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EXPERIMENTAL STUDY INTO THE INFLUENCE OF STRAW CONTENT IN FUEL ON PARAMETERS OF GENERATOR GAS

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Для газифікації соломовмісного палива пропонується газогенератор специфічної конструкції, у якого зони згорання та відновлення мають однаковий діаметр. В якості палива використано суміш деревини з солом'яними пелетами. Встановлено, що при використанні в паливі до 40 % і менше солом'яних пелет протягом 360 с роботи газогенератора відкладень на колосникових решітках не спостерігалося.

Проведено дослідження, що дозволяють оцінити вплив вмісту солом'яних пелет в паливі на концентрацію та обсяг CO в газі, загальний вихід газу, кількість виробленого газу із кілограма палива та тривалість роботи пропонованого газогенератора. Результат дослідження відображено однофакторними рівняннями. Для встановлення впливу вмісту солом'яних пелет в паливі на динаміку зміни концентрації CO в газі за часом роботи газогенератора виконано двофакторний експеримент. В кожній серії дослідів завантажувалась порція 2 кг палива, фіксувався час роботи та вміст CO в газі, через рівні проміжки часу. Причому, при кожному завантаженні газогенератора паливом вміст солом'яних пелет в паливі зростав від 0 % до 100 % із кроком 20 %.

Встановлено, що для ефективної газифікації соломовмісного палива без утворення твердих відкладень раціонально додавати до палива не більше 40 % солом'яних пелет. При використані 40 % соломи в порівнянні із деревиною на 25 % зростає концентрація та обсяг виробленого CO, проте зменшується на 5,3 % питомий вихід газу із палива. Хоча, при 100 % вмісті солом'яних пелет в паливі спостерігається збільшення концентрації CO в генераторному газі на 44,3 %, обсягу CO – на 40 %, загальний вихід виробленого газу зменшується на 7,7 %. Тривалість роботи газогенератора (при завантаженні 2 кг палива) зростає на 2,8 %. Зростання вмісту CO при використання в паливі 100 % вмісту соломи в порівнянні з 100 % вмістом деревини свідчить про збільшення теплотворної здатності отриманого газу на 13–18 %.

Тому раціональним є використання кількості соломи в паливі до 100 %, хоча це потребує розробки конструкцій газогенераторів, які дозволять уникнути утворення стійких відкладення на робочих поверхнях

Ключові слова: газогенератор, генераторний газ, солом'яні пелети, концентрація та обсяг CO, агломерація

1. Introduction

The growing demand for ecologically pure types of energy with reduced greenhouse gas emissions contributes to an increased interest in more efficient and intensive use of renewable fuels, e. g. biofuels [1]. According to the European Union's Low-Carbon Strategy, 40 % of energy should be produced from renewable sources by 2030 [2].

The amount of energy that can be obtained from biological raw materials and composition of emissions depend on many factors, namely, chemical and elemental composition of biofuel, ash content, volumetric density and moisture content [3, 4]. Wood is the common renewable biofuel species while the use of straw for energy production is less common because of high content of nitrogen, potassium, magnesium, sodium, chlorine and the tendency to ash and slag formation [5]. However, consumption of wood to meet energy needs is limited because of lack of this raw material in required quantities and the necessity of use of other biofuels, in particular straw.

The experience gained by many countries in introduction of latest energy-efficient technologies aimed at the raise of biofuel efficiency shows that gasification technology is the most promising method for producing energy from straw [6, 7]. Gasification means the process of converting the combustible portion of fuel into gas by means of interaction of fuel carbon with oxygen at high temperatures [6, 8]. Straw gasification has a number of significant advantages compared to the technology of obtaining heat, e.g. by direct combustion. Namely, the amount of ash decreases from 15–20 % (at direct burning) to 7 % [6, 7] and the amount of harmful emissions of SO_2 and NO_x is 20–25 % lower [6, 7]. Due to the high temperature (over 1,000 °C) in the active zone of the gasifier, dangerous substances such as dioxins and furans are destroyed [9]. Total thermal efficiency of the straw gasification process reaches 87–92 % [9, 10].

In addition to high environmental indicators, the issue of economic feasibility of switching to straw as an alternative energy source is of high importance. Therefore, improvement of existing technological processes and achievement of high efficiency of the gasification equipment are the main requirements in expanding application of the straw gasification technology to energy production. Besides, design of the gasification equipment must be reliable and technologically simple in operation and maintenance. Therefore, establishment of rational structural parameters of gasifiers, optimal conditions of straw gasification and their experimental study is an urgent task. Its solution will enable efficient production of ecologically pure fuel.

2. Literature review and problem statement

At present, fluidized-bed gasifiers [5–7, 12] are quite commonly used. They provide a more than 80 % conversion of fuel into combustible gas with calorific value up to 18.5 MJ/nm^3. However, fluidized-bed gasifiers have a complex design and require significant energy inputs in operation. Solid-bed gasifiers have a simpler design and significantly lower specific energy inputs but ensure gas generation from straw with calorific value of only 6.5 MJ/nm^3 [4]. Consequently, the issue of increasing efficiency of the straw gasification process in solid-bed gasifiers is relevant. In addition, the experience of operation of solid-bed gasifier units with various biofuels indicates that the direct-flow gasifiers of reverse gasification process should be used for gas production from straw and straw-containing fuels [6, 8, 11]. They provide stability of the gas formation process, high degree of resin decomposition and simplification of moisture and impurities removal from the generator gas [8–12].

However, high ash content and its ability to form ash-and-slag agglomerates is the barrier to a wider use of straw as a biofuel in the gasification process. The experience of gasification of fuels with various straw contents suggests that even a slight change in composition of the fuel mixture can significantly change the course of the gasification process and cause ash-and-slag agglomeration [13–15]. One of the methods for efficient production of gas from straw-containing fuels with control of CO, H_2, CH_4 contents and polluting emissions consists in determining proportion between the mixture components and the temperature conditions for each gasifier type.

The higher content of nitrogen, silicon, potassium, sodium, chlorine, and other low-melting substances in comparison with other hydrocarbons and coal is an essential disadvantage of using straw in the gasification process [4, 5]. Presence of low-melting substances, especially potassium and sodium salts, leads to formation of a sticky ash and causes formation of ash-and-slag agglomerates on the working surfaces of the heat producing equipment [16]. The straw of cereals has a low melting point (the starting temperature of slag formation is 1,050–1,160 °C) of ash resembling a dense paste-like mass [16]. As a rule, it covers the gasifier grate openings when exiting from the high temperature zone increasing resistance of the heat-producing equipment to flows and reducing gas permeability of the fuel. Increase in resistance and worsening of gas permeability of the fuel result in temperature fall in the reaction zones and, as a result, smaller content of components such as CO, H_2 and CH_4 in the combustible gas.

In view of availability of straw as a fuel, a tendency has emerged to a comprehensive solution of the problem of raising efficiency of gas generation from straw. To this end, activities in the field of development and improvement of the gasifier design have appeared [8–12]. Operation parameters consistent with the design and physical and chemical properties of fuel were established [4, 14, 17–19]. Gasification of fuel mixtures on the basis of wood, coal, high-ash sediments of sewage with addition of straw was studied [14, 17, 19]. It was stated in the above studies that the advantage of gasification of straw containing fuel mixtures consists in the ability of straw to emit a significant amount of heat in a small period of time. In particular, the presence of straw increases initial temperature of the gasification process by almost 100–150 °C [14]. However, the results of study of the heat and mass exchange processes and efficiency of the process of gasification of pure straw in the above-mentioned studies were presented mainly for the fluidized-bed gasifiers. In particular, an experimental study of heat processes in the reaction zones of gasifiers of the direct gasification process was carried out in [14] for gasification of a mixture of coal and wheat straw. The effect of gasification temperature (1,100–1,400 °C), straw content in a fuel mixture (0...1) and oxygen to carbon ratio in blast gases (0.35–0.65) on the content of H_2 and CO in the combustible gas was investigated. The study result has shown that addition of straw raised efficiency of the gasification process by 15 %. An increase in straw content in the fuel mixture increased initial temperature and reactivity index of the gasification process. With an increase in straw content in the fuel mixture from 0.25 to 0.75, temperature of the gasification process increased. Accordingly, the content of CO and H_2 increased and, on the contrary, the content of CO_2 and CH_4 decreased. However, with an increase in straw content in the fuel mixture from 0.75 to 1.0, temperature of the process fell which indicated an intensive behavior of the agglomeration processes. The results of the study can be partially used in the study of the gasification process in solid-bed gasifiers for another type of the gasification process. The drawbacks of the presented technology include design complexity of the systems for preliminary preparation of blast gases and the significant amount of fine soot particles in the resulting gas. Besides, a high content of low boiling resins, oils and higher hydrocarbons was observed in the resulting gas in gasification of fuels with high coal content. The ash content in coal is 10–35 % compared to 4 % in straw [16]. This requires development and use of complex structures of grates and evaporation systems for gasification of coal containing fuels.

The agglomeration processes occurring during gasification of wheat straw in a small gasifier based on the fluidized-bed technology were investigated in [13]. It was established that appearance of agglomerates (deposits) was caused by the reaction of alkali metals with silica. However, no methods for eliminating deposits were presented in the study. The authors of study [20] have presented a gasifier design for an efficient process of straw gasification in a gasifier with mechanical deposit removal. However, such a design includes complicated and expensive pneumatic cylinders to ensure the design efficiency at high temperatures.

In gasification of straw and wood fuel mixtures, there is a negative phenomenon as well, e. g. high resin content in the produced gas because of high content of resin in wood, especially coniferous species [8, 17]. There were attempts to solve the problem by designing the gasification chamber tuyere belt (tuyeres, pipes, air distribution boxes) and an additional thermal insulation of the hopper which provides temperature in the active zone within 1,100–1,400 °C [8, 12, 20–22]. This temperature range contributes to the maximum cracking of resins in the gasification chamber [4, 6, 8]. However, temperature increase in the active zone of the gasifier causes intensification of agglomerate (sediment) formation. In order to minimize the process of agglomeration, it was proposed to design gratings with knives and various firing tools [23] to eliminate the phenomenon of fuel chocking-up which also contributes to agglomeration. Disadvantages of these designs include low manufacturability, complexity of mounting and maintenance.

Efficiency of the process of producing gas from straw-containing fuels is also improved by selecting conditions of air supply to the gas-forming chamber [14, 17–19]. Steam-oxygen blast at normal and high pressures [17], oxygen enriched air blowing [19] and vapor-air gasification [18] are widely used. The advantages of steam-air and steam-oxygen blasting processes include acceleration of the reactions occurring in the reactor zones of the gasifier which contributes to raising calorific value of the resulting gas by 18–20 % [17, 18]. Low degree of water vapor decomposition within 32–40 % and use of expensive equipment for preparation of the blast gas are disadvantages of these processes. The results of use of oxygen-enriched air are presented in [19] for gasification of high-ash sewage sediments and straw in a fluidized-bed gasifier. Influence of straw content in the fuel mixture, oxygen content in the blast gas and type of the bed material (bauxite, calcined dolomite and olivine) on efficiency of the gasification process was investigated. The study results indicate that maximum efficiency of the gasification process was achieved with a 50 % straw content in a mixture, a 40 % oxygen content in blast gases and use of bauxite as the layer material. The high level of generator gas contamination with resins (over 160 g/nm^3), aromatic compounds and light polyaromatic hydrocarbons which requires the use of costly treatment equipment is disadvantage of the presented method. Suitability of using this method of gasification of a fuel mixture of straw and wood can only be established experimentally.

Analysis of the conducted studies on straw gasification states that the designers went by the way of creation of complex gasifier designs with application of energy-intensive technological processes. Such gasifiers enable an efficient straw gasification but complexity of the technological process does not allow them to be widely used. For simpler designs of gasifiers, e. g., direct-flow gasifiers in the solid-bed technology, study of the straw gasification process was not practically carried out because of intensive formation of solid deposits on the working surfaces of gasifiers. The problems of efficient gasification of straw in gasifiers with application of available technology remain unresolved. Therefore, further experimental studies of the effect of straw content in fuel on parameters of the obtained generator gas and formation of solid deposits must be conducted.

3. The aim and objectives of the study

The study objective was to determine the effect of straw content in the fuel on parameters of the obtained generator gas by means of experimental verification using a gasifier of a specific design in which the combustion and regeneration zones have the same diameter.

To achieve this goal, the following tasks were solved by variation of content of straw pellets and wood chips in the fuel:

– to study the changes in CO concentration, CO volume, total gas yield and specific volume of produced gas;

– to assess duration of the gasifier operation;

– to study the nature of change in CO concentration in the gas during the gasifier operation;

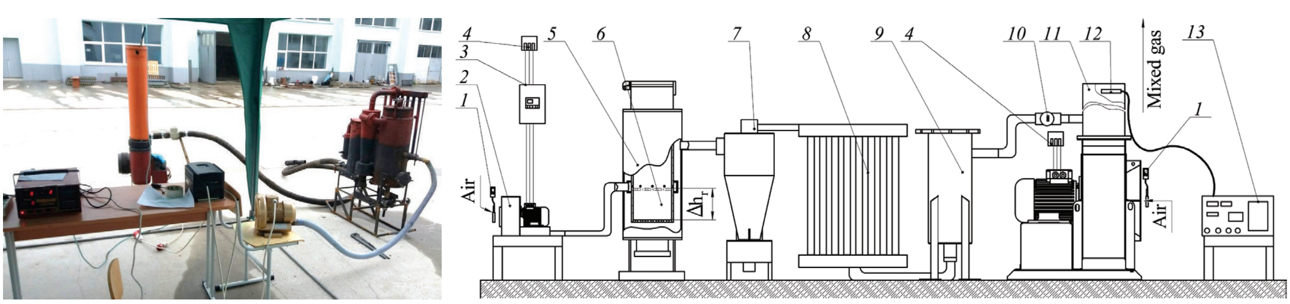
– to establish the modes of efficient gasification of straw containing fuel without formation of solid deposits.

4. Materials and methods of studying the influence of straw content in the fuel on the gasification process

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

A special gas generating unit has been developed for experimental study, Fig. 1.

Influence of straw pellet content in fuel on concentration and volume of CO in the generator gas, total gas yield, amount of gas produced per kilogram of fuel and duration of the gasifier operation were studied.



a *b*

Fig. 1. Experimental gas generating unit: general view (*a*); schematic diagram (*b*): Tenmars TM-402 anemometer (1); Goorui GHBH-0D5-34-1R2 blower (2); Hitachi-3G3JX-A4075-EF frequency converter (3); 0.4 kV socket (4); GG-1 gasifier (5); regeneration camera (6); coarse filter (7); cooler (8); fine filter (9); G-6-RL rotary gas meter (10); mixer (11); CO sensor (12); Infrakar-M2T gas analyzer (13)

The experimental gas-generating unit contains the GG-1 gasifier featuring the combustion and regeneration zones of the same diameter. This design feature makes it possible to increase efficiency of the gasification process when using the same kind of fuel, for example wood, by 15 % compared to similar solid-bed gasifiers. The height of the gasifier regeneration zone is 135±2 mm at a diameter of 200 mm. The regeneration zone height to diameter ratio is 0.625.

The gasifier was charged with the fuel containing hardwood in the form of cubes with a side of 40 mm and wheat straw pellets in certain proportions. Quality factors of the pellets corresponded to DIN 51731 and ONorm M 7135 (Table 1).

Table 1

Requirements of some standards to the quality of straw pellets

Pellet quality norms	Unit	ONorm M 7135 (Austria)	DIN 51731 (Germany)
Diameter, *D*	mm	4–10	4–10
Length	mm	5×*D*	<50
Density	kg/dm^3	>1.12	1.0–1.4
Moisture content	%	<10	<12
Ash content	%	<0.50	<1.50
Thermal value	MJ/kg	>18	17.5–19.5
Sulphur content	%	<0.04	<0.08
Nitrogen content	%	<0.3	<0.3
Chlorine content	%	<0.02	<0.03
Dust content	%	<2.3	–
Auxiliary component content	%	<2	<2

The content of straw pellets in the fuel varied from 0 to 100 % in increments of 20 % for each experiment (Table 2). Weight of one portion of fuel was 2 kg and was determined with the help of VTNE-15-T1 weights. Humidity of the fuel components was within 4.3±0.3 % and was measured by means of the digital MT-10 moisture meter.

The rate of air supply to the gasifier was 10 m/s and was controlled by the Tenmars TM-402 anemometer, air supply to the gasifier was 0.012 m^3/s and was constant for all experiments. Air supply to the mixer was 0.38 m^3/s. Excess pressure in the gasifier was 4 kPa.

Table 2

Fuel composition

Experiment No.	Fuel component content, %		Fuel component weight, kg		Total fuel, kg
	wood	straw	wood	straw	
1	100	0	2	0	2
2	80	20	1.6	0.4	2
3	60	40	1.2	0.8	2
4	40	60	0.8	1.2	2
5	20	80	0.4	1.6	2
6	0	100	0	2	2

Fuel was charged into the gasifier (Fig. 2, *a*) with the formed regeneration zone (Fig. 2, *b*) and then the gas analyzer readings were recorded at the set time intervals.

a *b*

Fig. 2. General view of the gasifier in working condition: charging the fuel into the gasifier (*a*); general view of the regeneration zone (*b*)

Volume of the obtained gas was recorded using the G-6-RL rotary gas meter. To measure CO concentration, Infracar-M2T gas analyzer was used with measurement of CO concentration in the range of 0...7 %. Since the range of measurements of the used gas analyzer was insufficient, concentration of CO was reduced within certain limits. For this purpose, a mixer consisting of a centrifugal fan and a turbulator of air and gas flows was used. The mixer provided an effective mixture of combustible gas from the generator and air supplied by the centrifugal fan from the environment.

The temperature conditions of the developed direct flow gasifier with the reverse gasification process varied in the following ranges depending on composition of the fuel mixture. Temperature was 105...300 °C in the drying zone; 400...850 °C in the dry distillation zone and 900...1,150 °C in the reaction zone (oxidation zone and regeneration zone).

As the study results have shown, the use of the proposed gasifier design increases efficiency of the process of gasification of straw-containing fuels due to the design of the gasifier active zone matched with gas blowing conditions. Thanks to this matching, we had a greater height of the reaction zone compared with counterparts and the geometry optimal for the gasification process. The active zone consisted of the oxidation zone and the regeneration zone. The latter occupied a significant part of the active zone height [4, 6, 8, 23]. The resulting generator gas had a higher concentration and volume of CO and, accordingly, higher heat of combustion.

This was achieved through the repeated passage of gases formed during the gasification process through a layer of heated fuel in the active zone of the gasifier. At high temperatures, heterogeneous reactions $C+CO_2 \rightarrow 2CO+407$ kJ/mol and $2C+O_2=2CO+244.5$ kJ/mol occur and carbon monoxide (a combustible component of the generator gas) is formed. These reactions take place simultaneously in accordance with the complex theory [24]. Action of O_2 in the blast gases on the reaction surface of fuel results in formation of the carbon-oxygen complex and subsequent decomposition to CO and CO_2. The $CO:CO_2$ ratio depends on temperature in the oxidation zone. Concentration of CO increases with temperature rise [24]. The heat released in the course of these reactions raises temperature in the oxidation zone and leads to ash melting.

At high temperatures and in the presence of water vapor in the regeneration zone, reactions of its conversion occur:

$C+(H_2O)_{vap}=CO+H_2$-122.6 kJ/mol and $C+(2H_2O)_{vap}=$ $=CO_2+2H_2$-75 kJ/mole. According to the experiments [24], these reactions take place with participation of hygroscopic and chemical moisture of the fuel material. The reactions are endothermic and their rate depends on temperature in the regeneration zone. With an increase in temperature of the reaction zone from 900 to 1,150 °C, the rate of chemical reactions increased which created favorable conditions for more intensive formation of hydrogen, another combustible component of the gas. Consequently, due to the high content of CO in the generator gas and somewhat lower content of H_2, heat of combustion of the gas is relatively high.

4. 2. The procedure for processing the results of experimental studies

One-factor experiments were carried out to estimate the effect of content of straw pellets in fuel on concentration and volume of CO in the gas, total gas yield, amount of gas produced per kilogram of fuel and duration of the gasifier operation.

A two-factor experiment was performed to determine effect of content of straw pellets in fuel on dynamics of changes in CO concentration in the gas during operation of the gasifier. In each series of experiments, a 2 kg portion of fuel was charged, the operating time and CO content in the gas were recorded at regular intervals. Moreover, the content of straw pellets in fuel was increased from 0 % to 100 % in a 20 % step at each charge of the gas-containing fuel.

Supply of air to the gasifier and the mixer was determined according to the anemometer readings by formula:

$$q=\frac{\pi v d^2}{4}, \qquad (1)$$

where q is supply of air to the gasifier or mixer, m^3/s; v is air velocity at the inlet to the generator or mixer, m/s; d is diameter of the inlet pipe, m.

The actual values of CO concentration in the generator gas were calculated by the formula:

$$n_{CO}=\frac{X_{CO}(q_z+q_d)}{q_d}, \qquad (2)$$

where n_{CO} is concentration of CO, vol.%; q_z is air supply to the mixer, m^3/s; q_d is gas yield in the gasifier, m^3/s; X_{CO} is CO concentration in the mixture formed in the mixer, vol. %.

Five experiments were duplicated in each series. Mandatory randomization was used to reduce the experiment error. Verification of reproducibility of experiments was carried out according to the Cochran criterion [25]. In the case of non-fulfillment of the condition of reproducibility by the Cochran criterion, the measurement accuracy and the experimentation conditions were checked which resulted in the maximum dispersion value.

In all experiments, significance of the coefficients of regression equations was estimated according to the Student's criterion and adequacy of the regression equations obtained was estimated according to the Fisher's criterion [25].

The resulting data were processed using the Microsoft Excel Search Solutions software [25].

Studies were conducted to determine degree of the generator gas contamination. The disperse composition of dust before the coarse filter 7 (Fig. 1, *b*) was determined by the aspiration method using the AFA-VP-20 filter. Before carrying out the analysis, the dust samples were treated with acetone to remove resinous materials and then dried at room temperature (18–22 °C). Dispersity was determined by the method of force analysis and mechanical sieving of fine fractions in the pneumo-classifier. The method of sieve analysis was used to determine the dispersity of fractions with particle size from 43 μm and above.

5. Results of determining the influence of the content of straw pellets in fuel on the parameters studied

Analysis of results of the conducted experiments has allowed us to determine the effect of content of straw pellets in fuel on the parameters under study, namely concentration and volume of CO in the gas, total gas yield, amount of the gas generated per kilogram of fuel and duration of the gasifier operation (Table 3).

Influence of content of straw pellets in fuel on CO content in the gas is described by a linear dependence (with a coefficient of approximation probability R^2=0.93):

$$n_{CO}=0.0865\cdot x_S+10.795, \qquad (3)$$

where n_{CO} is concentration of carbon monoxide in the combustible gas, vol. %; x_S is content of straw pellets in fuel, %.

The obtained mathematical dependence 3 is graphically represented in Fig. 3.

As it follows from analysis of the obtained graphic dependence (Fig. 3), with an increase in straw content in fuel from 0 to 100 %, the CO concentration also increased from 10.8 % to 19.4 %.

Table 3

The study results

Item No.	Gas counter readings, m^3 (initial – final)	Operation time, s	Total gas yield, m^3		Maximum volume of CO, m^3/s	Concentration of CO in gas, %	Volume of gas generated from 1 kg of fuel, m^3/kg
				in 1 s			
1	411.540–417.560	517	6.02	0.0116	0.0012	10.43	3.01
2	418.260–424.114	504	5.85	0.0116	0.0014	12.48	2.93
3	424.282–429.980	494	5.70	0.0115	0.0016	13.92	2.85
4	430.372–435.968	495	5.60	0.0113	0.0019	16.97	2.80
5	436.140–441.828	515	5.69	0.0111	0.0021	18.77	2.84
6	441.96–447.718	535	5.78	0.0108	0.0020	18.16	2.88

Influence of content of straw pellets in fuel on the resulting volume of CO is described by a quadratic dependence (with a coefficient of approximation probability $R^2=0.95$):

$$\upsilon_{CO}=-8\cdot10^{-08}x_S^2+2\cdot10^{-05}x_S+0.0012, \quad (4)$$

where υ_{CO} is yield of CO, m^3/s.

Graphical representation of mathematical dependence 4 is presented in Fig. 4.

With an increase in content of straw in the fuel from 0 to 100 %, volume of CO also increased from 0.0012 m^3/s to 0.0020 m^3/s (Fig. 4).

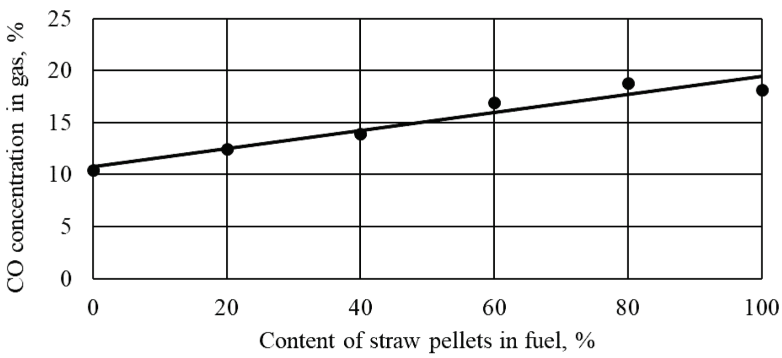


Fig. 3. Dependence of CO concentration in the generator gas on content of straw pellets in the fuel

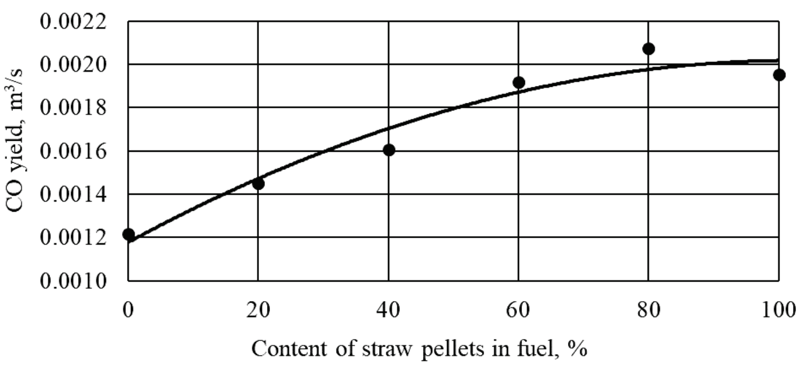


Fig. 4. Dependence of CO yield on content of straw pellets in the fuel

The nature of dependences (Fig. 3, 4) is explained by the fact that temperature of the material layer in which gasification processes take place in the gasifier grows with increase in amount of straw in the fuel. Generation of CO from hot carbon and CO_2 is one of main heterogeneous reactions in the regeneration zone. As gasification proceeds, CO_2 is absorbed by the Buduar reaction: $C+CO_2\leftrightarrow 2CO$. It is promoted by high temperature of the fuel layer in the gasifier (about 1,000 °C) [24]. This explains the cause of growth of molar CO fraction when temperature of the fuel layer in the gasifier increases, and, consequently, when quantity of straw in the fuel increases. CO is the major combustible component in the final mixture of gases obtained during gasification.

Another important reaction takes place in the regeneration zone between water vapor (hygroscopic and chemical moisture of the fuel material and air moisture) and carbon. Water contributes to formation of CO and H_2 products. The given heterogeneous and endothermic reaction ($C+H_2O\leftrightarrow N_2+CO$) is called the reaction of the primary water gas since both of its products are combustible. Due to this reaction, the yield of CO in the combustible gas obtained in the experimental unit is higher which also increases heat of combustion of the gas. Reaction of the primary water gas is significant in the temperature range from 1,000 to 1,200 °C and above. Reaction of the secondary water gas ($C+2H_2O\leftrightarrow 2N_2+CO_2$) begins to predominate between 500 and 600 °C while reaction of the mixed water gas is exclusively a gaseous reaction since it proceeds in the presence of unestablished steam. Since the endothermic reaction of formation of gaseous hydrogen proceeds in the fuel layer of the regeneration zone, heat is consumed as a result of exothermic reactions in the oxidation zone. Therefore, temperature in the oxidation zone falls. On the contrary, when exothermic reaction of water gas formation proceeds in the reaction zone, the heat released during reaction raises temperature in the oxidation zone. To obtain gaseous hydrogen, external heat (endothermic reactions) is required at temperatures above 1000 °C and the heat necessary for these reactions is provided by exothermic reactions. During gasification of the wood fuel containing straw pellets, endothermic and exothermic reactions were observed in the temperature range of 950–1,200 °C. The generator gas at the gasifier outlet had temperature above 500 °C.

With an increase in the content of straw pellets in fuel from 80 to 100 %, yield of CO in the combustible gas grew slowly. At such a content of straw pellets in fuel, temperature of the gasifier reaction zone was 1,150–1,200 °C. This temperature is the temperature of the straw ash slagging, so the phenomenon of ash-and-slag agglomeration was observed. Temperature in the gasifier reaction zone has started to fall.

If there is water in the reduction zone, the so-called reaction of mixed water gas ($CO+H_2O\leftrightarrow N_2+CO_2$) may occur. This exothermic reaction is usually regarded as unfavorable one since it lowers CO content in the gas and calorific value of the generator gas.

Most of hydrogen generated in the regeneration zone remains free. However, a part of this hydrogen together with carbon can form a small quantity of methane ($C+2H_2\leftrightarrow CH_4$).

The effect of content of straw pellets in fuel on the total gas yield is described by a quadratic dependence (with a coefficient of approximation probability $R^2=0.99$):

$$\upsilon_{pg}=9\cdot10^{-08}x_S^2-2\cdot10^{-07}x_S+0.00117, \quad (5)$$

where υ_{pg} is yield of the generator gas, m^3/s.

Graphical representation of mathematical dependence 5 is shown in Fig. 5.

As it follows from analysis of the graph in Fig. 5, amount of the obtained generator gas decreased from 0.0117 m^3/s to 0.0108 m^3/s with an increase in straw content in fuel from 0 to 100 %.

Although concentration and yield of CO increased at higher contents of straw pellets in fuel (Fig. 3, 4), a decrease in total yield of the generator gas was observed (Fig. 5). This phenomenon is caused by the fact that for production of gas from straw-containing fuels it takes more time for the full course of chemical reactions in the gasifier active zone which is explained by the theory of filtration [24].

Influence of the content of straw pellets in the fuel on duration of the gasifier operation at a full fuel charge (2 kg) is described by a quadratic dependence (with a coefficient of approximation probability R^2=0.97):

$$t_g = 0.0127x_S^2 - 1.0952x_S + 518.11, \qquad (6)$$

where t_g is the duration of the gasifier operation, s.

Equation 6 is graphically depicted in Fig. 6.

Analysis of the graph in Fig. 6 shows that with an increase in content of straw in the fuel from 0 to 40 %, duration of the gasifier operation has decreased from 520 to 495 seconds. Conversely, with an increase in content of straw in the fuel from 40 to 100 %, duration of the gasifier operation has increased from 495 to 535 seconds.

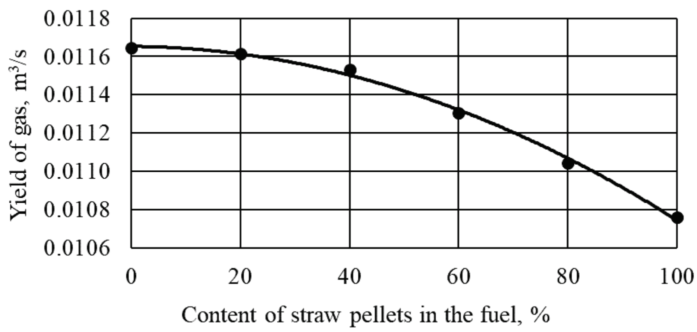


Fig. 5. Dependence of yield of generator gas on the content of straw pellets in fuel

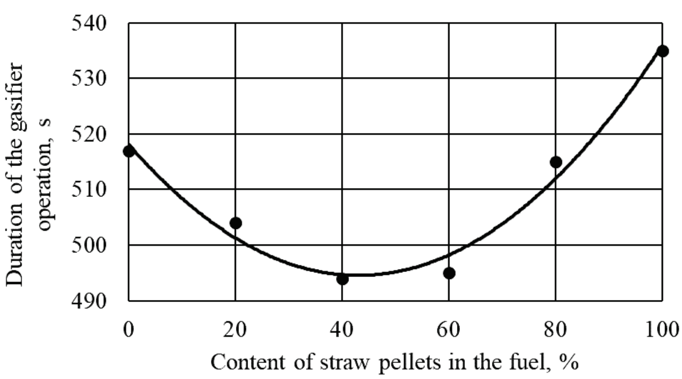


Fig. 6. Dependence of duration of the gasifier operation on the content of straw pellets in the fuel

This phenomenon is explained by the fact that when the content of straw pellets in the fuel increased from 0 to 40 %, temperature in the gasifier active zone got increased which intensified the gasification process. If air blow was properly organized, the time for completion of the main reactions was shortened, so the gasifier operating time was cut from 495 to 535 seconds. Since the gasifier volume was small and the amount of fuel was insignificant (2 kg), time reduction was insignificant (only 40 s).

When amount of straw in the fuel increased from 40 to 100 %, the increase in the gasifier operating time was caused by the decrease in the gas permeability of the material layer in the gasification zone. This phenomenon is explained by the fact that the amount of ash in the gasifier ashtray increased with an increase in straw content in the fuel. With growth of the ash amount, excess pressure in the gasifier increased. This phenomenon was accompanied by a sharp rise of the layer temperature in all measurement points of the gasifier. Further, a drop of the layer temperature caused by termination of the combustion process was observed which indicated the presence of ash and slag agglomerates on the gasifier grate. Restoration of combustion is possible only with removal of agglomerates and renewal of mobility of the fuel particles. The reaction zone volume and portion of the charged fuel were insignificant in the developed gasifier, so we did not see the onset of complete ash agglomeration. The portion of the charged fuel has burnt out faster than this phenomenon might appear. That is why only the phenomenon of slowing down the gasifier operation is seen in Fig. 6. The phenomenon of agglomeration can also be avoided or reduced by lowering temperature in the gasifier reaction zone from 1,200 to 1,000 °C and the hydraulic resistance of the ash layer. We achieved this by changing temperature and volume of air supplied to the gasification zone. However, the use of this technique has resulted in an almost 12 % decrease in CO concentration in the gas generated from a charge containing 100 % straw pellets. The amount of resin in the gas has also increased to 24 g/nm^3.

It can be concluded proceeding from the data analysis (Fig. 5, 6) that the increase in straw content in the fuel to more than 40 % slowed down the gas generation while duration of the gas generation increased (Fig. 7). The yield of the generator gas at a 0 % straw content was 3 m^3/kg and it decreased to 2.8 m^3/kg at a 60 % straw content but increased again to 2.9 m^3/kg at a 100 % straw content.

The effect of content of straw pellets in fuel on the yield of gas from one kilogram of the fuel is also described by a quadratic dependence (with a coefficient of approximation probability R^2=0.97):

$$\upsilon_f = 5\cdot 10^{-5}x_S^2 - 0.0062x_S + 3.0174, \qquad (7)$$

where υ_f is the yield of the generator gas from one kilogram of fuel, m^3/kg.

Compared with wood, when using straw in the gasifier, a 44.3 % increase in CO concentration was observed. Correspondingly, yield of CO has grown by 40 %. Duration of the gasifier operation (at a 2 kg fuel charge) has increased by 2.8 %.

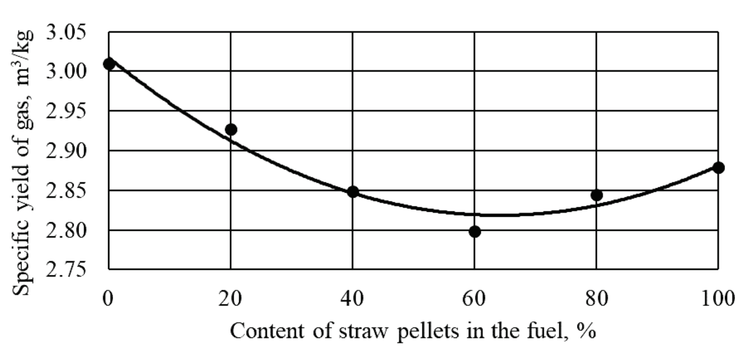


Fig. 7. Dependence of yield of the generator gas from 1 kg of fuel on the content of straw pellets in the fuel

However, total yield of the generator gas has reduced by 7.7 % and gas yield per kilogram of fuel has reduced by 3.3 %. The increase in CO content with a simultaneous decrease in yield of the generator gas at a 100 % straw content in fuel indicates an increase in calorific value of the resulting generator gas.

Also, based on the experimental data, dynamics of CO content in the generator gas during the gasifier operation at a single fuel charge of 2 kg was analyzed (Fig. 8). According to the analysis, it can be concluded that with increase in straw content in the fuel, maximum concentration increases and shifts to the right on the time scale of the gasifier operation.

In general, depending on the content of straw, CO concentration during the gasifier operation can be described by the empirical equation:

$$n_{CO} = 2.32 + 0.0689 t_g - 0.0191 x_S - 0.00014 t_g^2 + 0.00025 t_g x_S - 0.000099885 x_S^2, \quad (8)$$

and displayed graphically (Fig. 9).

Analysis of the graph in Fig. 9 shows that maximum CO concentration was achieved at 80 to 100 % content of straw pellets in fuel during 300 to 360 s of the gasifier operation which is 62.5 to 76.9 % of the total gasifier operation time, respectively. This time range of 300 to 360 s is the so-called time of stabilized operation of the gasifier when all parameters of the gasification process are consistent and therefore CO concentration is maximal.

It should be noted that when more than 60 % of straw was used in the fuel, a phenomenon of formation of solid glassy deposits (agglomerates) on the grate surface was observed (Fig. 10, 11).

The presence of sediments is explained by the content of silicon, potassium, sodium, and other low-melting matter in the straw ash which caused formation of ash and slag agglomerates on the grate surface. It should be noted that when fuel with a 40 % or less content of straw pellets was used for the above-mentioned time of the gasifier operation, no deposits on the grate were observed.

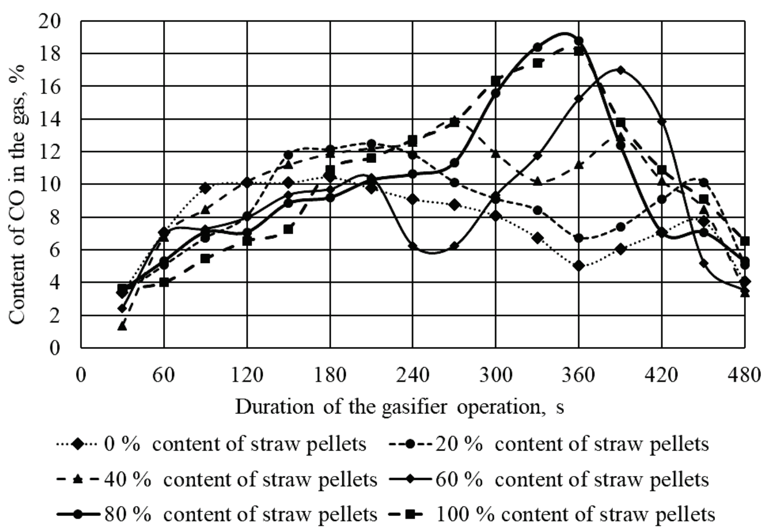


Fig. 8. Dynamics of changes in CO concentration during the gasifier operation

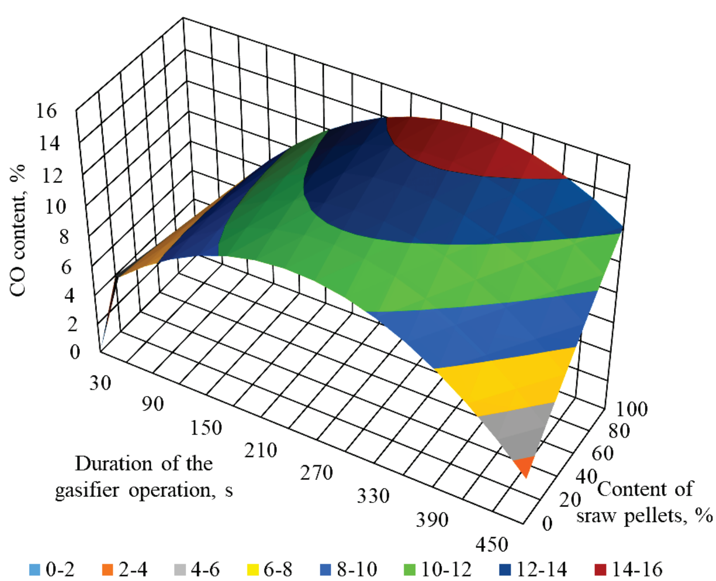


Fig. 9. Dependence of CO concentration on duration of the gasifier operation and the content of straw pellets in the fuel (the color areas characterize CO concentration (%) in the resulting gas)

Fig. 10. Solid glassy deposits on the grate surface when the gasifier operated at an 80 % straw content in the fuel

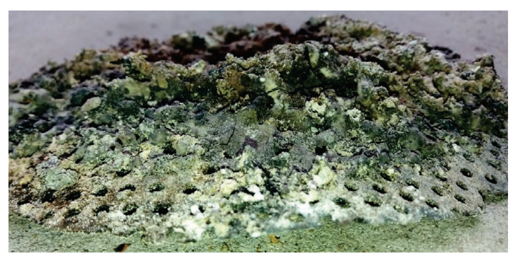


Fig. 11. Solid glassy deposits on the grate surface when the gasifier operated at a 100 % straw content in the fuel

6. Discussion of results of determining the influence of the content of straw pellets in the fuel on the parameters under study

The design of a highly effective low-power solid-bed gasifier differs from the known gasifier designs in that the combustion and regeneration zones had the same diameter. The proposed gasifier makes it possible to solve the problem of the environmental state and obtain cheap energy from plant biofuels.

The experimental studies have proved efficiency of adding straw to fuels in order to obtain a higher content of CO, the main combustible component in the generator gas which increases the calorific value of gas by 13–18 %. The efficiency of adding straw to fuels in the gasification process was also noted in [14, 17, 19] where this technological method has ensured generation of gas with calorific value higher than 15 % or more.

The maximum concentration of CO was achieved at an 80–100 % content of straw pellets during 300–360 s of the gasifier operation which is 62.5 to 76.9 % of the total operating time of the gasifier, respectively. This period is the period of stable gasification (Fig. 9). Such character of obtaining CO in the gasification process can be explained by the influence of stoichiometric conditions on the combustible gas composition. The calorific value of the gas was stable high in all conducted studies, namely, slightly higher than 10.6 MJ/nm^3. According to recent studies, gaseous fuel with calorific value of 10.4 MJ/nm^3 [12] has been obtained in solid-bed gasifiers by wood gasification.

Temperature of the generator gas changed to a greater extent from experiment to experiment varying in the range from 465 to 610 °C clearly indicating the energy needs of the process. In more detail, these needs can be divided into three phases. The first phase is the process of pyrolysis in which the straw-containing fuel is converted by heating to charcoal and volatile compounds such as steam, resins, etc. However, our objective was to provide temperature conditions in the gasifier reaction zones favorable for rapid pyrolysis, thus increasing the yield of volatile gaseous products like CO. In this way, we avoided intensive formation of higher hydrocarbons with further cracking. The second phase is an exothermic reaction in which part of the carbon is oxidized to carbon dioxide. During the third phase, a part of carbon dioxide, volatile compounds and steam are recovered to carbon monoxide, hydrogen and methane.

The system is autothermal, that is, the only external energy source is the source straw containing fuel. All internal energy needs are satisfied by the produced combustible gas in the fuel layer.

Based on the results of experimental studies, regressive dependences of influence of straw pellets in the fuel on the parameters under study were obtained, namely, dependences of influence on concentration and volume of CO in the gas, total gas yield, amount of the gas generated per kilogram of fuel and duration of the gasifier operation. The resulting regression equations can serve as the basis of rational carrying out and control of the gasification process.

However, as the graphs show (Fig. 8, 9), the technological scheme of gas production with high CO content needs further optimization.

Analysis of the obtained experimental results shows that the decisive factor for the further development of the technological scheme of gasification of straw containing fuels and obtaining of high CO content in the combustible gas is maintenance of a slag-free gasification conditions.

Although we encountered a negative phenomenon of formation of vitreous deposits on the grate surface (Fig. 10, 11) in the course of study, the phenomenon of ash agglomeration did not lead to stopping of the gasifier. This is explained by small size of the gasifier and a small amount of fuel in one full charge (2 kg). However, when transferring the study results to industrial gas-generating units of this type, one can come across the scale effect of both positive and negative phenomena of gasification of the straw containing fuels. To reduce the phenomenon of agglomeration, efforts were applied to reduce temperature in the gasifier reaction zone from 1,200 to 1,000 °C. This was achieved by varying temperature and volume of air supplied to the gasification zone. However, the amount of resin in the gas has grown to 24 g/nm^3 which is unacceptable for the gas intended for power generating units.

In order to avoid ash agglomeration, it was proposed in studies [18, 26] to add water vapor to the reaction zone in order to equalize temperature conditions and stabilize the gasification process.

There is a genuine procedure to diagnose the process of ash agglomeration [27] although it concerns straw gasification in a fluidized state. The procedure is based on the assumption that all processes associated with transfer of gas flows and solid particles in the layer are determined by formation, rise and destruction of gas bubbles, their size and frequency with which they are formed and destructed. Displacement and destruction of gas bubbles cause pressure gradients in a layer that is easy to record. When fractional composition of the layer particles varies, size of the bubbles, frequency of their formation and destruction change and it is reflected in statistical characteristics of the random process of variation of the pressure gradient in the layer. This technique can be adapted to diagnostics of the ash agglomeration processes in a continuous-layer gasifier. Development of a consistent system that includes fuel, gasifier design and gas-blowing conditions will make it possible to regulate the slag-free gasification conditions for fuels with straw content from 80 to 100 %.

In the future, it is also advisable to consider technological schemes that use the waste heat from purifying and cooling equipment of the gas generating unit.

During gasification of wood and straw fuel with a content of straw pellets from 60 to 80 %, the generator gas contained insignificant amount of resins (up to 0.5 g/nm^3) formation of which was suppressed namely by high-temperature gasification. In some experiments, it was necessary to reduce high temperature in the reaction zones from 1,200 to 1,000 °C to stabilize the gasification process and avoid the phenomenon of ash agglomeration (this measure explains the decrease in total gas yield), Fig. 5. Temperature reduction in the reaction zone to 1,000 °C led to an increase in the amount of resin in the generator gas to 24 g/nm^3 and above. If further studies are planned to be carried out at a temperature in the gasifier reaction zone 1000 °C and lower, it will be necessary to consider the use of catalysts for conversion of resins and other polyaromatic hydrocarbons. When using the generator gas in internal combustion engines or in turbines, the content of resins in the gas should not exceed 0.1–0.25 g/nm^3.

Gas at the gasifier outlet contained a minimum amount of mechanical impurities in the range of 0.6...1 g/m^3 when fuel with straw content from 40 to 60 % was gasified. At the content of straw in the fuel from 80 to 100 %, mechanical dust content was the highest (1.6...2.3 g/m^3). This is explained by the fact that the phenomenon of agglomeration contributes to a mechanically incomplete combustion of fuel and entrainment of fuel particles with the generator gas. Dust of mechanical impurities was also studied to obtain data on their abrasive properties. Because it was impossible to completely remove dust, coalescence of its particles was recorded which greatly influenced the experiment error. The dispersion composition of dust in percent was as follows: 56 % at particle size of 50...60 μm; 12 % at 40...50 μm; 8 % at 30...40 μm; 7 % at 20...30 μm; 3 % at 10...20 μm; 10 % at 5...10 μm; 4 % at 2.5...5 μm. The dust consisted of 93 % of carbonaceous particles. After passing through the purification system (Fig. 1, *b*), the content of mechanical impurities decreased to 15...22 mg/m^3. The permissible level of mechanical pollution of the generator gas is 20...30 mg/m^3 for the use, e. g. in engines [23, 24].

In addition, there was a phenomenon of chloride-sulfate corrosion during gasification of the fuel containing straw pellets. The deposits mainly consisted of KCl and $CaSO_4$. It is assumed that there is a close connection between sediments during gasification of straw and high-temperature corrosion. Potassium chloride condenses on superheated surfaces where it forms sulfates, for example $K_2Fe(SO_4)_3$ together with corrosion products. Complex potassium sulfates have a low melting point and are strong corrosion accelerants. The most intense corrosion takes place in the temperature range of 900–1,100 °C.

Chemical analysis of scale layers taken from the surfaces of the gasification chamber has indicated that chlorine content in the scale layers was significantly higher than the value of average chlorine concentration in the volatile ash of the gasifier. Chlorine content in the scale layers when burning 100 % straw pellets was 7 times higher than in the case of burning 100 % wood pellets. Sulfur concentration was the same as in ash and sodium and potassium concentration was 2 times lower. According to the results of X-ray spectral analysis, one may state that enrichment with chlorine takes place mainly on the iron/scale interface. The corrosion mechanism is explained by formation of a significant amount of alkali metal chlorides in the process of gasification. They precipitate on the metal surface and react with intermediate gases released during gasification in the reaction zone. Sulfates are formed and free chlorine is released. Some part of it repeatedly diffuses through the scale pores to the metal surface and reacts with formation of $FeCl_2$ and $FeCl_3$. The latter form Fe_3O_4 and Fe_2O_3 in reaction with oxygen. Therefore, chlorine acts as an accelerator of the corrosion process. The thick and porous layers of scale do not protect metal surfaces of the gasifier and as a result, constant destruction of material takes place.

The corrosion studies conducted within the scope of this work are only of an evaluative nature because of their short-term nature.

This study is a continuation of the scientific study [4] (State registration number 0116U008732) regarding improvement of efficiency of gasification of the straw containing fuels in low-power solid-layer units to ensure stable energy supply to the consumer. Based on the results of the conducted studies, it is planned to design gasifiers that will avoid the agglomeration phenomenon.

7. Conclusions

1. As a result of experimental studies, the following was observed when gasifying the fuel with 100 % straw content compared to that with 100 % wood content.

– a 44.3 % increase in CO concentration and a 40 % increase in the volume of CO produced;

– a 7.7 % decrease in total yield of generator gas;

– a 2.8 % increase in duration of the gasifier operation (at a 2 kg fuel charge);

– a 3.3 % reduction of gas yield per kilogram of fuel.

The growth of CO content with simultaneous reduction of the gas yield when using fuel with a 100 % straw content indicates an increase in calorific value of the resulting generator gas.

2. Dynamics of change of CO content in the generator gas during the gasifier operation was analyzed for a single 2 kg fuel charge. According to the analysis results, an increase in straw content in the fuel results in a growth of CO concentration and its maximum shift to the right in the timeline of the gasifier operation. Maximum CO concentration is achieved with an 80–100 % content of straw pellets in 300–360 s of the gasifier operation which is 62.5–76.9 % of the total operating time of the gasifier, respectively.

3. The conducted studies have made it possible to draw a conclusion on usability of straw as a fuel for gas generation. However, when the gasifier was operated at straw content of 40 % or more, formation of solid glassy deposits on the grate surface was observed. When 40 % and less straw pellets were used in fuel for 360 hours of the gasifier operation, there were no deposits on the grate. Therefore, to intensify the gasification process and maintain it with no slag formation, it is rationally to add no more than 40 % of straw pellets to the fuel. When 40 % of straw is used in the fuel, the concentration and volume of produced CO increase by 25 %, however, the gas yield per one kilogram of fuel decreases by 5.3 % compared to the use of wood.

4. The use of fuel with straw content above 40 % requires the gasifier design which will avoid formation of firm deposits on the working surfaces.

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