З метою газифікації низькосортних палив пропонується конструкція високоефективної газогенераторної установки з прямопотоковим газогенератором, в конструкцію якої включено газоповітряний рекуператор та випаровувач для попередньої підготовки пароповітряної суміші. Процес газифікації є повністю контрольованим, оскільки робота випаровувача узгоджена з роботою системи подачі газів дуття, завдяки чому програмується вологість суміші, що подається в зону газифікації. В якості палива використано гранули із стебел рапсу 10 мм.

Проведено двофакторні експерименти, що дозволяють оцінити вплив об'єму та вологості повітря на нижчу теплоту згорання генераторного газу і на витрати маси палива на процес газифікації. Також досліджено вплив об'єму повітря та його вологості на температуру пароповітряної суміші, необхідної для процесу газифікації.

Встановлено, що оптимальна температура пароповітряної суміші складає 550…570 °С і досягається при об'ємі газів дуття, що надходять в газогенератор, в діапазоні 37…42 м^3/год та за вологості повітря 55…65 %. За цих умов нижча теплота згорання генераторного газу складає 12,3 МДж/м^3, що на 15,1 % вище порівняно з теплотою згоряння газу, отриманого без використання пароповітряного дуття в процесі газифікації.

Витрати гранул на процес газифікації зменшуються на 14,7 %, а об'єм газу, виробленого з кілограму гранул, зростає на 18 % і складає 3,2 м^3/кг.

Загальна енергетична ефективність використання наведеної технологічної схеми виробництва генераторного газу з гранул із стебел рапсу складає 23,5 %.

Представлено оригінальну методику складання теплового балансу для процесу пароповітряної газифікації рослинної сировини. За результатами експериментальних досліджень складено тепловий баланс для розробленої конструкції газогенераторної установки. Даний баланс свідчить про високу ефективність ведення процесу пароповітряної газифкації. Коефіцієнт корисної дії прямопотокового газогенератора складає 79 %, а газогенераторної установки в цілому 74,6 %.

Представлені дослідження можуть бути покладені в основу осучасненої методології теплових розрахунків мобільних та стаціонарних газогенераторних установок

Ключові слова: пароповітряна газифікація, газогенераторна установка, генераторний газ, теплота згорання газу, тепловий баланс

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THE RESULTS OF STUDY INTO THE EFFECT OF AIR-STEAM BLAST ON THE LOW-GRADE FUEL GASIFICATION PROCESS

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1. Introduction

Substantial progress in designing gas generating equipment and a thorough theoretical study of the process of gas production from agricultural plant raw materials indicate that considerable attention to this issue is paid currently [1, 2]. However, there are a number of technical issues that hinder obtaining expected results from the application of gas generation technologies because of lack of practical data [3]. The ways to raising calorific value of gas [4] and intensifying the process gasification of low-grade fuels (e.g. sunflower husk, cob core, grain straw, rape stems as well as briquettes and pellets produced from them) were not yet found [5, 6].

These issues are being addressed both by design and technological methods. In particular, design methods should include improvement of such structural members as gasification chambers, grates, bins, etc. [7, 8]. Technological improvements should provide use of steam-oxygen blast at normal and high pressures [9] or oxygen-enriched air blast [10]. There are methods for improving efficiency of the gasification process by providing high temperatures in the active zone of the gas generator [11] and expansion of reacting surface area of fuels [12].

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The use of air-steam blast is promising for intensifying the gasification process. This method will make it possible not only to ensure continuity of the process through maintenance of a constant high temperature in the active zone of the gas generator but also higher content of CO, H_2, and CH_4 in the gas. Therefore, technology of air-steam gasification of biomass is an urgent task solution of which will ensure obtaining of gas with technical and operational characteristics higher in comparison with other gasification methods.

2. Literature review and problem statement

The gasification process is one of the most promising technologies of thermochemical conversion of plant raw materials into combustible gas [1, 4, 13] and the method of gas production in gas generators with a continuous bed is the simplest and most economical method [11, 14].

However, in known designs of gas generating units with a continuous bed, combustible gas produced from plant raw materials has calorific value not more than 10 MJ/Nm^3 [15, 16]. Unlike this type of gas generators, modern gas generators with a fluidized bed have efficiency factor up to 80 % and calorific value of combustible gas reaches 18.5 MJ/Nm^3 [9]. However, they have an elaborate design requiring significant energy consumption in operation and maintenance.

Consequently, the issue of improving efficiency of the process of gasification of low-grade plant raw materials in continuous-bed gas generators and production of a generator gas with high technical characteristics remains unresolved.

The gas blowing regime [17] and the gasification chamber design play an important role in generator gas production [8, 11]. The theories discussed in [17] consider the concept of maximum path passed by air jet from a tuyere of a certain diameter through a layer of fuel material, that is, ability of the jet to maintain necessary speeds at a certain distance from the tuyere hole which ensures high efficiency of gas production. However, the studies presented in [17] have relation to cold blast.

The use of steam [18, 19] is effective in production of high-energy gas (9–13 MJ/nm^3) although this technology requires significant heat consumption for formation of air-steam blast with involvement of costly equipment.

Scientific studies devoted to this subject and conducted using gas generators with direct gasification of coal are known [17]. Two main lines of practical application of air-steam gasification are considered. The first of them is use of oxygen (or oxygen-enriched air) and steam [20]. This technology requires significant capital investment in equipment for accumulation and supply of oxygen in the reaction zones of the gasification unit which makes them less attractive for their commercial use.

Alternative technology avoids the need for preliminary preparation of the air-steam mixture by separating the processes of combustion and gasification/pyrolysis into two parallel zones: air is supplied to one of them and steam to the other. This technology is widely used in gas generating units with a fluidized bed for coal gasification. Heat from the combustion zone to the gasification zone is transferred by circulating the layer through two zones [21, 22]. Commercial plants in the United States, Austria and Denmark are operated using this technology but the capital expenditures for this technology are also quite high and the prospects of its widespread use are rather vague.

In Europe, ways of fuel gasification with the help of pure steam [23, 24], steam-oxygen or steam and oxygen containing mixtures are being developed [21, 25, 26]. The purpose of these studies is production of generator gas with high hydrogen content. Although vegetable raw materials are used as fuel, all known laboratory, demonstration and commercial gas-generating plants utilize direct gasification process. No studies of use of air-steam blast for gas generators utilizing the reverse gasification process were conducted.

The views of many scholars are mixed regarding the use of air-steam blast in the gasification process although high efficiency of application of this technique is confirmed in the vast majority of scientific papers. Unlike air blasting, the resulting gas has high H_2 content and low tar content due to its almost complete cracking in the reactor at high temperatures (1,000–1,100 °C). This effect can be intensified by the use of catalysts [27, 28].

When studying the air-steam gasification process in [29], autothermal conditions of reactor operation were not changed. Studies are known [30, 31] in which autothermal gasification with air was used to intensify the process but the use of low-power plants (up to 150 kW/h) made it impossible to conduct adiabatic studies.

The studies for determining optimal values of the ratio of steam and air to fuel in the air-steam gasification process are of interest. It has been shown in [31] that the carbon conversion coefficient and the calorific value of gas have increased by almost 20 % just due to an increase in steam to fuel ratio from 0.58 to 0.71 kg/kg. This effect was obtained during autothermal coal gasification in a fluidized-bed gas generator. The results of these studies may be partially useful in studying the process of air-steam gasification of plant raw materials in gas generators using the reverse gasification process.

In studies [13, 14, 32], chemical equilibrium was combined with energy balance where temperature of the adiabatic reaction is obtained at the expense of energy conservation. The equilibrium constant characterizes the ratio of speed of reverse reaction to that of direct reaction. Relative yield of reaction products is established according to this parameter. The number of combustible components in the gas is the greater the higher numerical value of the equilibrium constant. This statement is valid under conditions of air-steam gasification of coal in direct-process gas generators. However, practical application of the equilibrium model to the conditions of air-steam gasification of plant raw materials in reverse-process gas generators is doubtful. The importance of conducting such studies is mentioned in [33].

It is noted in [28, 31] that considerable attention should be paid to operational properties and chemical composition of the blast mixture when practicing air-steam gasification of plant materials. The use of technically inferior mixtures with a high steam to fuel ratio leads to reduction of temperature in the active zone of the gas generator although the use of small amounts of steam can greatly improve quality of the generator gas due to intensification of the processes of hydrocarbon reforming and tar cracking and the heterogeneous process conditions.

Consequently, in order to improve efficiency of the process of chemical-thermal conversion of plant materials into a combustible gas in a direct-flow gas generator, a complex of studies using achievements of modern scientific thought and methodology should be conducted. The most intensive way to produce gas is air-steam gasification of fuels [19, 22–25]. The advantages of this gasification method are as follows:

high calorific value of gas, possibility of using gas for power generation needs due to insignificant content of tars and volatile compounds; simplicity of design; high degree of conversion of hydrocarbons.

3. The aim and objectives of the study

This study objective was to substantiate the use of air-steam blast to improve efficiency of the process of gasification of low-grade fuels in a direct-flow gas generator.

To achieve this goal, it was necessary to fulfill the following tasks:

– to develop a design of a gas generator with air-steam blast for gasification of low-grade fuels;

– to determine technical and operational parameters of the process of air-steam gasification, namely:

a) the effect of volume and humidity of blast air on the lower heat of combustion of the generator gas in the process of gasification of low-grade fuels;

b) the effect of volume and humidity of blast air on the fuel mass loss in the gasification process;

c) the effect of volume and humidity of blast air on temperature of the air-steam mixture supplied to the gas generator;

– to develop a procedure for compiling heat balance and apply it to the compiling heat balance of the experimental plant.

4. Materials and methods used in studying the influence of input parameters on the process of air-steam gasification

4. 1. Materials and equipment used in the experimental studies

An analytical study of influence of air-steam blast on heat of combustion of generator gas and minimization of fuel consumption will make it possible to find rational regime parameters of the gasification process and operation of the gas generator itself. This will enable development of a flowsheet of the gasification process and the design of a production prototype.

Pellets (10 mm size) produced from rape stems were used as fuel for the gas generator. The pellets were prepared according to TU U 37.2-36783545-001:2011 Palletized Biofuel. Specifications. Chemical and technical parameters of the pellets produced from rape stems effecting working condition are as follows. Moisture: 8.88 %; ash: 7.26 %; volatile matter: 67.43 %; sulfur: 0.11 %; lower heat of combustion: 15.04 MJ/kg; higher heat of combustion: 17.91 MJ/kg; chlorine (dry state): 0.085 %. Standardized fuel was used to eliminate the effect of its humidity on the gasification process.

The task was to determine dependence of temperature of the air-steam mixture, lower heat of combustion of gas and the fuel mass consumption for the gasification process in a direct-flow gas generator on humidity and air volume.

A technological process for generator gas production and the block diagram of a gas generating plant with a direct-flow gas generator have been developed for experimental studies (Fig. 1).

The plant included the following: a direct-flow gas generator 1; a system for feed of blast gases; a system for generator gas purification; unit 16 for gas sampling. The gas generator output was 60–68 m^3/h.

The blast gas supply system included fan 2 for air supply to the active zone and a flow controller. The system for purifying the generator gas included cyclone 11, fine purification unit 12 with condensate drainage pipe 23. Tekhnovagy Co. TVE 500-10 laboratory scales 3 made according to DSTU EN 45501 were used for continuous recording the fuel volume consumed by the gas generator during its operation cycle and scales 24 TVE 150-5 were used for ash weighing.

To remove residual moisture from the gas, moisture separator 15 was used previously to making gas analysis in unit 16.

Thermocouples used for recording temperature in the characteristic locations of the plant: tungsten-rhenium TVR-251 (4) and Chromel-Alumel TKhA-KhA-2388 065-16 (5, 6, 10). Timing of the plant operation was carried out with the use of the SOSpr-25-2-000-4 mechanical stopwatch. Total time of the experiment was 70 seconds (15 seconds for sampling and 55 seconds for the sample analysis).

Vacuum pump 14 was installed in the gas withdrawal line in order to simulate the consumer thermal equipment. Receiver 22 was used to accumulate and equalize composition of the generator gas. Supply of generator gas was regulated with throttle washer 17 and valve 18 was used for the pipeline shut-off. Measurement and registration of the caloric content of the produced gas was carried out with the CM6G calorimeter 13. The measurement results were automatically integrated by a PC. Agilent's 6890N chromatograph was used to determine chemical composition of the gas in accordance with requirements of DSTU ISO 6974-1:2007. A heat balance was compiled according to chemical composition of the gas.

The recent methods of air-steam gasification [9, 19] offered to produce generator gas from biomass with a heating value of 9–10 MJ/Nm^3, are difficult in their maintaining. The task was to develop a simple by design and in maintenance system for preparation and feed of air-steam mixture to the direct-flow gas generator. This system should enable production of gas with higher heat of combustion at minimal fuel consumption for the gasification process.

With the designed plant including a direct-flow gas generator, this is achieved by the use of air-gas recuperator 7 which utilizes about 90 % of the generator gas temperature and transfers it to the blown air. While moving along channels of recuperator 7, the air preheated to a temperature of about 400–600 °C passes return valve 25 and enters evaporator chamber 20 where it is moistened with water steam. Evaporator 20 operation is synchronized with operation of the blast gas supply system programming humidity of the air to be supplied into the gasification zone. Gas pipe 8 is an integral part of the recuperator. Since temperature of the gas in recuperator 7 is significantly reduced, liquefaction of the moisture contained therein takes place. To remove condensate from the recuperator and drain it to the storage tank contained in evaporator 20, pipe 19 is provided. This pipe is equipped with a return valve, so that the water steam does not enter the gas.

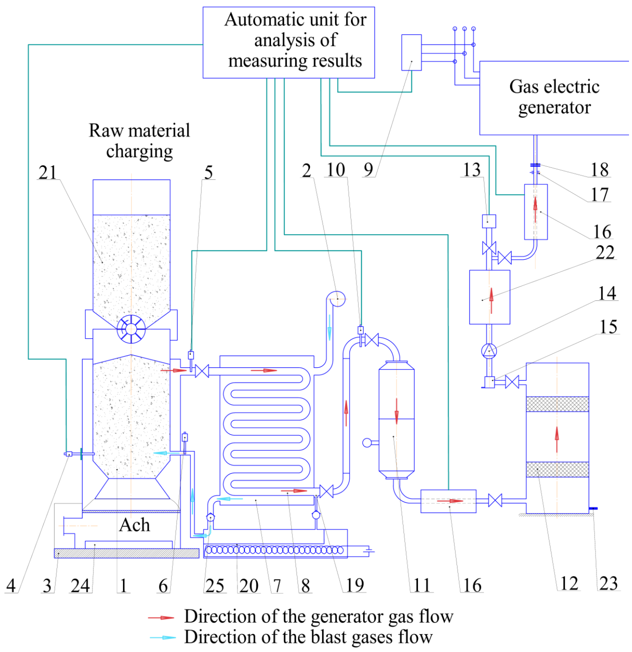
The gas generator is equipped with raw material bin 21 to maintain a constant level of fuel. It was necessary in the experiments to exclude influence of complete burning of fuel on the results obtained.

To utilize the produced gas, a gas electric generator was included in the design and counter 9 was used for recording electricity produced by it.

The studies were carried out in the gas generator at an atmospheric pressure of 0.1–0.3 MPa.

The studies conducted involved planning of a two-factor experiment with two controlled variables and three initial measured values, such as a lower heat of combustion of the resulting gas, loss of mass of the raw material gasified, as well as temperature of the gas-air mixture at the entrance to the gas-generating chamber.

According to the study results, use of the gas generating plant of the proposed design ensures increase in efficiency of the gasification process by means of air-steam blast.



a

b

Fig. 1. Experimental gas-generating plant with a direct-flow gas generator: block diagram (*a*); general view (*b*)

4. 2. Procedure for processing the results of experimental studies

The task was to establish dependence of the lower heat of combustion of gas and the consumption of fuel required for gas production, air volume and humidity. It was also necessary to establish dependence of the air-steam mixture temperature formed by the air recuperator and evaporator on the volume and humidity of the air from which it was formed. A two-factor experiment was used to determine the effect of variable factors on temperature of the air-steam mixture, reduction of fuel consumption and the lower heat of combustion. Levels and intervals of variation of the factors are presented in Table 1–4.

Table 1

Levels and intervals of factor variation

Factor name	Factor designation		Levels of factor variation			Intervals of factor variation
	natural	normalized	(–1)	(0)	(+1)	
Air humidity, %	W	X_1	40	62.5	85	22.5
Air-steam mixture volume, m^3/hr	V_{air}	X_2	30	40	50	10

Table 2

Designation of dependent factors

Lower calorific value of the gas, MJ/nm^3	Q^L_{gg}	Y1
Variation of fuel mass consumption related to heat of combustion of the generated gas, kg/MJ	dm/dQ^L_{gg}	Y2
Temperature of the blast air-steam mixture at the entrance to the gasification chamber, °C	$T_{air.sum.}$	Y3

Table 3

Matrix of the two-factor experiment planning

Experiment No.	*X1*	*X2*	*Y1*	*Y2*	*Y3*
1	–1	–1	y_{11}	y_{21}	y_{31}
2	+1	–1	y_{12}	y_{22}	y_{32}
3	–1	+1	y_{13}	y_{23}	y_{33}
4	+1	+1	y_{14}	y_{24}	y_{34}
5	0	–1	y_{15}	y_{25}	y_{35}
6	+1	0	y_{16}	y_{26}	y_{36}
7	0	+1	y_{17}	y_{27}	y_{37}
8	–1	0	y_{18}	y_{28}	y_{38}
9	0	0	y_{19}	y_{29}	y_{39}

The experiments were performed in triple repeats with mandatory randomization to reduce the experimental errors.

Reproducibility of experiments was verified according to the Cochran criterion. In the case of non-fulfillment of the condition of reproducibility by the Cochran criterion, accuracy of measurement and the conditions of conducting the experiments were checked, which resulted in the maximum variance value.

In all experiments, significance of the coefficients of the regression equations was estimated according to Student's criterion and adequacy of the regression equations obtained was estimated according to Fisher's criterion. The resulting data were processed using the Microsoft Excel Search Solution software.

Table 4

Processing of experimental results and construction of correlation models

Experiment No.	Experimental values of variable parameters		Experimental (average) values of dependent parameters			Values of dependent parameters by the results of regression analysis			Correlation of experimental results with regression dependences		
	$X1$	$X2$	$Y1_{cep}$	$Y2_{cep}$	$Y3_{cep}$	$Y1_{p}$	$Y2_{p}$	$Y3_{p}$	δ_1	δ_2	δ_3
1	40	30	7.69	0,79	403	3.717	0.799	403	–0.0035	–0.0113	0
2	80	30	8.31	0.79	391	8.168	0.802	395	0.0174	–0.0150	–0.0101
3	40	50	12.11	0.85	349	8.337	0.848	345	0.4526	0.0024	0.0116
4	80	50	6.96	0.89	377	6.87	0.896	381	0.0131	–0.0067	–0.0105
5	62,5	30	9.35	0.80	405	9.104	0.796	409	0.0270	0.0050	–0.0098
6	80	40	8.64	0.79	483	8.497	0.780	487	0.0168	0.0128	–0.0082
7	62,5	50	8.66	0.90	382	8.514	0.893	387	0.0171	0.0078	–0.0129
8	40	40	9.28	0.77	549	9.116	0.773	540	0.0180	–0.0039	0.0167
9	62,5	40	12.35	0.74	548	12.202	0.751	548	0.0121	–0.0146	0

4. 3. The procedure for determining the components of the gas generator heat balance

According to the results of experiments, components of the gas generator heat balance are determined as follows:

Higher calorific value, q_1, of the fuel gasified per hour, J/h:

$$q_1 = Q_{wf}^{H} \cdot \frac{B}{h}, \tag{1}$$

where Q_{wf}^{H} is the higher calorific value of the working fuel, J/ kg; B is the total fuel quantity, kg; h is time, hour.

Sensible heat, q_2, of fuel, J/h:

$$q_2 = \frac{B}{h} \cdot C_f \cdot t_f, \tag{2}$$

where C_f is the fuel heat capacity in the temperature range from 0 to t_f, J/(kg·°C); t_f is temperature of the fuel loaded to the gas generator, °C.

Heat content of dry air, q_3, introduced into the gas generator, J/h:

$$q_3 = G_{dry\ air} \cdot (C_p)_{air} \cdot t_{mix}, \tag{3}$$

where $(C_p)_{air}$ is the heat capacity of the air in the temperature range from 0 to t_{mix}, J/(kg·°C); t_{mix} is temperature of the air-steam mixture at the entry to the gas generator, °C; $G_{dry\ air}$ is the hourly amount of dry air, kg/h.

Heat content of steam, q_4, in the air-steam mixture, J/h:

$$q_4 = (G'_{steam} + d_{air} \cdot G_{dry\ air})(1 - X) \cdot i_{steam}, \tag{4}$$

where i_{steam} is the heat content of a kilogram of saturated steam at temperature t_{mix}, J/kg; G'_{steam} is the hourly amount of steam actually entered into the gas generator, kg/h; d_{air} is the moisture content in air, kg/kg; X is the humidity of steam in the mixture, %.

Heat content of moisture brought in drops to the gas generator by blasting, q_5, J/kg:

$$q_5 = (G'_{steam} + d_{air} \cdot G_{dry\ air}) \cdot X \cdot t_{mix}. \tag{5}$$

The consumption items consist of a higher calorific value of the produced dry gas, its sensible heat, heat content of water steam in the gas, calorific value of tar, ejected dust, coke-like residue of biomass and the residual component containing heat loss to environment and all unaccounted heat losses and observation errors.

The higher calorific value of an hourly gas amount, q'_1, J/h:

$$q'_1 = Q_{gg}^{H} \cdot G_{dry\ gas}, \tag{6}$$

where Q_{gg}^{H} is the higher calorific value of the generator gas, J/kg; $G_{dry\ gas}$ is the hourly dry gas weight, kg/h.

Sensible heat of gas, q'_2, J/h:

$$q'_2 = G_{dry\ gas} \cdot (C_p)_{gas} \cdot t_{gas}, \tag{7}$$

where $(C_p)_{gas}$ is the heat capacity at a constant pressure of one kilogram of dry generator gas in the temperature range from 0 to t_{gas}, J/(kg·°C).

Heat capacity of the generator gas, $(C_p)_{gas}$, is determined from the heat capacities of the gas components, J/ kg of the dry gas:

$$(C_p)_{gas} = (C_p)_{CO_2} \cdot \frac{CO_2^g}{100} + (C_p)_{O_2} \cdot \frac{O_2^g}{100} + (C_p)_{C_2H_4} \cdot \frac{C_2H_4^g}{100} + \\ + (C_p)_{CH_4} \cdot \frac{CH_4^g}{100} + (C_p)_{CO} \cdot \frac{CO^g}{100} + (C_p)_{H_2} \cdot \frac{H_2^g}{100} + (C_p)_{N_2} \cdot \frac{N_2^g}{100} \tag{8}$$

where CO_2^g and O_2^g are the weight percentages of the corresponding gases per kilogram of gas.

Heat content of methane and ethylene is determined as in [14].

Heat content of water steam in a generator gas, q'_3, J/h:

$$q'_3 = d_{gas} \cdot G_{dry\ gas} \cdot i_{h.steam}, \tag{9}$$

where d_{gas} is moisture content in gas, kg/kg.

Since water steam in the gas is overheated, heat content of a kilogram of steam, $i_{h.steam}$, is determined from the following formula, J/kg steam:

$$i_{h.steam} = i_{d.p.} + (C_p)_{steam} \cdot t_{gas} - t_{d.p.}, \tag{10}$$

where $i_{d.p.}$ is the heat content of a kilogram of saturated steam at the dew point corresponding to the gas saturation, J/kg steam; $(C_p)_{steam}$ is heat capacity of steam in the temperature range from $t_{d.p.}$ to t_{gas}, J/(kg·°C); $t_{d.p.}$ is temperature of the dew point determined by elasticity of the water steam according to the psychrometer readings, °C.

High calorific value of tar contained in gas, q_4', J/h:

$$q_4' = Q_{tar}^H \frac{m_{tar}}{h}, \qquad (11)$$

where Q_{tar}^H is the higher working calorific value of the tar, J/ kg; m_{tar} is the total amount of tar, kg.

The higher calorific value of the matter removed from dust collectors and channels, q_5', J/h:

$$q_5' = Q_{matter}^H \frac{m_{matter}}{h}, \qquad (12)$$

where Q_{matter}^H is the highest working calorific value of the removed matter, J/kg; m_{matter} is total amount of removed matter, kg.

The higher calorific value of dust contained in gas, q_6', J/h:

$$q_6' = Q_{dust}^H \frac{m_{dust}}{h}, \qquad (13)$$

where Q_{dust}^H is the highest working calorific value of dust flying in the gas, J/kg; m_{dust} is the total amount of dust flying in the gas, kg.

Heat lost in coke-like residues of biomass, q_7', J/h:

$$q_7' = 339.3 \cdot 10^3 \cdot C_R \frac{B}{h}, \qquad (14)$$

where $339.3 \cdot 10^3$ is the amount of heat released during combustion of one kilogram of the fuel carbon according to the Mendeleyev's formula; C_R is amount of carbon in the coke-like residues of biomass in per cents of the fuel weight, %.

Losses of heat to environment, q_8' etc. combined into a residual component are determined from the difference in the heat gain and the already estimated losses:

$$q_8' = \Sigma q_{1-5} - \Sigma q_{1-7}'. \qquad (15)$$

The proposed procedure provides an opportunity of general energy assessment for the process of air-steam gasification of plant raw materials in a direct-flow gas generator and determination of this process efficiency.

To determine efficiency factor of the direct-flow gas generator and the plant as a whole, the procedure described in [36] was used.

5. Results obtained in the study of influence of input parameters on the process of air-steam gasification of low-grade fuels

5. 1. Results obtained in the study of influence of volume and humidity on the lower heat of combustion of the generator gas

Mathematical description of dependence of the lower heat of combustion of the generator gas on humidity and volume of air is presented as a polynomial of the second order:

$$Q_{gg}^L = -43.17 + 0.73 \cdot W + 1.63 \cdot V_{air} - -0.005 \cdot W^2 - 0.0024 \cdot V_{air} \cdot W - 0.02 \cdot V_{air}^2. \qquad (16)$$

The table value of the Cochran coefficient is $G(0.05; n; f_U)=0.05157$ for the 5 % level of significance, the number of experiments $n=8$ and the number of degrees of freedom of each experiment $f_U=2$ at $m_0=3$ repetitions [35]. The estimated value of the Cochran coefficient $G=0.432<G(0,05; n; f_U)=0.5157$ indicating reproducibility of the experiments. The calculated Fischer coefficient $F=0.786<F(0.05; f_{ad}; f_y=3.838$, hence the model is adequate and can be used to describe the object.

Dependence of the lower heat of combustion of gas on the volume of air and its humidity is graphically presented in Fig. 2.

It is seen from Fig. 2 that the obtained dependence has a clear peak which defines the rational range of regulation of parameters such as humidity, W, and volume, V_{air}, of air for raising the indicator of low calorific value of combustion, Q_{gg}^L, of the produced generator gas.

For the values of blast air volume, V_{air}, below 35 m^3/h, there are characteristic low values of lower heat of combustion, Q_{gg}^L, of the generator gas because of the low concentration of oxidant in the gasification zone. The lower heat of gas combustion, Q_{gg}^L, reaches as much as 8…10 MJ/m^3. With an increase in air volume, V_{air}, to 37…42 m^3/h, there is a phenomenon of complete oxidation of fuel particles accompanied by a growth of temperature in the reaction zone, and the lower heat of combustion of gas reaches $Q_{gg}^L = 12.3$ MJ/m^3. With further increase in the volume of blast air, V_{air}, over 45 m^3/h, it is observed that the fuel particles that have not completed their participation in the gasification process and the heat are transferred from the gasification zone which leads to a sharp decrease in the lower heat of gas combustion, Q_{gg}^L.

At values of air humidity, W, in the range from 50 % to 75 %, maximum values of the lower heat of combustion, Q_{gg}^L, of the generated combustible gas are observed. This phenomenon is explained by the fact that the water steam at temperatures of 1,000…1,100 °C decomposes into oxygen and hydrogen which take an active part in formation of CO and H_2 molecules. In a gas generator of this type, with an increase in air humidity, W, by more than 75 %, the amount of heat consumed for heating and decomposition of water steam increases. This, in turn, leads to a temperature drop in the gasification zone and worsening of gas quality. If the value of the lower heat of combustion of the generator gas is known, the higher heat of combustion can be calculated according to [11, 17] so that the data agreed with the heat balance.

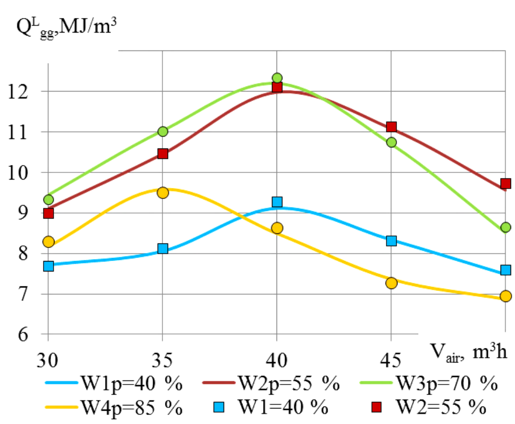


Fig. 2. Change of the lower heat of combustion of the generator gas, Q_{gg}^L, depending on humidity, W, and volume, V_{air}, of air

5. 2. Results obtained in the study of influence of air volume and humidity on the fuel mass loss in the gasification process

Mathematical description of dependence of the fuel mass loss on volume and humidity of air is presented in the form of a polynomial of the second order:

$$dm/dQ = 1.735 - 0.003 \cdot W - 0.048 \cdot V_{air} + 0.0006 \cdot V_{air}^2. \quad (17)$$

The value of the Cochran coefficient $G=0.2832<G(0.05; n; f_U)=0.5157$ for the 5 % level of significance, the number of experiments, $n=8$, and the number of degrees of freedom of each experiment $f_U=2$, which indicates reproducibility of experiments. The value of the Fisher coefficient $F=0.623<F(0.05; f_{ad}; f_y)=3.838$. So, the model is adequate.

The dependence obtained in accordance with the experimental data (Fig. 3) confirms the initial hypothesis about existence of a range of blast modes in which minimization of fuel consumption for gas generation takes place.

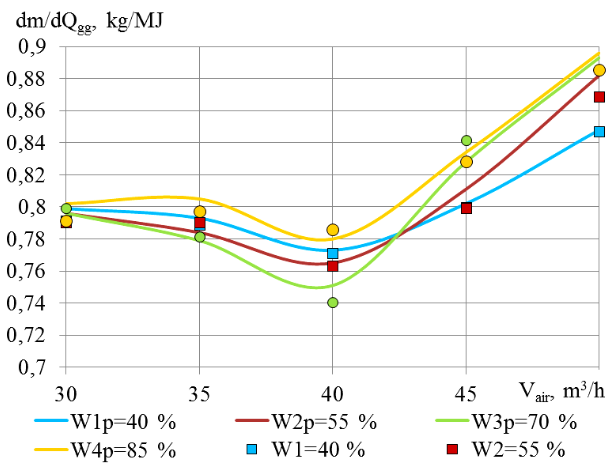


Fig. 3. Change of fuel mass consumption for the gasification process depending on humidity, W, and volume, V_{air}, of air

In this case, under the blast regime, we mean combination of the blast air volume and humidity.

Thus, for all investigated humidity values in the range of air blast from 37 to 42 m^3/h, there was a decrease in fuel mass consumption to the level of 0.75 kg of rape stem pellets for obtaining 1 MJ of calorific value of the produced generator gas. At lower values, there was an oxidant deficiency and with an increase in air blast volume above 42 m^3/h, removal of heat and fuel particles from the gas formation zone was observed resulting in a decrease in calorific value of the gas produced.

Humidity of the blast air affects fuel consumption in the gas production process to a lesser extent compared with the blast air volume. However, according to Fig. 3, there is a rational range of variation of this parameter values in which fuel consumption for gas production will be the smallest. Consequently, rational range of humidity values is W=45...70 %. With an increase in humidity above 70 %, energy consumption for air heating grows, which, in turn, increases fuel consumption.

5. 3. Results obtained in the study of influence of air volume and humidity on temperature of the air-steam mixture fed to the gas generator

Mathematical description of dependence of temperature of the formed air-steam mixture on air volume and humidity is presented in the form of a polynomial of the second order:

$$T_{air.st.mix.} = -1622.37 + 100.35 \cdot W + 6.77 \cdot V_{air} - 1.33 \cdot W^2 - 0.05 \cdot V_{air} \cdot W - 0.074 \cdot V_{air}^2. \quad (18)$$

The value of the Cochran coefficient $G=0.328<G(0.05; n; f_U)=0.5157$ for the 5 % level of significance, the number of experiments, $n=8$, and the number of degrees of freedom of each experiment, $f_U=2$ which indicates reproducibility of the experiments. The value of the Fisher's coefficient $F=2.347 < F(0.05; f_{ad}; f_y)=3.838$. So, the model is adequate.

Dependence of temperature of the air-steam mixture on humidity and volume of air is shown graphically in Fig. 4.

The dependence (Fig. 4) reflects relation between the regime parameters of the blast air (humidity, volume) and temperature attained by the formed air-steam mixture when it passes through the recuperator and the evaporator. When passing through the recuperator, air takes heat from the generated gas, heats up and it humidifies when passing through the evaporator.

According to Fig. 4, in the range of blast air volume 37 to 42 m^3/h, maximum values of temperature of the air-steam mixture reaching 550...570 °C are observed. The effect of humidity on temperature of the air-steam mixture was quite noticeable in this experiment. This is explained by a significant amount of water steam. The highest temperatures of the air-steam mixture were observed at humidity of 47 % to 67 %.

With an increase in the blast volume over 42 m^3/h, there was a significant reduction in temperature of the air-steam mixture below 470 °C which is associated with a shorter time of air contact with the heat exchanger. At air flow lower than 35 m^3/h, production of generator gas decreases and its temperature at the outlet of the gas generator decreases.

Thus, maintenance of the air blast regime in a rational range of values from 37 to 42 m^3/h at air humidity of 55...65 % will reduce fuel consumption to maintain the gasification process, thus affecting the dependences presented above.

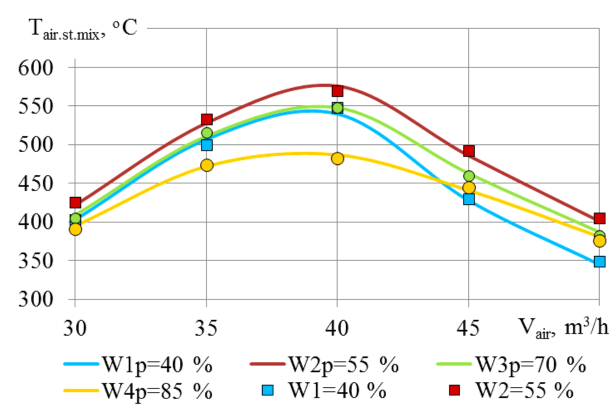


Fig. 4. Variation of the air-steam mixture temperature, $T_{air.st.mix.}$, depending on humidity, W, and volume, V_{air}, of air

5. 4. Heat balance of the gas generating plant

Heat balance of the gas generator includes all heat supplied to the gas generator and taken from it. At the same time, the balance can be drawn up both for higher and lower calorific values of the gasified fuel and produced generator gas. The heat brought to the gas generator consists of the calorific value of the fuel, its sensible heat and the heat content (enthalpy) of the steam and air introduced into the active zone of the gas generator.

Consumption items include the higher calorific value of the produced dry gas, its sensible heat, heat content of water steam in the gas as well as the calorific value of tar, taken-off matter, dust, coke-like residue of the biomass and a residual component. The residual component contains heat losses to environment and all unaccounted heat losses and observational errors.

The calculated values of the heat balance substituted into Table 2 give a general picture of energy flow in the gas generator.

The flow sheet includes an electric evaporator (to provide the air-steam regime) and a heat exchanger that enables the use of sensible heat of the generator gas. Therefore, relevant items are included in the balance sheet calculation. In addition to the calorific value of the generator gas, the consumption part of the balance includes the amount of sensible heat of the gas, residual matters of the gasification process, and the like. In this case, the balance sheet will take the form shown in Fig. 5.

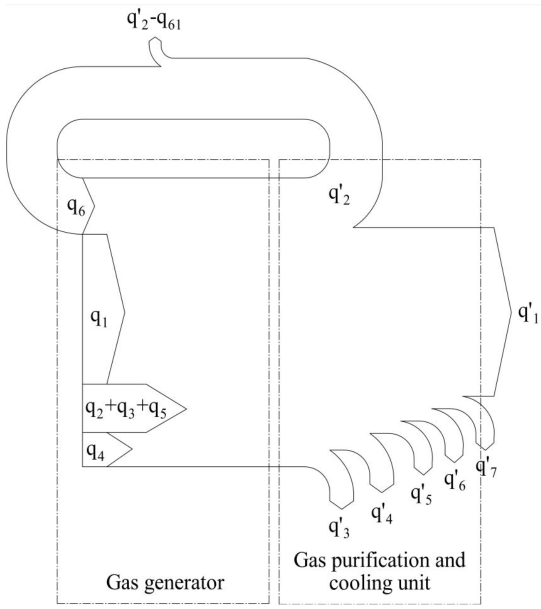


Fig. 5. Heat balance of the gas generating plant

Analysis of the resulting heat balance of the process of air-steam gasification of plant raw materials allows us to establish useless heat losses, determine causes of the losses, the ways of eliminating them and helps to select the operation mode that provides the highest efficiency.

The heat balance of the plant is divided into two units according to the equipment groups involved in the process of gas generation and preparation for combustion. In the gas generator, the heat input items including calorific value of the fuel, q_1, sensible heat of the fuel, q_2, heat content of air, q_3 and water steam, q_4, as well as a portion of the generator gas heat, q_6, which is transferred to the blast gas through the heat exchanger is taken into account. To increase accuracy, heat content of the condensed water in the blast mixture, q_5, is included to the heat balance.

Consumption items of the heat balance are taken into account in the purification and cooling units. Calorific value of the produced generator gas, q_1' is the most significant of them. Sensible heat of gas is used partially for heating blast gases, except for irreversible losses $(q_2'-q_6)$ magnitude of which depends on the type and quality of the heat exchanger.

Table 5

Heat balance of the gas generator

Heat input	J/h	%
Calorific value of the fuel	q_1	59
Sensible heat of the fuel	q_2	1
Heat content of dry blast air	q3	5
Heat content of blast water steam	q_4	15
Heat content of condensed water in the blast mixture	q_5	0.5
Utilization of sensible heat of the generator gas	q_6	19.5
Total	Σq1–5	100 %
Heat consumption	J/h	%
Calorific value of the gas	q_1'	73.7
Sensible heat of the gas	q_2'	21.5
Heat content of water steam in the gas	q_3'	1,5
Calorific value of the tar	q_4'	0.3
Calorific value of the carry-over	q_5'	1.3
Calorific value of the dust	q_6'	1
Residual component	q_8'	0.7
Total	$\sum q_{1-8}'$	100 %

According to the results of experimental studies, efficiency of direct-flow gas generator was 79 %, and that of the gas generating plant as a whole was 74.6 %.

6. Discussion of results obtained in the study of influence of input parameters on the process of air-steam gasification

The design of a highly efficient gas generating plant with a direct-flow gas generator for vegetable fuels is distinguished from known gas generator designs by using air-steam gasification for gas production. The plant includes an air-gas recuperator and an evaporator for preliminary preparation of the air-gas mixture and simultaneous cooling of the generator gas. Moving along the channels of the recuperator, air preheated to 400–600 °C enters the evaporator chamber where it is moistened with water steam. Operation of the evaporator is synchronized with operation of the system supplying blast gases which ensures programing of humidity of the mixture to be fed into the gasification zone. Consequently, the gasification process is completely controlled.

Experimental studies have established the possibility of producing generator gases in a direct-flow gas generator with the lower heat of combustion equal to 12.3 MJ/m^3 (Fig. 2). This figure is achieved at the volume of air blast V_{air}=37...42 m^3/h and humidity W=55...65 %. At these values of V_{air} and W (Fig. 4), peak temperatures of the air-steam mixture, $T_{air.st.mix}$=550...570 °C, are observed.

The value of gas combustion heat, MJ/m^3, is 15.1 % higher compared to the heat of combustion of the generator gas obtained with other well-known designs of direct-flow gas generators [1, 3, 6, 10, 14, 21].

This is explained by the fact that the use of steam-gas blast ensures equalization of the temperature regime (temperature is 1.000–1.100 °C in the active zone) and stabilization of the gasification process. This temperature regime is favorable for rapid pyrolysis which increases yield of volatile gaseous products, such as CO. In this way, intensive formation of higher hydrocarbons with further cracking is avoided. Consequently, addition of water steam to reaction zones of gas generators makes it possible to avoid the negative process of formation of ash-slag agglomerates.

Similar studies were carried out in [37] with a fluidized-bed gas generating plant and a positive influence of the use of steam and gas blast in the process of gasification of plant material was observed. Also, addition of water steam contributes to an increase of content of such combustible component as H_2 in the generator gas. In comparison with other studies on the biomass gasification in continuous-bed gas generators [11, 14, 16], addition of water steam has resulted in a 13 % increase in H_2 content in the gas.

For all studied values of humidity at the volume of blast air V_{air}=37...42 m^3/h, there was a decrease in the mass loss of fuel to the level of 0.75 kg of pellets to obtain 1 MJ calorific value of the produced generator gas. According to the results of the two-factor experiment, blast air humidity affected the losses of fuel for the gas production process to a lesser extent compared with the of blast air volume. However, there is a range of variation of humidity values (W=55...65 %) in which fuel consumption for gas production will be the smallest (Fig. 3).

Consequently, the presented results provide benefits of using air-steam blast in the process of gasification of plant raw materials and open up prospects for designing new effective gas generating plants with a continuous bed. In comparison with the designs discussed in [7, 8, 16], cost of gas generators for these plants will be 18–22 % less due to simplification of the design of the gasification chamber, the tuyere belt, the grates and absence of a fuel poking system.

In order to eliminate influence of fuel humidity on the gasification process, standardized fuel was used. It was manufactured according to TU U 37.2-36783545-001:2011. In addition, gasification of fuels with humidity up to 40 % was studied. The studies indicate that values of parameters within limits of V_{air}=37...42 m^3/h, W=55...65 % and $T_{air.st.mix}$=550...570 °C are rational for fuels with humidity up to 30 %. For fuels with higher humidity, parameters V_{air} and W should be defined more precisely. In [23], in steam-gas gasification of lignin-containing fuels in a fluidized-bed gas generator, their maximum permissible humidity was 30 % as well.

The obtained range of rational values of blast air humidity and volume is valid only under the condition of gasification of fuels of vegetable origin in continuous-bed gas generators utilizing reverse gasification process. For other types of gas generators and other types of fuels (peat, coal), it should be determined experimentally.

Disadvantage of using air-steam blast in the process of gasification consists in a phenomenon of high-temperature chloride-sulfate corrosion. Deposits consist of $CaSO_4$ and KCl. Reacting with corrosion products, potassium chloride forms sulfates $K_2Fe(SO_4)_3$. Complex potassium sulfates are strong corrosion accelerators and have a low melting point. Corrosion proceeds most intensively in the temperature range 900–1,100 °C.

Equations of heat balance were presented for gas generators of air-steam gasification type. These equations differ from the equations for conventional gas generators by presence of specific heat inputs and consumptions identified during testing of experimental equipment.

Taking into account these components has allowed us to optimize quantitative and qualitative composition of the produced combustible gas. Maximum productivity of the gas generator and the maximum content of CO and H_2 in the gas with the maximum heat of combustion were taken as optimality criteria. Since the steam energy (external source) was used to achieve the above criteria, studies have established that thermal potential of the produced combustible gas is several times higher than the amount of energy spent on its production. On the basis of the heat balance analysis, general effectiveness of the process of gasification of plant raw materials was determined (23.5 %).

Efficiency factor of the direct-flow gas generator was 79 %, and that of the gas-generating plant as a whole was 74.6 %.

The developed procedure can be used to optimize the gas generation process during gasification of fuels in plants of any type.

Proceeding from the experimental data obtained, further studies have been planned to substantiate technical and operational parameters of the steam blast regime for gas generators with a moving bed, gas generators with a power output more than 200 kW and for plant fuels with humidity more than 30 %.

This study has continued the research work titled Substantiation of Parameters and Operation Process of the Gas Generating Power Unit Adapted To Raw Materials of Vegetable Origin (State registration number: 0116U008732) carried out at the Faculty of Engineering and Energy of the Zhytomyr National Agroecological University, Ukraine.

7. Conclusions

1. A gas-generating unit with a direct-flow gas generator was developed. Its design includes a gas-air recuperator and an evaporator for preliminary preparation of the air-steam mixture. It was established that the use of air-steam blast increases by 18 % the volume of gas produced from a kilogram of pellets produced from rape stems. Calorific value of such gas is increased by 15.1 %. The total energy efficiency of using this flowsheet in production of gas from plant raw materials makes up 23.5 %.

2. By conducting a two-factor experiment, technical and operational parameters of the air-steam gasification process were studied:

– it was established that the maximum value of the lower heat of combustion of the generator gas was Q_{gg}^{L} = 12.3 MJ/m^3 and achieved at the volume of blast gases entering the gas generator in the range of 37...42 m^3/h and a 55...65 % humidity;

– consumption of 10 mm pellets produced of rape stems for the gasification process was reduced by 14.7 % and the volume of gas produced from a kilogram of pellets was 3.2 m^3;

– optimum temperature of the air-steam mixture ranged 550...570 °C and was achieved at the volume of blast gas entering the gas generator within 37...42 m^3/h and a 55...65 % humidity.

3. An innovative procedure of compiling heat balance of the air-steam gasification process for low-grade fuels was developed. According to the presented procedure, high efficiency of the experimental gas generator plant has been established and confirmed. The efficiency factor of the direct-flow gas generator was 79% and that of the gas-generating unit as a whole was 74.6 %.

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