RESEARCH ON CHANGES IN BIOMASS DURING GASIFICATION
/
ДОСЛІДЖЕННЯ ЗМІНИ МАСИ РОСЛИННОЇ БІОМАСИ В ПРОЦЕСІЇ ЇЇ ГАЗИФІКАЦІЇ

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ABSTRACT
The article suggests that the rate of plant biomass gas generation is proportional to the amount of plant biomass, which can still be gasified. To analyse the change in fuel mass during the operation of the gasifier for a certain period of time, three models can be used with the following assumptions: the change in fuel mass is inversely proportional to the fuel mass and time, the change in fuel mass is inversely proportional to the fuel mass, the change in fuel mass is inversely proportional to time. The coefficients of the fuel gasification rate are experimentally found.

АБСТРАКТ
В статті зроблено припущення, що швидкість газогенерації рослинної біомаси пропорційна кількості рослинної біомаси, що ще може бути газифікована. Для аналізу зміни маси палива в процесі роботи газогенератора упродовж певного періоду часу можна використати три моделі із наступними допущеннями: зміна маси палива обернено пропорційна масі палива і часу, зміна маси палива обернено пропорційна масі палива, зміна маси палива обернено пропорційна часу. Експериментальним шляхом знайдено коефіцієнти швидкості газифікації палива.

INTRODUCTION
When burning plant biomass there are difficulties associated with the heterogeneity of biomass, relatively high humidity, low specific energy, low melting point of ash *(Golub et al, 2018a; Golub et al, 2018b; Thiagarajan et al, 2018)*. Therefore, the use of gasifiers for biomass gasification will be appropriate for the consumer to obtain a stable energy supply (*Patra, Sheth, 2015)*. Analysis of scientific research allows us to conclude that the gasification of biomass is a complex process based on the equations of thermochemical equilibrium, kinetics, heat transfer and mass transfer *(Melgar et al, 2007; Zainal et al, 2001; De La Hoz et al, 2017*), which are based on the rate of biomass gasification.

Taking into account the stoichiometric equilibrium of the reaction of combustible gas formation *(Fani Mostafa et al, 2018; La Villetta et al, 2017; Jia et al, 2018)* and considering the formation of resins, the equation of wood gas formation will be:

$$\begin{gathered} m_1 C_x H_y O_z N_n + m_2 H_2 0 + m_3 \left(O_2 + \lambda N_2\right) = \\ = m_4 CO + m_5 H_2 + m_6 CO_2 + m_7 H_2 0 + m_8 CH_4 + \left(n m_1 + \lambda m_3\right) N_2 + m_9 C_{xtar} H_{ytar} O_{ztar}, \end{gathered} \tag{1}$$

where: m_1 – specific consumption of dry fuel (biomass) in the formation of combustible gas, mol/sec; m_2 – specific fuel moisture consumption, mol/sec; m_3 – specific air consumption, mol/sec; m_4 – specific content of carbon monoxide in the wood gas (output), mol/sec; m_5 – specific content of hydrogen in the wood gas (output), mol/sec; m_6 – specific content of carbon dioxide in the wood gas (output), mol/sec; m_7 – specific content of moisture in the wood gas (output), mol/sec; m_8 – specific content of methane in the wood gas (output), mol/sec; m_9 – specific content of resin in wood gas (output) , mol/sec; λ – coefficient characterizing the nitrogen content in the air (λ=3.76); x – the number of carbon molecules in the fuel mole; y – the number of hydrogen molecules in the fuel mole; z – the number of oxygen molecules in the fuel mole; n – the number of nitrogen molecules in the fuel mole; x_{tar} – the number of carbon molecules in the resin mole; y_{tar} – the number of hydrogen molecules in the resin mole; z_{tar} – the number of oxygen molecules in the resin mole.

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Taking into account the equivalence ratio (*ER*) which determines the ratio of the oxygen amount supplied to the gasifier to the oxygen amount required according to the stoichiometric combustion of fuel *(Maneerung et al, 2018; Yan et al, 2018)* we obtain: $ER = 0.21m_3 / \left(xm_1 + 0.25ym_1 + 0.5zm\right)$, the value of the air flow will be:

$$m_3 = 4.76ER(xm_1 + 0.25ym_1 + 0.5zm_1)\,. \tag{2}$$

Substituting the equation 2 in 1 and taking into account that the coefficient characterizing the nitrogen content in the air is λ=3.76, we obtain:

$$m_1\begin{pmatrix} C_xH_yO_zN_n + 4.76ER(x+0.25y+0.5z)(0_2+3,76N_2) - \\ -(n+17.9ER(x+0.25y+0.5z)N_2 \end{pmatrix} + m_2H_20 =$$
$$= m_4CO + m_5H_2 + m_6C0_2 + m_7H_20 + m_8CH_4 + \left(nm_1 + 3.76m_3\right)N_2 + m_9C_{xtar}H_{ytar}O_{ztar}\,. \tag{3}$$

If we take into account the molar masses of the chemical components included in equation (4), it can be written as the calculated material balance:

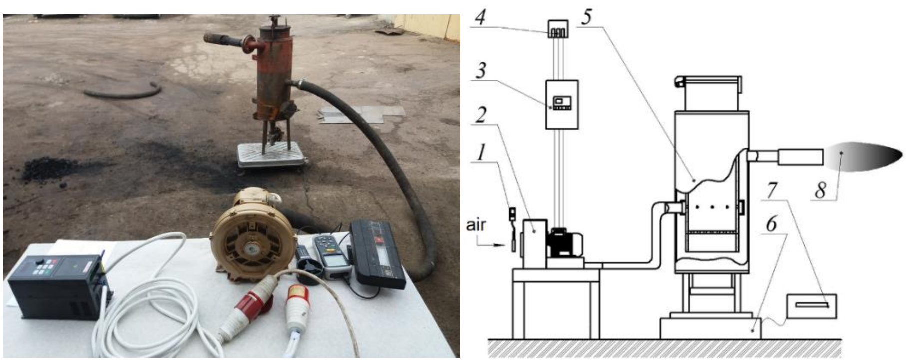
$$\mu_1 m_1\begin{pmatrix} C_xH_yO_zN_n + 4.76ER(x+0.25y+0.5z)(0_2+3,76N_2) - \\ -(n+17.9ER(x+0.25y+0.5z)N_2 \end{pmatrix} + 18m_2H_20 =$$
$$= 28m_4CO + 2m_5H_2 + 44m_6C0_2 + 18m_7H_20 + \tag{4}$$
$$+16m_8CH_4 + 28\left(nm_1 + 3.76m_3\right)N_2 + \mu_9 m_9C_{xtar}H_{ytar}O_{ztar}\,,$$

where: μ_1 – molar mass of fuel, g/mol; μ_9 – molar mass of resin, g/mol.

Obviously, in equation 5, the product $\mu_1 m_1$ is the fuel consumption rate or the rate of plant biomass gas generation. Nevertheless, the study of biomass gasification rate is difficult for theoretical research due to the complexity of interaction, diversity and transience of the corresponding processes *(Yan et al, 2018; Ali et al, 2016)*. This complexity prevents theoretical models from achieving the necessary accuracy to optimize the gasification process *(Mazaheri et al, 2018)*. In addition, the insufficient amount of experimental data on the rate of biomass gasification also does not allow the developed theoretical models of the gasification process to achieve the required accuracy *(Gu et al, 2019).* Therefore, it is necessary to accumulate experimental data in the real range of parameters of gasifiers and create simple mathematical models that adequately describe the biomass gasification rate.

MATERIALS AND METHODS

A specially designed research plant was used for experimental studies of biomass gasification rate (Fig. 1 a, b). The structure of the plant included a gasifier of the reverse process. The diameter of the recovery zone was 200 mm; the height of the recovery zone was 110 mm and was determined according to the studies described in (*Golub et al, 2019)*. The number of tuyere holes was 12; their diameter was 10 mm. The flow of air into the gasifier was carried out by a blower and was varied in the range of 0.0009 m^3/sec and 0.012 m^3/sec. The performance of the blower was adjusted by frequency converter. The gasifier was installed on the scales, loaded with fuel and put into operation. Operating mode was fixed by steady burning of gas torch.



a) b)

Fig.1 - Appearance (a) and scheme (b) of the plant for the study of changes in the fuel mass in the process of combustible gas production

1 – anemometer Tenmars TM-402; 2 – blower Goorui GHBH-0D5-34-1R2; 3 – frequency converter Hitachi-3G3JX-A4075-EF; 4 – socket 0.4 kV; 5 – gasifier GG-1; 6 – scale; 7 – scale indicator; 8 – wood gas torch

Straw pellets, wood pellets, wood pieces and peat pieces were used as fuel. With the help of scales, the mass of fuel remaining in the gasifier was fixed at equal intervals. For the final moment of time, it was accepted the moment when the torch of combustible gas extinguished. Further, the mass of fuel remaining in the gasifier and the mass of ash were recorded.

RESULTS

Theoretical studies

Assuming that the rate of gas generation of plant biomass is proportional to the amount of plant biomass that can still be gasified, three models with the following assumptions can be used to analyse the change in fuel mass during the operation of the gasifier for a certain period of time: the change in fuel mass is inversely proportional to fuel mass and time; the change in fuel mass is inversely proportional to the fuel mass; the change in fuel mass is inversely proportional to time.

The first model is based on the assumption that the fuel mass change $dM/d\tau$ is inversely proportional to the fuel mass M and time τ:

$$\frac{dM}{d\tau} = -k_{M\tau} M \tau \ , \tag{5}$$

where:

M – the fuel mass, kg; τ – gasifier operating time, sec; $k_{M\tau}$ – the speed ratio of the fuel gasification according to mass and time.

The solution of the equation (5) will be as follows:

$$\frac{dM}{M} = -k_{M\tau}\tau d\tau; \quad \ln M - \ln M_0 = -\frac{k_{M\tau}}{2}(\tau^2 - \tau_0^2)\,.$$

Considering that $\tau_0 = 0$, we will obtain:

$$\ln\frac{M}{M_0} = -\frac{k_{M\tau}\tau^2}{2}, \quad \frac{M}{M_0} = \exp\left(-\frac{k_{M\tau}\tau^2}{2}\right),$$

$$M = M_0 \exp\left(-\frac{k_{M\tau}\tau^2}{2}\right), M_g = M_0\left(1 - \exp\left(-\frac{k_{M\tau}\tau^2}{2}\right)\right); \tag{6}$$

where:

M_0, M, M_g – initial, final, and the mass of the gasified fuel, %.

In this case, the rate coefficient of fuel gasification based on research data can be determined by the formula:

$$k_{M\tau} = \frac{2}{\tau^2}\ln\frac{M_0}{M}\,. \tag{7}$$

The second model is based on the assumption that the fuel mass change $dM/d\tau$ is inversely proportional to the fuel mass M:

$$\frac{dM}{d\tau} = -k_M M; \tag{8}$$

where:

k_M – the speed ratio of the fuel gasification according to the mass.

The solution of the equation (8) will be as follows:

$$M = M_0 \exp\left(-k_M\tau\right),\ M_g = M_0\left(1 - \exp\left(-k_M\tau\right)\right). \tag{9}$$

In this case, the rate coefficient of fuel gasification based on research data can be determined by the formula:

$$k_M = \frac{1}{\tau}\ln\frac{M_0}{M}\,. \tag{10}$$

The third model is based on the assumption that the change in fuel mass $dM/d\tau$ is inversely proportional to the operating time of the gasifier τ:

$$\frac{dM}{d\tau} = -k_\tau \tau; \tag{11}$$

where:

k_τ – the speed ratio of gasification according to the time.

The solution of the equation (11) will be as follows:

$$M = M_0 - \frac{k_\tau}{2}\tau^2, \; M_g = M_0 - \left(M_0 - \frac{k_\tau}{2}\tau^2\right). \tag{12}$$

In this case, the rate coefficient of fuel gasification based on research data can be determined by the formula:

$$k_\tau = 2\frac{M_0 - M}{\tau^2}. \tag{13}$$

Experimental studies

Experiments on the gasification rate of straw pellets at different modes of oxidizer (air) supply to the gasifier oxidation zone at the optimum height of the reduction zone were carried out and the results given in table 1 were obtained.

Table 1

Experimental values of fuel mass change in the process of straw pellets gasification

Indicator	**Mass of gasified fuel, kg**					
	0	**1**	**2**	**3**	**4**	**4.8**
The air supply to the gasifier 0.012 m³/sec						
Ash mass, kg	0	0.04	0.08	0.12	0.16	0.2
Gasifier operation time, sec	0	135	250	415	620	840
Current fuel mass, kg	5	3.96	2.92	1.88	0.84	0
Ash content, %	0	0.8	1.6	2.4	3.2	4.0
The air supply to the gasifier 0.006 m³/sec						
Ash mass, kg	0	0.04	0.08	0.12	0.16	0.2
Gasifier operation time, sec	0	150	300	475	740	1015
Current fuel mass, kg	5	3.96	2.92	1.88	0.84	0
Ash content, %	0	0.8	1.6	2.4	3.2	4
The air supply to the gasifier 0.0009 m³/sec						
Ash mass, kg	0	0.04	0.08	0.12	0.16	0.2
Gasifier operation time, sec	0	315	621	1040	1630	2100
Current fuel mass, kg	5	3.96	2.92	1.88	0.84	0
Ash content, %	0	0.8	1.6	2.4	3.2	4

Substituting the value of the initial and final mass and time (from table 1) in formulas 9, 13 and 1, the coefficients of the gasification rate of straw granules were determined and the change in the fuel mass was calculated according to the above three models (table 2).

Since the calculated coefficient of determination is the highest for the model with the assumptions that the change in fuel mass is proportional to the fuel mass, it is the closest to the experimental values of the change in the mass of straw granules during the operation of the gasifier for a certain period of time. The obtained dependences are shown in Fig. 2.

Similar calculations were also performed for other values of air supply to the gasifier.

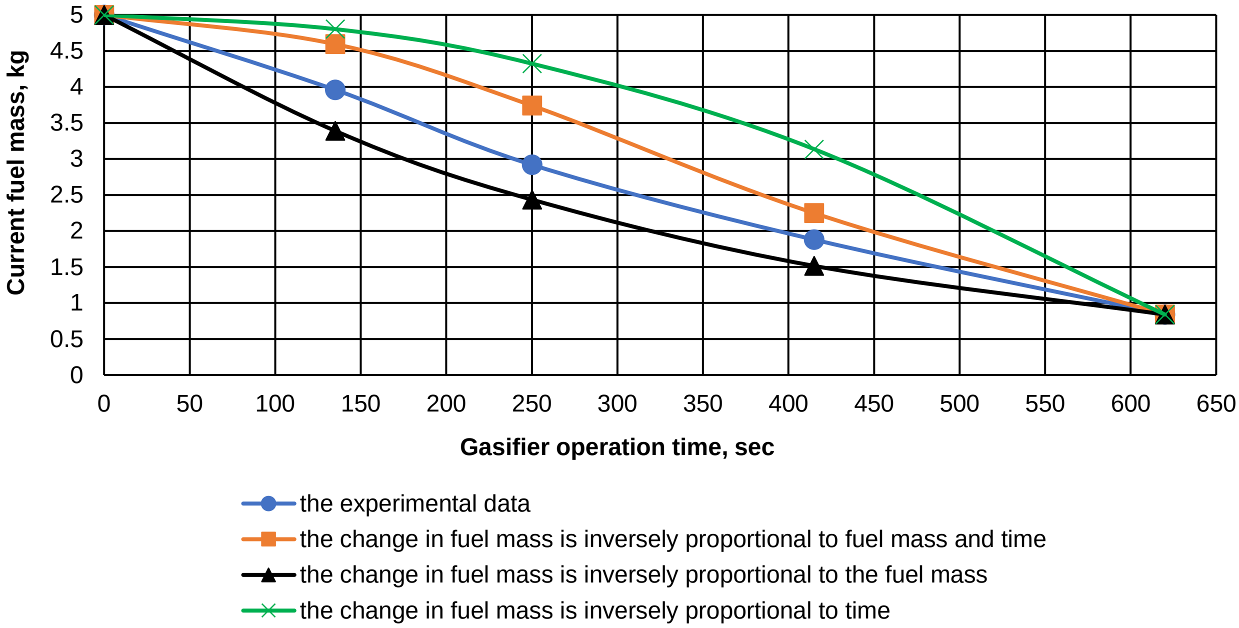


Fig. 2 - Change of fuel mass in the process of straw pellets gasification during air supply 0.01169 m^3/sec

Table 2

Calculated values of fuel mass change in the process of straw pellets gasification (initial fuel mass 5 kg, air supply to the gasifier 0.012 m³/sec, time 620 sec)

Indicator	Gasifier operation time, sec					The sum of the values
	0	135	250	415	620	
Experimental data						
Current fuel mass, kg	5	3.96	2.92	1.88	0.84	14.6
The square of deviation of experimental values from the general arithmetic mean	1.8225	0.0961	0.5329	3.1329	7.8961	13.4805
The change in fuel mass is inversely proportional to fuel mass and time						
The ratio of gasification rate, sec^{-2}	$9.2809 \cdot 10^{-6}$					
Current fuel mass, kg	5	4.59	3.74	2.25	0.84	16.42
Square of deviation of experimental data from theoretical one	0	0.3969	0.6724	0.1369	0	1.2062
Coefficient of determination	0.955					
The change in fuel mass is inversely proportional to the fuel mass						
The ratio of gasification rate, sec^{-1}	0.002877					
Current fuel mass, kg	5	3.39	2.44	1.52	0.84	13.19
Square of deviation of experimental data from theoretical one	0	1.44	1.69	0.5329	0	3.6629
Coefficient of determination	0.973					
The change in fuel mass is inversely proportional to time						
The ratio of gasification rate, kg·sec-2	$2.1644 \cdot 10^{-6}$					
Current fuel mass, kg	5	4.8	4.32	3.14	0.84	18.1
Square of deviation of experimental data from theoretical one	0	0.7056	1.96	1.5876	0	4.2532
Coefficient of determination	0.848					

Similarly to the study of the rate of straw pellets gasification, the experiments on the rate of gasification of wood pellets, wood pieces and peat pieces were conducted (table 3-5).

Table 3

Experimental parameters of fuel mass change in the process of pellets and wood gasification (air supply to the gasifier 0.012 m³/sec)

Indicator	Mass of gasified fuel, kg					
	0	**1**	**2**	**3**	**4**	**4.85**
Ash mass, kg	0	0.03	0.05	0.08	0.1	0.15
Gasifier operation time, sec	0	105	230	390	580	785
Current fuel mass, kg	5	3.97	2.95	1.92	0.9	0
Ash content, %	0	0.6	1	1.6	2	3

Table 4

Experimental parameters of fuel mass change in the process of gasification of wood pieces (air supply to the gasifier 0.012 m³/sec)

Indicator	Mass of gasified fuel, kg					
	0	**1**	**2**	**3**	**4**	**4.8**
Ash mass, kg	0	0.04	0.08	0.12	0.16	0.2
Gasifier operation time, sec	0	125	235	405	615	830
Current fuel mass, kg	5	3.96	2.92	1.88	0.84	0.00
Ash content, %	0	0.8	1.6	2.4	3.2	4.0

Table 5

Experimental parameters of fuel mass change in the process of gasification of peat pieces (air supply to the gasifier 0.012 m³/sec)

Indicator	Mass of gasified fuel, kg					
	0	**1**	**2**	**3**	**4**	**4.65**
Ash mass, kg	0	0.07	0.14	0.21	0.28	0.35
Gasifier operation time, sec	0	109	222	375	595	800
Current fuel mass, kg	5	3.93	2.86	1.79	0.72	0
Ash content, %	0	1.4	2.8	4.2	5.6	7

According to the results of experimental studies, the values of the gasification rate coefficients depending on the air supply to the gasifier were calculated (Fig. 3). It was established that for other types of biomass the closest to the experimental values of the fuel mass change and during the operation of the gasifier for a certain period of time was a model with the assumptions that the fuel mass change was proportional to the fuel mass. Empirical equations for determining the coefficient of fuel gasification rate by mass depending on the air supply to the gasifier are given in table. 6.

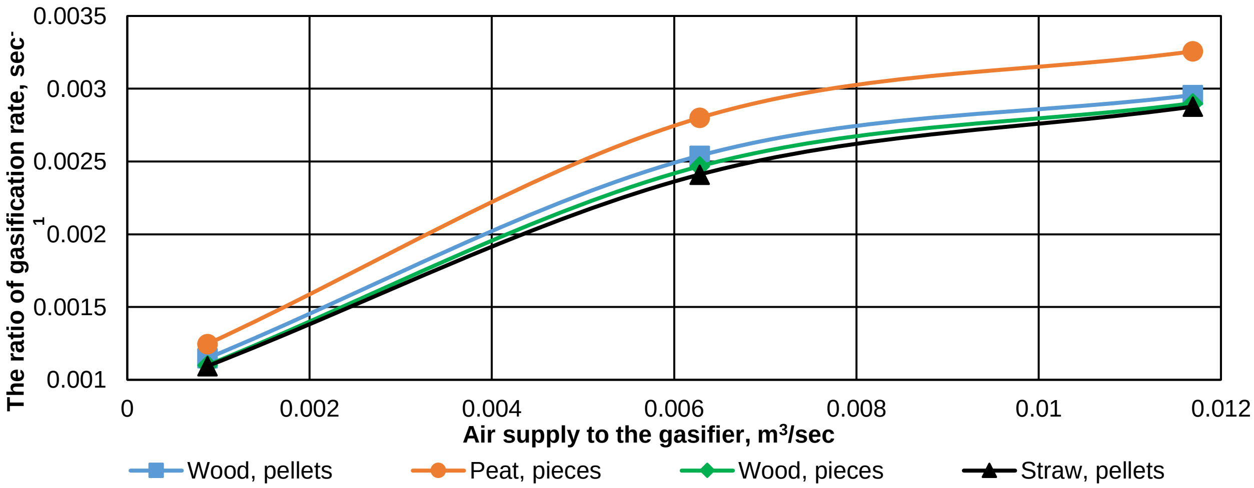


Fig. 3 - Change in the speed of gasification depending on the air supply

Table 6

The values of the speed ratio of biomass gasification

Fuel type	Air supply q_g, m³/sec			Empirical equation
	0.0009	0.006	0.012	
Wood, pellets	0.001148	0.00254	0.002957	k_M=-16.733q_g^2+0.3776q_g+0.0008
Peat, pieces	0.001246	0.0028	0.003257	k_M=-18.819q_g^2+0.4226q_g+0.0009
Wood, pieces	0.001101	0.002467	0.0029	k_M=-15.994q_g^2+0.3675 q_g+0.0008
Straw, pellets	0.001094	0.002411	0.002877	k_M=-14.57q_g^2+0.3481q_g+0.0008

According to the values of the coefficient of biomass gasification rate, peat pieces have the highest gasification rate, and straw pellets – the lowest one. The proposed method of biomass gasification rate estimation can be used for other types and sizes of gasifiers.

CONCLUSIONS

Mathematical models of fuel mass change in the gasifier in the process of wood gas depending on the air supply to the gasifier are developed.

In mathematical models, the following assumptions were made: change in fuel mass is inversely proportional to the mass of fuel and time; change in the mass of the fuel is inversely proportional to the mass of fuel; change in the mass of the fuel is inversely proportional to time.

It is found that the closest to the experimental values of the fuel mass change during the operation of the gasifier for a certain period of time is the model of the fuel mass change proportional to the fuel mass.

On the basis of experimental studies, it was found that peat pieces have gasification coefficient of 0.0033 sec^{-1}, wood pellets – 0.003 sec^{-1}, wood pieces and straw pellets – 0.0029 sec^{-1} when the air supply to the tuyere belt of the gasifier equals 0.012 m^3/sec.

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