EXPERIMENTAL STUDY OF GASIFICATION RATE OF FAST-GROWING WILLOW BIOMASS

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Abstract. The biomass of fast-growing hybrid plants can be an effective source for energy conversion. The biomass of energy plants: hybrid poplar, hybrid willow etc., is a potential fuel for obtaining thermal and electrical energy. It should be noted that a small size downdraft gasifier, which is economically available and the most reliable equipment, is the most suitable for the use in small or medium production conditions for energy conversion of fast-growing willow biomass. The experimental confirmation of the mathematical model of fast-growing willow biomass gasification rate is proposed to carry out in the paper. According to the model, the rate of biomass gasification is proportional to the amount of biomass remaining ungasified. The gasification rate coefficients of four fractions of fast-growing willow biomass pieces and pellets were determined by the research results. During the research, the supply of oxidizer (air) to the working area (zone) of the downdraft gasifier was changed. When the air supply into a gasifier is minimal, the gasification rate coefficient is actually the same for all biomass fractions of fast-growing willow Salix Viminalis, L. and is $4.1 \cdot 10^{-5} \pm 0.1 \cdot 10^{-5}$ s^{-1}. With an increase in air supply the gasification rate coefficient increases and reaches its maximum value at an air supply of $9 \cdot 10^{-3}$ m$^3 \cdot$s^{-1}, further increase in the air volume does not lead to an increase in the gasification rate coefficient. As the size of fuel pieces decreases, the rate coefficient also increases and is $9.476 \cdot 10^{-5}$ s^{-1} for the fraction with the smallest pieces.

Keywords: biomass, gasification, reduction zone, coefficient, rate.

Introduction

The biomass of fast-growing hybrid plants can be an effective source for energy conversion. The biomass of energy plants: hybrid poplar, hybrid willow etc., is a potential fuel for obtaining thermal and electrical energy [1-3]. However, the efficiency of energy conversion largely depends on the parameters of the working equipment (in particular, boilers, gasifiers, pyrolysis plants, etc) and on the technological processes [4; 5].

A species of willow named Salix Viminalis, L. is considered to be one of the most suitable for energy conversion [6; 7]. The biomass from Salix Viminalis, L. is used in combustion processes, because it has a rather high heating value (approximately 18.6 MJ$\cdot$kg^{-1}) [8]. However, some technical and technological problems, which are associated with the heterogeneity of biomass, significant moisture, significant formation of ash and its melting, arise in the process of combustion [9; 10]. In addition, biomass combustion allows consumers to receive only thermal energy and, for example, we need biomass gasification for receiving electric energy [3; 11-13].

The obtained gas can be used to drive internal combustion engines, in particular, in mobile power plants [14]. It should be noted that a small size downdraft gasifier, which is economically available and the most reliable equipment, is the most suitable for general use [14; 15].

In the previous studies the effects of the temperature and the air supply during the process on the efficiency of the thermochemical decomposition of biomass in gasifiers was analysed [13; 15; 16-18]. The works [19; 20] describe how air supply in gasifier's working zones affects the biomass gasification process. However, there are no conclusions regarding the effect of the air supply on the rate of biomass gasification. The analysis of the research allows us to conclude that gasification process of biomass highly depends on the rate of fuel combustion or the rate of gasification. That is why the study the relationship between the fuel parameters (fuel type, fuel size) and the parameters of the gasification process, for example, the supply (inflow) of air (oxidizer) or equivalence ratio is an important scientific question. Studies [20; 21] indicated that the rate of biomass gasification is proportional to the amount of biomass (fuel) in the gasifier at a given time. In addition, it is claimed that the change in fuel mass can also be proportional to the duration of the gasification process (time). However, the mathematical studies given in the research require additional experimental studies in order to confirm the adequacy of the given mathematical models of the gasification rate.

The accumulation of the experimental data on the gasification efficiency of biomass for existing models of gas generators will contribute to the creation of simple mathematical models of gasification rate of biomass. In addition, fuel gasification rate studies are also important to establish rational parameters of the work process and the gasifier construction with continuous supply of fuel (9,22-24) (continuous work process of gasification).

Materials and methods

Biomass gasification rate theoretical equation [21], which purpose is to establish the non-gasified fuel amount at the current moment is presented below:

$$m = m_1 + \left(m_0 - m_1\right)\ \exp\left(-k\tau\right), \tag{1}$$

where m – fuel that was not gasified (turned into gas) at the current moment, kg;
m_0 – initial mass of fuel, kg;
m_1 – mass of ash, kg;
k – gasification rate coefficient, s^{-1};
τ – gasification duration, s.

The mass of fuel mg, that has been gasificated at the given moment of time, can be found according to the equation:

$$m_g = m_0 - \left(m + m_1\right). \tag{2}$$

And the gasification rate coefficient can be determined from the dependence [21]:

$$k = \frac{1}{\tau}\ln\frac{m_0 - m_1}{m - m_1}. \tag{3}$$

Herewith, the duration of gasification, the ash volume and the amount of fuel that was not gasified at the current moment of time were determined using the experimental studies.

A special experimental plant was used for conducting the experimental studies (Fig. 1).

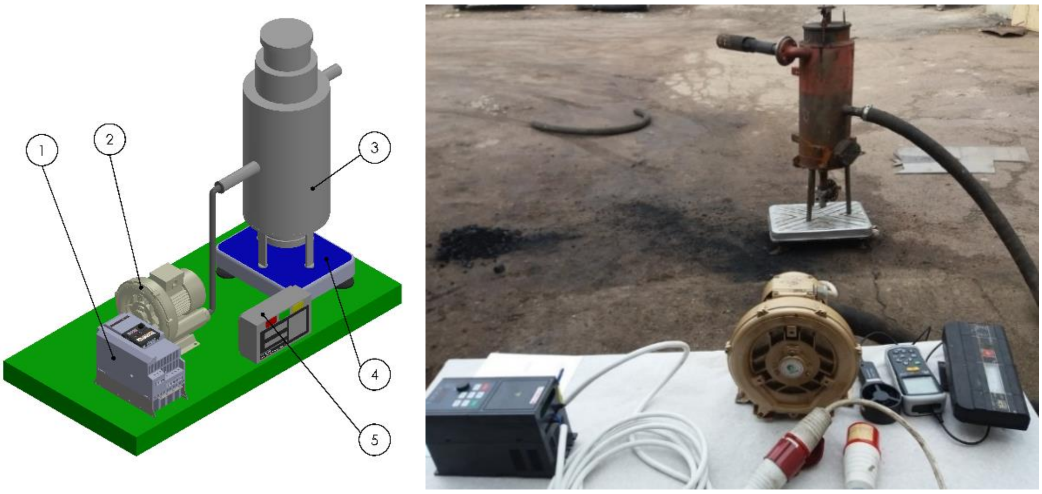

Fig. 1. **Experimental plant:** 1 – frequency converter Hitachi-3G3JX-A4075-EF; 2 – blower Goorui GHBH-0D5-34-1R2; 3 – downdraft gasifier; 4 – weight scales; 5 – weight scales indicator

According to studies [20; 21], the parameters of a gasifier were chosen to ensure the highest quality of generator gas. In particular, the diameter of the working area is 200 mm, the height of the working area is 110 mm. In the process of experimental studies, the air flow into the working area of the gasifier varied from 0.88-103 $m \cdot s^{-1}$ to 11.69-107 $m \cdot s^{-1}$ due to changes in the performance of the blower using a frequency converter. The air supply to the gasifier was monitored using the anemometer Tenmars TW-402. The temperature of the air supplied to the gasifier corresponded to the ambient temperature and was 18-20°C.

The gasifier was installed on the scales. In the process of conducting the research some change in the gasifier mass was recorded.

Fast-growing willow Salix Viminalis, L. biomass was used as fuel. The fuel moisture was minimal possible. The fuel was divided into four fractions, plus fuel pellets (Table1). The ratio [25] was used as a parameter of the size of the fuel fraction:

$$SVR = \frac{S}{V}, \tag{4}$$

where S – full side area, mm^2;
V – fraction volume, mm^3.

Table 1

Geometric characteristics of fuel fractions

Fraction				
Large	Medium	Small	Very small	Fuel pellets
				
Average Sizes, mm (Length-Width-Thickness)				
40-15-12	30-12-8	20-9-5	10-4-4	10-4*
***SVR*, mm^{-1}**				
0.35	0.48	0.72	1.20	1.20

*Diameter

The research was carried out according to the experimental plan (Tables 2 and 3). The obtained equations were tested for adequacy using Student's and Fisher's tests.

Table 2

Experimental planning matrix for fuel pellets

No	**Air supply, Q m^3·s^{-1}**		**Number of repetitions**
1	-1	$0.88\cdot10^{-3}$	3
2	0	$6.28\cdot10^{-3}$	3
3	1	$11.69\cdot10^{-3}$	3

Table 3

Experimental planning matrix for wood in pieces

No	**Parameter of the size of the fuel fraction *SVR***		**Air supply *Q*, m^3·s^{-1}.**	
1	a	0.35	-1	$0.88\cdot10^{-3}$
2	a	0.35	0	$6.28\cdot10^{-3}$
3	a	0.35	+ 1	$11.69\cdot10^{-3}$
4	b	0.48	-1	$0.88\cdot10^{-3}$
5	b	0.48	0	$6.28\cdot10^{-3}$
6	b	0.48	+ 1	$11.69\cdot10^{-3}$
7	c	0.72	-1	$0.88\cdot10^{-3}$
8	c	0.72	0	$6.28\cdot10^{-3}$
9	c	0.72	+ 1	$11.69\cdot10^{-3}$
10	d	1.20	-1	$0.88\cdot10^{-3}$
11	d	1.20	0	$6.28\cdot10^{-3}$
12	d	1.20	+ 1	$11.69\cdot10^{-3}$

The methodology of the experimental studies is described in detail in [20; 21].

Results and discussion

During the experimental studies several values including the duration of gasification, ash volume and the amount of fuel that was gasified at the current moment of time were obtained. An example of the obtained and calculated parameters of the fuel pellets under an air supply of $0.88 \cdot 10^{-3}$ $m^3 \cdot s^{-1}$ (experiment I, Table 2) is given in Table 4. Similar calculations were carried out for other experiments.

Table 4

Example of obtained and calculated parameters for fuel pellets under air supply of $0.88 \cdot 10^{-3}$ $m^3 \cdot s^{-1}$

Parameter	Duration of operation of the gas generator, s					
	0	260	578	996	1698	2003
Mass of gasified fuel, kg	0	1	2	3	4	4.6
Ash mass,kg	0	0.03	0.06	0.09	0.11	0.15
Mass of fuel that remained , according to the experimrntal studies, kg	5	4	3	2	1	0.25
Ash content, %	0	0.6	1.2	1.8	2.2	3
Coefficient of gasification rate, s^{-1}	$4.243 \cdot 10^{-5}$					
Mass of fuel that remained according to the theoretical studies, kg	5.00	3.96	2.93	1.92	0.94	0.24
Mass of fuel gasified according to the theoretical studies, kg	0.00	1.01	2.01	2.99	3.95	4.61

Therefore, we were able to calculate the gasification rate coefficient of hybrid fast-growing willow Salix Viminalis, L. biomass using the formula (3) (Table 5).

Table 5

Coefficient of gasification rate for fast-growing willow Salix Viminalis biomass, s^{-1}

Type of fuel	Air supply Q, $m^3 \cdot s^{-1}$		
	$0.88 \cdot 10^{-3}$	$6.28 \cdot 10^{-3}$	$11.69 \cdot 10^{-3}$
Pellets	$4.243 \cdot 10^{-5}$	$8.906 \cdot 10^{-5}$	$9.970 \cdot 10^{-5}$
SVR 1.2	$4.224 \cdot 10^{-5}$	$8.906 \cdot 10^{-5}$	$9.476 \cdot 10^{-5}$
SVR 0.72	$4.216 \cdot 10^{-5}$	$7.857 \cdot 10^{-5}$	$8.469 \cdot 10^{-5}$
SVR 0.48	$4.053 \cdot 10^{-5}$	$7.233 \cdot 10^{-5}$	$7.784 \cdot 10^{-5}$
SVR 0.35	$4.001 \cdot 10^{-5}$	$6.844 \cdot 10^{-5}$	$7.381 \cdot 10^{-5}$

With an increase of the air supply to the working area of the gasifier, the gasification rate coefficient also increases, in particular for the fuel pellets. The change in the coefficient can be described by the dependence:

$$k = -0.6077Q^2 + 0.0129Q + 3 \cdot 10^{-5}, \quad (5)$$

where Q – air supply, $m^3 \cdot s^{-1}$.

For the fractions of wood in pieces the gas rate coefficient depends not only on the air supply, but also on the size of the fraction (6):

$$k = 1.953 \cdot 10^{-5} + 3.576 \cdot 10^{-5} SVR + 0.008Q - 1.909 \cdot 10^{-5} SVR^2 + 0.002 SVRQ - 0.408Q^2 . \quad (6)$$

As a result of solving equation 6, the response surface was obtained (Fig. 2).

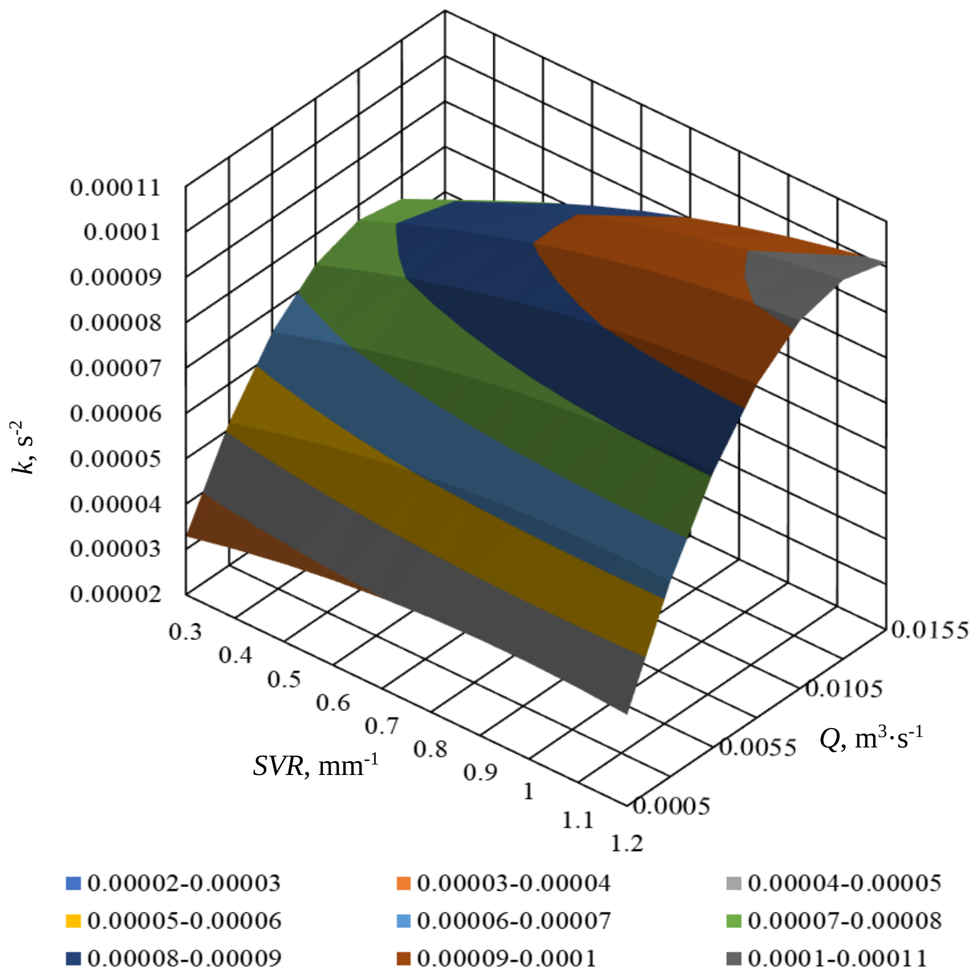

Fig. 2. **Change in the coefficient of gasification rate depending on air supply and fuel sizes**

During the period of minimal gasifier air supply ($0.88 \cdot 10^{-3}$ $m^3 \cdot s^{-1}$), the gasification rate coefficient remained unchanged – $4.1 \cdot 10^{-5} \pm 0.1 \cdot 10^{-5}$ s^{-1} for all fuel fractions. Moreover, with a further decrease in the air supply into the gasifier, the biomass gasification process stops. If the air supply increases, the gasification rate coefficient increases as well and reaches its maximum level at the air supply of $9 \cdot 10^{-3}$ $m^3 \cdot s^{-1}$. With a further increase in the air supply, the increase in the rate of gasification slows down to a significant extent, and actually stops. As the size of fuel pieces decreases, the gasification rate coefficient also increases and is $9.476 \cdot 10^{-5}$ s^{-1} for the fraction with SVR – 1.2, which is 26.0% more than for the fuel with SVR – 0.35. For pellets the rate coefficient is actually the same as the rate coefficient for fuel with SVR – 1.2 and lies in the range from $4.297 \cdot 10^{-5}$ to $9.970 \cdot 10^{-5}$ depending on the air supply.

An increase in the gasification rate coefficient with a decrease in the size of pieces of fuel can be explained by an increase in the active size of fuel which is subject to the thermochemical transformations [9]. Also, an increase in the gasification rate is facilitated by an increase in the air supply into the working area of the gasifier, although an excessive increase in the air supply will not ensure the growth of the gasification coefficient. This statement is relevant to the results of studies [20,21,26]. This can be explained, according to the authors, by the fact that when the optimal equivalence ratio is reached, an increase in the air supply does not lead to the intensification of the thermochemical transformations of the fuel in the gasifier.

Conclusions

1. During the period of minimal gasifier air supply – $8.8 \cdot 10^{-4}$ $m^3 \cdot s^{-1}$, the gasification rate coefficient is actually the same for all biomass fractions of fast-growing willow Salix Viminalis, L. and is $4.1 \cdot 10^{-5} \pm 0.1 \cdot 10^{-5}$ s^{-1}. With an increase in the air supply the gasification rate coefficient increases and reaches its maximum value at an air supply of $9 \cdot 10^{-3}$ $m^3 \cdot s^{-1}$. As the size of fuel pieces decreases,

the rate coefficient also increases and is $9.476 \cdot 10^{-5}$ s^{-1} for the fraction with *SVR* – 1.2 which is 26% more than for fuel with *SVR* 0.35. For pellets the gasification rate coefficient is actually the same as for the gasification rate coefficient of fuel with *SVR* – 1.2 and lies within $4.297 \cdot 10^{-5}$ and $9.970 \cdot 10^{-5}$ depending on the air supply.

2. Obtaining of the biomass gasification rate provides a possibility to determine the fuel consumption level while using a downdraft gasifier with different geometric sizes during the process of receiving gas. Moreover, the biomass (fuel) consumption calculation makes it possible to evaluate technical and economic aspects of using gasifiers and biomass gasification technologies.
3. After analysing the conducted research, we can make a conclusion that the biomass gasification rate is an important parameter of gasifiers with a continuous fuel supply working process. In addition, it is important to accumulate experimental data for existing models of gasifiers and develop new mathematical models related to the biomass gasification rate.

Author contributions

Conceptualization, A.J. and S.K; methodology, S.K., O.S. and V.K.; validation, O.S. and V.K; formal analysis, S.K and O.S.; investigation, A.J., S.K., O.S. and V.K.; data curation, S.K. and O.S.; writing – original draft preparation, S.K.; writing – review and editing, A.J. and S.K.; visualization, S.K. and O.S.; project administration, A.J. All authors have read and agreed to the published version of the manuscript.

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