xie, D., Wang, S., Zhang, R., Wu, Z., Meng, H., Chen, L., Wang, T., & Guo, Y. (2021). Hydrogen-rich syngas produced from co-gasification of municipal solid waste and wheat straw in an oxygen-enriched air fluidized bed. *International Journal of Hydrogen Energy,* 46(34), 18051-18063. doi: 10.1016/j.ijhydene.2021.02.137.

[24] Arnold, R.A., Motta, I.L., & Hill, J.M. (2020). Impact of particle size and catalyst dispersion on gasification rates measured in a thermogravimetric analysis unit: Case study of carbon black catalyzed by potassium or calcium. *Fuel*, 288, article number 119677. doi: 10.1016/j.fuel.2020.119677.

[25] Kozak, R.O. (2018). Determination of straw particles layer porosity. *Scientific Bulletin of UNFU*, 94(28), 1, 91-94. doi: 10.15421/40280118.

[26] Melnikov, S.V., Atselkin, V.R., & Roshchin, P.M. (1980). *Planning experiment of agricultural processes research*. Leningrad: Kolos.

[27] Akberdin, A.A., Kim, A.S., & Sultangaziev, R.B. (2018). Experiment planning in the simulation of industrial processes. *Steel in Translation*, 48, 573-577. doi: 10.3103/S0967091218090024.

[28] Mysak, J., Lys, St., & Martynyak-Andrushko, M. (2017). Research on gasification of low-grade fuels in a continuous layer. *Easten-European Journal of Enterprise Technologies*, 2(8), 16-23. doi: 10.15587/1729-4061.2017.96995.

Експериментальні дослідження конструкційно-технологічних параметрів протипотокового газогенератора на рослинній біомасі

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Анотація. Актуальність дослідження обумовлена необхідністю розробки та впровадження конструкційно-технологічних рішень щодо підвищення ефективності процесу хіміко-термічної конверсії біомаси в горючий газ. У рамках зазначеного розроблено конструкцію газогенераторної установки, яка містить протипотоковий газогенератор, що працює на рослинній біомасі. Представлені дослідження пов'язують кількість теплоти, яку можна отримати при утилізації синтез-газу, виробленого за цикл роботи установки, з параметрами газодуттьового режиму та фізико-хімічними властивостями біомаси. Для поглибленого дослідження впливу газодуттьового режиму на кількість і теплотворну здатність синтез-газу, виробленого з біомаси, введено поняття коефіцієнту якості дуттьового перекриття. Даний коефіцієнт характеризує якість перекриття перерізу горловини камери газоутворення газовими струменями фурмової зони. Мета роботи полягала у встановленні впливу коефіцієнту якості дуттьового перекриття, об'єму газів дуття та порозності насипного шару біомаси на кількість теплоти, яку можна отримати при утилізації синтез-газу, виробленого за цикл роботи установки. Сплановано та проведено багатофакторний експеримент, який пов'язує залежний фактор із змінними, та побудовано відповідні поверхні відгуку. За результатами досліджень встановлено, що максимальне значення кількості теплоти, отриманої при утилізації синтез-газу, виробленого за годинний цикл роботи установки, становило 519 МДж. Дане значення досягається при коефіцієнті якості дуттьового перекриття 0,8, об'ємі газів дуття 47,4 м^3/год та порозності насипного шару біомаси 46,75 %. Результати вимірювань мають високу відповідність розрахунковим даним. Коефіцієнт детермінації становив R^2=0,983. Практична цінність дослідження полягає в обґрунтуванні раціональних конструкційно-технологічних параметрів роботи протипотокового газогенератора на біомасі, що дозволить підвищити ефективність виробництва енергії з біомаси. Отримані результати можуть бути використані як для створення конструкцій нових газогенераторних установок, так і для підвищення ефективності роботи вже наявних

Ключові слова: протипотоковий газогенератор, камера газоутворення, синтез-газ, фурмовий пояс, порозність, коефіцієнт якості дуттьового перекриття