ENERGY CONVERSION OF BIOMASS FROM FAST-GROWING PLANTS FOR HEAT PRODUCTION

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Abstract. In the realm of sustainable energy production, converting biomass from fast-growing plants into thermal energy stands out as a promising avenue. To actualize this concept, we propose the utilization of a top-fired boiler that incorporates innovative features to enhance its performance. This boiler comprises two distinct working areas, namely the combustible gas formation area and the combustible gas combustion area. The segregation of these zones facilitates a more controlled and efficient biomass-to-energy conversion process. Central to the improved efficiency of this proposed boiler is the incorporation of an air distributor in its design. This crucial element optimizes the combustion process by facilitating air distribution within the system. The air distributor plays a pivotal role in enabling the boiler to operate in the biomass gasification mode. This mode allows for efficient burning of the resulting combustible gas, thereby maximizing the energy output and minimizing waste. During the course of experimental investigations, several key parameters were explored to evaluate the performance of the boiler. One such parameter was the size of fuel pieces fed into the boiler. The size of fuel pieces was found to have a little effect on the overall efficiency of the system. Additionally, the air supply to the boiler furnace was identified as another critical factor influencing efficiency. Proper control and management of the air supply contribute to the combustion process, impacting the overall efficiency of the boiler as well as the level of harmful gas emissions.

Keywords: boiler, gas, emissions, thermal, power, CO.

Introduction

Wood obtained from the fast-growing hybrid plants can be an effective fuel [1] for obtaining thermal energy [2]. However, the efficiency of the obtained thermal energy depends on the correctly selected parameters of working devices (boilers) and the processes taking place in these devices [3; 4]. It has been established that one of the most effective in terms of obtaining thermal energy is the willow species Salix Viminalis [5; 6]. In particular, the wood obtained from Salix Viminalis has a rather high heating value (more than 19.5 MJ·kg^{-1}) [7; 8]. However, when burning Salix Viminalis biomass, some problems may arise related to the heterogeneity of the fuel, high moisture level, large yield of ash formation and the formation of solid conglomerates as a result of ash melting [9; 10]. In addition, incorrectly selected operating modes of the boiler (boilers) can significantly increase the emissions of pollutants produced as a result of burning biomass in the boiler [11]. This can have a harmful effect on human health, cause disruption of the chemical composition of the atmosphere and affect the deterioration of the climate. Studies show that burning biofuel in boilers with top-down combustion improves the combustion process and reduces the amount of pollutant emissions [12; 13].

However, this happens only with correctly selected operating parameters of the boiler. In particular, in work [12] it was determined that different sizes of fuel require different modes of operation in the boiler. And, for example, in studies [13] it was established that the rational regulation of air supply to the furnace (working area) of the boiler significantly improves the efficiency of combustion and, as a result, reduces harmful emissions in the process of burning fuel. However, in scientific papers [12; 13] there is no information about the mutual influence of the fuel size and air supply on the level of harmful emissions and fuel combustion efficiency. In addition, each specific type of biomass that is burned requires specific parameters of the boiler, in particular, a clearly defined amount of air entering the fuel combustion chamber [14; 15].

Therefore, the task arises in the course of experimental studies to evaluate the combined effect of the size of fuel pieces and air supply to the furnace of a top-burning boiler on the overall efficiency of the boiler, as well as on the level of emissions of harmful gases.

Materials and methods

To conduct research on the influence of top-burning boiler parameters on the energy efficiency of grain straw burning, the KGV-20 boiler developed by the authors of the paper (Fig. 1) and equipped with an electronic control system based on the ATOS microprocessor device was used. The structure of the boiler and the principle of its operation are described in detail in scientific publications [16; 17]. To supply air to the boiler furnace, an air supply system based on a WPA -06 fan, equipped with an asynchronous engine with a capacity of 83 W was used. To evaluate the thermal power of the boiler, it was equipped with an air supply system into the heating cavity (water jacket) based on an OBR-200M-2K fan equipped with a 600 W electric motor.

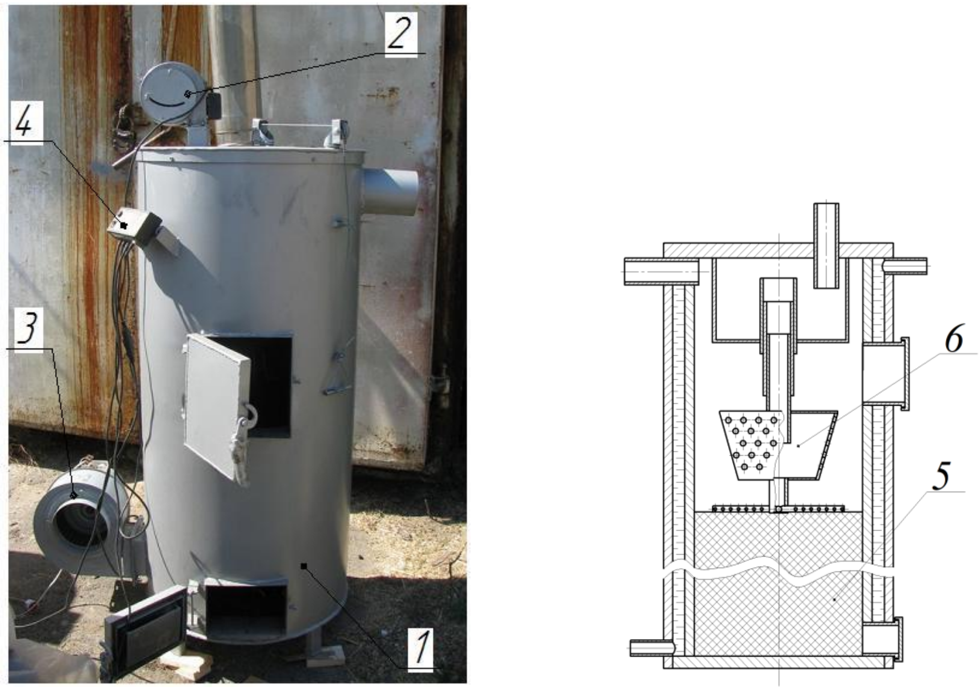

Fig. 1. **General view of the experimental installation**: 1 – boiler; 2 – fan WPA-06; 3 – fan OBR-200M-2K; 4 – electronic control system ATOS; 5 – fuel; 6 – air supply system

Fast-growing willow Salix Viminalis wood was used as fuel. The fuel was divided into three groups by size (Table 1). The surface-volume ratio was used as a size parameter [5]:

$$SVR = S/V, \quad (1)$$

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

During the research, the air supply to the fuel combustion zone varied from 0.0015 to 0.04 m^3·s^{-1}.

The volume of incoming air and its temperature were determined using an anemometer – thermometer CEM DT 620. The composition of flue gases was determined using a gas analyzer OKCI 5M. The average deviations of all parameters were below 5%.

The actual thermal power of the boiler was determined by the formula:

$$P = c\upsilon\left(t_2 - t_1\right), \quad (2)$$

where P – actual thermal power of the boiler, W;
c – heat capacity of air, J·(kg K)$^{-1}$;
υ – specific volume of heated air, m^3·s^{-1};
t_1 – air temperature at the water jacket inlet of the boiler, ºC;
t_2 – air temperature at the water jacket outlet of the boiler, ºC.

In each experiment, at least three measurements of the corresponding parameter were carried out. Based on the measured parameters, the average value was calculated. To express the analytical relationship, taking into account the nature of data, a second-order regression equation was chosen [18]:

$$CO\,or\,P = b_1 + b_2 SVR + b_3 Q + b_4 SVR^2 + b_6 Q^2 + b_5 SVR \cdot Q\,, \quad (3)$$

where CO – specific content of CO in the flue gases, $mg \cdot m^{-3}$,
P – thermal power of the boiler, kW
SVR – ratio of the total area of the external surface of a piece of fuel to its volume, mm^{-1};
Q – volume of air intake into the combustion zone, $m^3 \cdot s^{-1}$.
b_i – equation coefficients.

It should be noted that the second-order regression equation was chosen due to the fact that such equation most accurately takes into account the mutual relation-ship between independent parameters in relation to the influence on the dependent parameters [18]. Further analysis of the coefficients of this equation was conducted to identify statistically insignificant indicators, and to simplify the equation to a pure quadratic form or a linear form, if necessary.

The method of least squares was used to determine the coefficients of the regression equation [19]. Since function 3 is non-linear, in order to find the coefficients, it was reduced to a linear form by recalculating the independent coefficients.

The adequacy (significance) of both the equation and coefficients of the equation was assessed using the F-test and t-test. For this, a comparison of the actual and tabular (theoretical) values of the F-criterion (Fisher's test) and the t-criterion (Student's test) was used. The corresponding values were calculated in Microsoft Excel using the Data Analysis package [20].

Table 1

Fuel groups by size

Groups		
I	II	III
		
Average linear dimensions of a piece of fuel (length, width, thickness), mm		
40x15x12 (±5%)	30x12x8 (±5%)	20x9x5 (±5%)
Full area of the external surface of a piece of fuel, mm^2		
2520	1392	650
Volume of a piece of fuel, mm^3		
7200	2880	900
Ratio of the total area of the external surface of a piece of fuel to its volume *SVR*, mm^{-1}		
0.35	0.48	0.72

Adequacy (significance) of the equation and equation coefficients was assessed using the F-test and t-test. For this, a comparison of actual and tabular (theoretical) values of the F-criterion (Fisher's test) and the t-criterion (Student's test) was used.

Results and discussion

The numerical values of the indicators obtained as a result of the experiment are shown in Table 3. As a result of regression analysis of the obtained numerical values, two empirical equations of the second order were constructed.

Table 2

Plan of the experiment type 3^2

No. of research	Ratio of the total area of the external surface of a piece of fuel to its volume *SVR*, mm^{-1}	Volume of air intake into the combustion zone *Q*, m^3·s^{-1}	No. of research	Ratio of the total area of the external surface of a piece of fuel to its volume *SVR*, mm^{-1}	Volume of air intake into the combustion zone *Q*, m^3·s^{-1}
1	(-1) – 0.35	(-1) – 0.0015	6	(+1) – 0.72	(0) – 0.0208
2	(0) – 0.48	(-1) – 0.0015	7	(-1) – 0.35	(+1) – 0.0400
3	(+1) – 0.72	(-1) – 0.0015	8	(0) – 0.48	(+1) – 0.0400
4	(-1) – 0.35	(0) – 0.0208	9	(+1) – 0.72	(+1) – 0.0400
5	(0) – 0.48	(0) – 0.0208			

Table 3

Numerical values of the research results

No. of the research	Ratio of the total area of the external surface of a piece of fuel to its volume *SVR*, mm^{-1}	Volume of air intake into the combustion zone *Q*, m^3·s^{-1}	Specific content of CO in flue gases *CO*, mg·m^{-3}	Thermal power of the boiler *P*, kW
1	0.35	0.0015	502	13.4
2	0.48	0.0015	492	14.0
3	0.72	0.0015	480	14.8
4	0.35	0.0208	389	17.4
5	0.48	0.0208	385	17.5
6	0.72	0.0208	362	17.8
7	0.35	0.0400	635	17.0
8	0.48	0.0400	632	17.0
9	0.72	0.0400	620	17.4

The first equation (3) shows the mutual influence of the geometric dimensions of the fuel particles and the amount of air entering the combustion zone on the CO content in the flue gases (R_2 = 0.94). And the second (4) shows the mutual influence of the geometric dimensions of the fuel particles and the amount of air entering the combustion zone on the thermal power of the boiler (R_2 = 0.92).

$$CO = 534.40\text{-}3.84SVR - 16992.52Q - 58.62SVR^2 + 490281.70Q^2 + 428.87SVR \cdot Q\,, \quad (4)$$

$$P = 12.09\text{+}2.54SVR + 334.02Q + 0.78SVR^2 - 5296.53Q^2 - 66.90SVR \cdot Q\,. \quad (5)$$

The analysis of the obtained equation for extrema made it possible to construct the corresponding surfaces (Fig. 2, Fig. 3) and to obtain several rather interesting conclusions.

The change in the size of the fuel pieces actually has a not-so-evident effect on the CO emissions. When the air supply to the fuel combustion zone changes from 0.0015 m^3·s^{-1} to 0.04 m^3·s^{-1}, a gradual decrease in the concentration of CO in the flue gases first occurs. The CO content decreases from about 300 mg·m^{-3} to a minimum value of 156 mg·m^{-3}. In the experimental boiler, the minimum value of the concentration of CO in the flue gases is provided by the air supply of 0.017 m^3·s^{-1}. A further increase in the air supply to the boiler causes an increase in the CO content in the flue gases. Thus, at the maximum technically achievable air supply of 0.004 m^3·s^{-1}, the level of the CO content reaches a maximum level of 440 mg·m^{-3}. It should be noted that for the experimental boiler, the maximum boiler emissions are 182% higher than the minimum recorded during the research. The change in the level of the CO content in the flue gases can be explained as follows: at the initial stage, when the air supply is minimal, incomplete combustion of fuel occurs, which is accompanied by significant release of CO. When the air supply reaches a value of 0.017 m^3·s^{-1}, the fuel burns in the optimal mode and the CO content in the flue gases is minimal.

With a further increase in the air supply, the intensity of fuel burning increases, the temperature in the boiler furnace increases, the process of partial pyrolysis of the fuel occurs, and synthesis gas is actively released. Combustion of synthesis gas requires additional air supply. However, this statement requires additional experimental verification and theoretical justification, and probably an improvement of the boiler design.

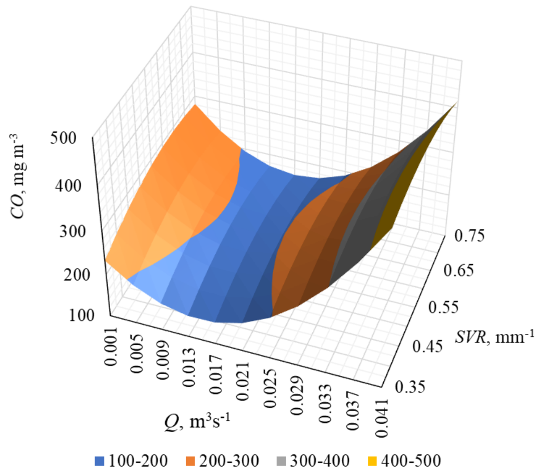

Fig. 2. **Influence of geometric dimensions of fuel particles and the amount of air entering the combustion zone on the content of CO in flue gases**

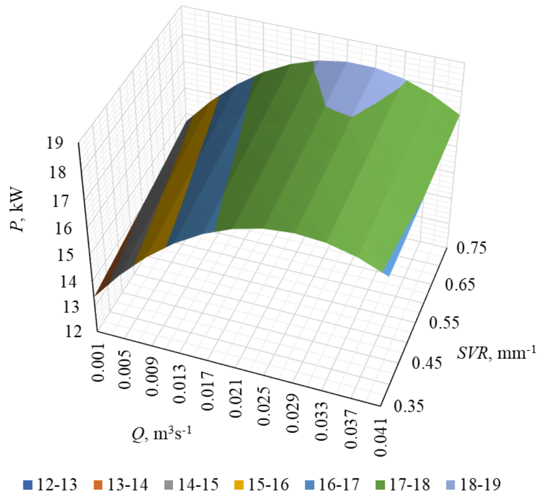

Fig. 3. **Influence of geometric dimensions of fuel particles and the amount of air entering the combustion zone on the thermal power of the boiler**

It was also established that the use of smaller pieces of fuel allows to increase the thermal power of the boiler by an average of 2.5% with the same air supply, which is not a significant influence factor. An increase in the air supply from 0.0015 $m^3 \cdot s^{-1}$ to 0.017 $m^3 \cdot s^{-1}$ causes a further significant increase in the thermal power of the boiler from 14.0 kW to 17.25 kW or by 23.7%. A further increase in the air supply to the maximum technically possible value of 0.04 $m^3 \cdot s^{-1}$ leads to only a slight increase in the power by 0.30 kW, i.e the boiler capacity is virtually constant in the range of the air supply from 0.017 to 0.040 $m^3 \cdot s^{-1}$. Therefore, it can be stated that the value of the air supply to the fuel combustion zone at the level of 0.017 $m^3 \cdot s^{-1}$is optimal for the boiler under study, which ensures the maximum thermal power of the boiler and the minimum CO content in flue gases for fuel from Salix Viminalis wood.

Conclusions

1. A change in the air supply to the fuel combustion zone from 0.0015 $m^3 \cdot s^{-1}$ to 0.04 $m^3 \cdot s^{-1}$initially causes a gradual decrease in the concentration of CO in the flue gases. The CO content decreases from 300 $mg \cdot m^{-3}$ to a minimum value of 156 $mg \cdot m^{-3}$. The minimum value of the concentration of CO in the flue gases is provided by the air supply of 0.017 $m^3 \cdot s^{-1}$. A further increase in the air supply to the boiler causes an increase in the CO content in the flue gases. At a maximum air supply of 0.004 $m^3 \cdot s^{-1}$, the level of the CO content reaches a maximal value of 440 $mg \cdot m^{-3}$. The boiler maximum emissions are 182% higher than the minimum recorded during the research. Changing the size of the fuel pieces actually has a not-so-evident effect on the CO emissions.
2. The use of smaller pieces of fuel allows to increase the heat output of the boiler by an average of 2.5% with the same air supply. An increase in the air supply from 0.0015 to 0.017 $m^3 \cdot s^{-1}$ causes a rather significant increase in the thermal power of the boiler from 14.00 to 17.25 kW or by 23.7%. A further increase in the air supply to the maximum technically possible value of 0.04 $m^3 \cdot s^{-1}$ leads to only a slight increase in the power by 0.34 kW, i.e. the power of the boiler is actually constant and maximal in the range of the air supply from 0.017 to 0.040 $m^3 \cdot s^{-1}$.
3. For the boiler under study the optimal value of the air supply to the fuel combustion zone is 0.017 $m^3 \cdot s^{-1}$, which ensures the maximum thermal power of the boiler and the minimum CO content in the flue gases for fuel from Salix Viminalis wood.

Author contributions

Conceptualization, S.K and A.J.; methodology, S.K., O.S. and M.K.; validation, O.S. and M.K; formal analysis, S.K and O.S.; investigation, A.J., S.K., O.S. and M.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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