*ISSN: 0975-8585*

# Research Journal of Pharmaceutical, Biological and Chemical Sciences

## Study of Combustion Optimization for High Ash-Content Biopellets in an Experimental Burner.

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**ABSTRACT**

This paper summarizes experimental results for combustion of biopellets in an experimental burner. The purpose of this paper is to assess the use of the innovative range of energy-efficient heating systems to obtain heat energy from timber processing wastes and agricultural feedstock showing high ash content, the primary element of which is a burner operating with any type of pelleted biofuel. Biofuel combustion experiments have been conducted with burners of nominal power between 25 kW and 50 kW. Oxygen is one of the primary factors affecting the efficiency of a heating system and the amount of contaminant emissions to the atmosphere. The effect of the combustion optimization with varying oxygen supply on the efficiency of the experimental heating system has been studied. The study of burning various types of pelleted fuel with varying oxygen supply revealed an optimal oxygen concentration for which the maximum efficiency and minimal contaminant emissions had been obtained.
**Keywords:** Calorific capacity, ash content, combustion, pelleted biofuel burner, environmental parameters, thermal performance.

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ISSN: 0975-8585

## INTRODUCTION

The modern energy generation is primarily based on using non-renewable power sources, predominantly such hydrocarbons as gas, oil products and coal. In aggregate, non-renewable power sources contribute to 95% of the global fuel and energy balance, whereas the renewable ones are only responsible for 5%. The modern world proves it necessary to search and use alternative energetic and feedstock resources that could compete with oil and natural gas.

Currently, renewable resources draw increased attention in the field of heat energy production. The wastes produced as a result of timber processing, chemical production, processing of agricultural products, peat mining and food industry can be conversed into high quality fuel feedstock. Globally and in Russia, state-of-the-art technologies of plant waste processing are intensively implemented.

The amount of the biomass used for energy production constantly grows, since this type of energy production shows a number of advantages, which include less amount of wastes occurring during combustion. The most widely spread appear to be wood pellets. However, as compared to food wastes, raw wood is a more popular and more expensive product, since it is used in related productions, for example, in the production of wood-filled composites. So, the studies intended to investigate fuel feedstock made of other types of wastes are important. In particular, sunflower husk generated in high amounts at oil extraction plants requires expensive disposal [2]. Currently, alternative ways of heating with solid biofuel are created. The most efficient of them is considered to be pelleted biofuel in which the wastes of timber processing (wood powder), agricultural (straw) and food (sunflower husk) are primarily used as feedstock.

The most popular heat generator used in any heating system is a heating boiler. Depending on the type of resources used, there are gas, solid-fuel and liquid-fuel boilers. The gas boiler is easy to manufacture and convenient to operate, but frequently it is impossible to supply gas to the facilities distantly located from urban or rural areas, in the amounts required for full-scale heating. In this case, a solid fuel boiler is used that ensures convenient and affordable heating. There is a wide range of heating devices available for biopellet combustion.

The biopellet burning efficiency strongly differs among various boilers. The biopellet burning efficiency in the boiler may greatly vary and depends on the pellet burner design being one of the primary parameters having a predominant effect on the burning process.

The fuel produced from agricultural wastes shows a 12.5 higher ash content that in the fuel from timber wastes. A high-ash-content fuel has a negative impact on the air supply and the combustion process in general. The ash content affects the dust concentration in combustion gases. The ash softening and liquefaction temperature is 1000 to 1100 °C, unlike timber wastes where the ash becomes powder at 1100 °C. Most fuel pellets made of agricultural wastes emit high amount of carbon oxide (CO). Non-organic substances contained in agricultural wastes exceed those contained in timber wastes. For example, sunflower husk pellets contain 7.7 times more potassium (K) that in wood pellets [4]. These negative qualities occurring in biopellet combustion can be reduced by optimizing the burning process. The oxygen supply is one of the primary factors that affects the heat losses, the boiler efficiency and emission levels.

Another important factor that requires consideration is heat losses through building envelopes. The data on temperature distribution over the surface of external building envelopes at actual ambient and internal air temperatures allows evaluating the given resistance to heat transfer of individual elements of building envelopes, and calculating the amount of heat lost on the surface of these elements [5].

The experimental burner is designed to incinerate biopellets with high ash content, so its combustion chamber has such a shape and dimensions that allows removing excessively high amounts of ash. The experimental burner integrates an automatic controller to control the fuel supply and retention time. The fuel is transported with a screw conveyer to the combustion chamber. The primary purpose of this study is to increase the efficiency of the combustion process of granules in the experimental burner by means of finding out the optimal air supply. Several types of fuel have been experimentally studied in order to find out the optimal conditions for oxygen supply and its effect on the burning process.

## STUDY METHODOLOGY

Optimization of oxygen supply conditions is one of the most frequently used methods to increase the burning efficiency. The studies have been undertaken by burning biopellets in the experimental burner. The following study samples were selected: sunflower husk pellets, wood pellets and straw pellets (Table 1).

**Table 1. Characteristics of selected pellets.**

| Characteristics | Sunflower husk pellets | Timber processing waste pellets (1 class) | Hay pellets |
|---|---|---|---|
| Diameter, mm | 6-8 | 6-8 | 6-8 |
| Length, mm | 10-50 | 10-30 | 10-50 |
| Humidity, % | 7.7 | 7.3 | 6.8 |
| Ash content, % | 5.4 | 2 | 5.7 |
| Density, $t/m^3$ | 1.1 | 0.6 | 0.65 |
| Heat conductivity, MJ/kg | 18.46 | 16.9 | 16.0 |
| Elemental analysis | | | |
| Carbon (C) % | 50.0 | 48.5 | 47.3 |
| Hydrogen (H) % | 6.0 | 6.9 | 5.8 |
| Oxygen (O) % | 38.5 | 39.8 | 40.43 |
| Nitrogen (N) % | 5.5 | 0.19 | 0.66 |
| Sulfur (S) % | 0.10 | 0.10 | 0.10 |

To justify the perspectives of applying the experimental burner for burning of pellets made of high-ash-content agricultural wastes, the following generally accepted study methods have been applied:

- determination of contaminant emissions GOST ISO 9096-2006, European Standard EN 13284-1 and Finnish Standard;
- determination of ash chemical composition under GOST R 50852-96, GOST 10538-87;
- determination of calorific value under GOST 147-95;
- humidity, ash content and concentration of volatile substances were determined under standard methodologies of GOST R 54211-2010, GOST R 54185-2010, GOST R 54184-2010.
- the results were assessed under proved methodologies using software programs.

The boiler efficiency is the parameter that indicates its performance factor. The boiler efficiency is the ratio of the used heat to the entire heat introduced into the boiler furnace during fuel combustion under GOST 32452-2013 (EN15270:2007).

$$\eta = \left(\frac{Q_1}{Q_1^r}\right) \times 100\% \qquad (1)$$

For some reasons, not all the heat generated during fuel combustion and introduced with air supplied for combustion is used for heating of the heat-carrying medium. Some share of heat is lost. There are five primary heat losses in the boiler [6]:

- ✓ with the heat of exhaust gases,
- ✓ through chemical incompleteness of fuel combustion,
- ✓ through mechanical incompleteness of fuel combustion,
- ✓ fuel losses to ambient [13],
- ✓ losses with the physical heat of the slag.

Correctly selected daft and blowing will allow achieving the optimal air excess coefficient in the furnace and fuel completeness of burning-out. The increased air excess coefficient will cause increased losses with exhaust gases, and the decreased air excess coefficient will cause areas with insufficient oxygen to appear. These areas show incomplete oxidization of fuel elements and soot formation. Combustion stability and fuel completeness of burning-out are controlled if the following basic rules are observed: fuel should be loaded evenly (sufficiently), there should be no focal burning and the fuel layer should cover the entire bed of the layer grid and burn over its entire surface. The evenly time-distributed fuel loading allows reducing the fuel drying period and achieving the flame stability [7].

The fuel heat value is described by the fuel calorific value or calorific capacity, e.g., the amount of heat emitted in case of incomplete burning of a fuel mass unit. The calorific value is referred to as the highest if it includes the water steam condensation temperature contained in combustion products due to moisture being present in the fuel and oxidation of hydrogen contained in fuel. The fuel calorific effect is determined in the bomb calorimeter under GOST 147-54. Let us define the fuel calorific effect in the bomb calorimeter ($Q_b^a$), which is used to calculate the lowest calorific value ($Q_i^r$). Since we know the lowest calorific value, let us calculate the highest calorific value, kJ/kg,

$$Q_s^a = Q_b^a - (\beta S_t^a + \alpha Q_b^a) \quad (2)$$

where β = the coefficient to account for the sulfuric acid calorific value during oxidation of products of sulfur burnt in the bomb $S_t^a$,%, from $SO_2$ to $SO_3$ and during the dissolution of it in water quantitatively being 94 kJ per 1% of sulfur; α = the coefficient to account for the nitric acid heat of formation [8, 10].

The bed combustion technology is used in the experimental burner. The fuel is supplied from a fuel hopper by using a screw mechanism and is then forwarded to the furnace. The pellets in the burner are combusted in the air flow created by the burner fan. The combustion air is supplied by special nozzles through the gaps between grate elements. To achieve the combustion intensity in the combustion space, the air is additionally supplied in the form of overfire jets through the nozzles located in the rear wall. Pellets supplied to the combustion area are intensively converted into burning char and burn out to form a flame jet which temperature may reach 1200 °C. A flow of hot gases is directed into the convective part of the boiler, to flue tubes, and transfers its heat to the heat-carrying medium in the system and then is forwarded to the exhaust duct. The ash remained from fuel pellets fall from the combustion area to the ash-bin where it is evacuated by using a motorized screw to the heat storage vessel as in the case of large burners.

**STUDY**

In burner tests, three various types of pellets were combusted: wood pellets, straw pellets and sunflower husk pellets. Three series of combustion test were conducted with varied oxygen concentration in flue gases from 5 to 15%.

The pellets were combusted in experimental burners 25 and 50 kW. The wood pellets showed the highest combustion efficiency (93%). The second efficient were the sunflower husk pellets, followed by the straw pellets (91% and 90%). To determine the chemical composition of combustion gases (CO, $CO_2$, $NO_x$), Testo 350 gas analyzer was used. All concentrations of combustion gases were calculated in equal conditions – 10% $O_2$. The sunflower husk pellet showed the highest CO and dust emissions. The straw pellets showed the highest concentration of nitrogen and sulfur oxides. The following parameters were controlled during tests: combustion gas temperatures, chemical composition, speed of combustion gases, draft in the flue, flow rate of fuel pellets and the thermal performance of the burner. A TXA thermocouple type K was used to measure the temperatures of combustion gases. The pressure of combustion gases in the experimental burner was measured by using a differential pressure gage. All data were aggregated and processed using a computer.

The burner was placed on the balance to determine the amount of heat used in each burner test. The fuel mass flow rate on the firebox grate was calculated for each experiment by dividing the entire amount of fuel combusted by the total combustion time. The ash mass flow rate on the firebox grate was calculated according to the concentration of ash for each type of fuel and by subtracting the amount of ash lost as dust emissions.

The heating-performance analysis was done for the prepared samples. Chemical and thermal performance of ash experimental pellets was analyzed in accordance with respective standard methods and properties given in Table 2. The humidity, ash content and concentration of volatile substances were determined according to standard methodologies. Heat losses with exhaust gases and losses caused by burning incompleteness were calculated according to the standard. The percentage of primary elements was measured: C, H, N, S, with O concentration calculated from the mass balance.

**Table 2. Physical and chemical parameters of pellets used for experimental burner tests.**

| Characteristics | Sunflower husk pellets | Timber processing waste pellets (1 class) | Hay pellets |
|---|---|---|---|
| Humidity, % | 7.7±0.04 | 8.1±0.05 | 6.8±0.03 |
| Ash content, % | 5.4±0.03 | 1.6±0.03 | 5.7±0.02 |
| Heat conductivity, MJ/kg | 18.46±0.5 | 17.6±0.6 | 16.0±0.5 |
| Elemental analysis | | | |
| Carbon (C) % | 49.2±1.5 | 47.2±1.7 | 47.3±1.4 |
| Hydrogen (H) % | 5.8±0.7 | 6.9±0.4 | 5.8±0.5 |
| Oxygen (O) % | 38.7±1.2 | 38.8±1.6 | 40.43±1.3 |
| Nitrogen (N) % | 5.3±0.5 | 0.19±0.6 | 0.66±0.4 |
| Sulfur (S) % | 0.08±0.03 | 0.07±0.03 | 0.10±0.02 |

After comparing the results of elemental analysis with the published data, it should be noted that the elemental analysis of various pellets shows rather similar values, slightly varying in C, H and O concentrations, which is reflected in Table 1. Multiple papers have been published where various biofuels are analyzed. Most of them give elemental composition [7], with the carbon concentration in time being 45-50%, that for hydrogen within 5-8% and oxygen 30-40%. The results given in Table 2 comply with the published data [8].

Some amount of combustion gases emits during combustion. For biofuel, volatile substances start emitting at the temperatures between 160 and 250 °C. The CO, $CO_2$, $NO_2$, NO, $SO_2$ and $O_2$ concentrations in the combustion gases were constantly controlled. Before a particle ignites during the combustion process, the fuel organic mass is thermally decomposed and volatile substances emit. These substances include a significant amount of fuel agents such as $CH_4$, $H_2$ and CO that are primary determinants of fuel ignition. The composition of combustion gases also includes valuable chemical substances: resins, acids, etc. that can be extracted during fuel thermal processing. During this process, volatile substances are emitted. The quasistatic yield of thermal decomposition products for solid biofuel allows clarifying the fuel properties only to assess the process of slow thermolysis. If the fuel is located in the combustion area for several seconds or fractions of a second during fast heating, the kinetics of volatile substances emission must be taken into account.

The amount of volatile substances emitted depends on their number in the initial fuel and on the decomposition of definite groups of bonds. In the conditions of an isothermal process, the total amount of volatile substances V that can be emitted by the time τ will be:

$$V = V_0 \Sigma C_{0i}[1 - exp(1 - k_i \tau)] \quad (3)$$

$V_0$ = total amount of volatile substances that can be emitted by the moment of thermolysis completion; $i$ = the number of reaction groups taken into account when describing the thermolysis process; $C_{0i}$ = quantitative characteristic of a specific group of volatile substances, with $C_{01} + C_{02} + \ldots + C_{0i} = 1$; $k_i$ being the decomposition rate constant; we assume that it complies with the Arrhenius law [9].

The combustion tests were conducted for the full 100% loading. The mass flow rate of various types of pellets varies greatly. The fuel weight was within 3.5 to 4.5 kg. As a result, the energy supply to the boiler also differed. The energy loading varied within 15 to 40 kW. Differences in mass and energy flows can be explained by differences in the volumetric density of pellets [10]. The pellets of agricultural and timber biomass usually show the volumetric density between 480 to 700 kg/m$^3$. The fuel supply system is also affected by such factors as the size of pellets, the amount of small particles and the surface of pellets [11].

The oxygen concentration in combustion gases greatly affects the combustion process [5, 12]. The first experiment was conducted by using timber waste pellets as fuel. The experiment results showed that changing oxygen concentration in combustion gases from 5% to 14% causes the temperature of combustion gases to change from 120 °C to 180 °C. The temperature of combustion gases increases together with the oxygen concentration (Figure 1).

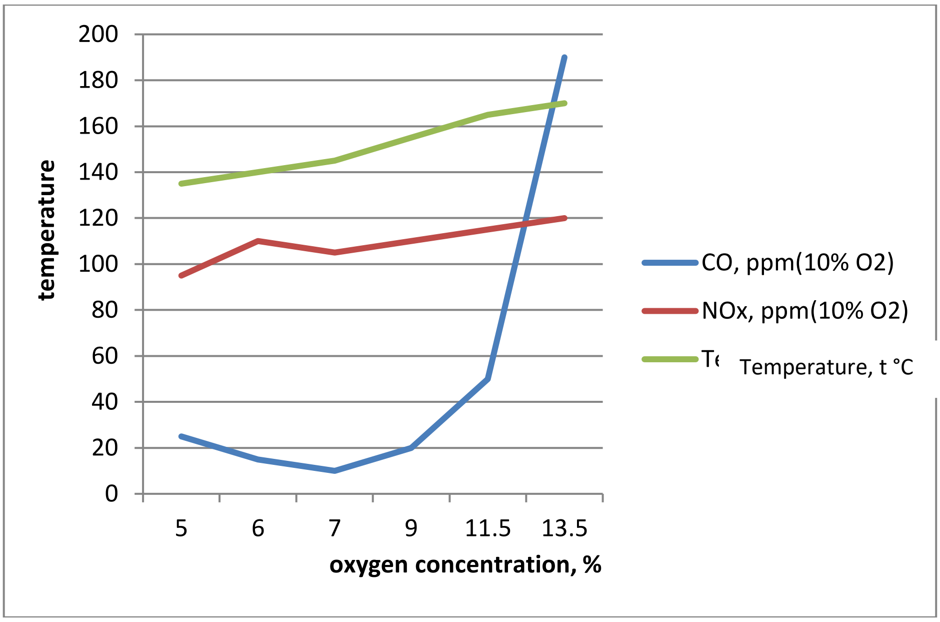


**Figure 1. The temperature of combustion gases changing with oxygen concentration.**

The oxygen concentration affects the $NO_x$; however, it grows not as rapidly as the CO concentration. The minimal amount of CO is 30-50 ppm and is calculated in normal conditions with oxygen concentration in combustion gases of 6-7%. Heat losses for oxygen concentration in combustion gases of 6-7% were 0.1% due to incomplete combustion. For higher oxygen concentration, heat losses will be 1.5% with CO concentration in the combustion gas significantly increased. Heat losses with combustion gases and incomplete combustion for chemical reasons have a dominating effect on the combustion efficiency. The boiler efficiency in this case varies within 76 to 90%. The maximum efficiency was found for oxygen concentration in combustion gases of 6.0%.

The speed of combustion gases was determined both directly by using Testo 425 thermal mass flowmeter and indirectly. The results have shown that the calculation data corresponds to the measured data. The speed of combustion gases rapidly increases from 0.65 m/s for $O_2$ concentration in exhaust gases of 5% to 1.3 m/s for $O_2$ concentration in exhaust gases of 14% (Figure 2). The increased rate of combustion gases has a negative impact on the combustion efficiency.

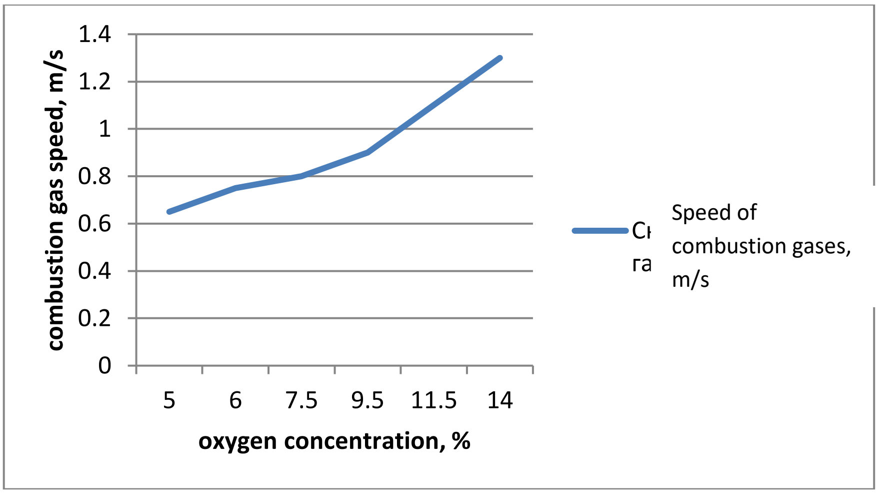


**Figure 2. Dependence of combustion gas rate from oxygen concentration.**

The next series of experiments was conducted with straw pellets and sunflower husk pellets. The results were obtained for the effect of oxygen concentration on the combustion gas temperature, heat losses, and CO concentration. When burning sunflower husk pellets, the combustion gas temperature is slightly higher than in the previous experiment, since these pellets show higher heat conductivity. The CO amounts were almost similar in all test samples. The results of using various pellets were almost similar. The dust concentration was minimal for the oxygen concentration in combustion gases of 6.0%, but higher than for oxygen concentration of 14% (Figure 3).

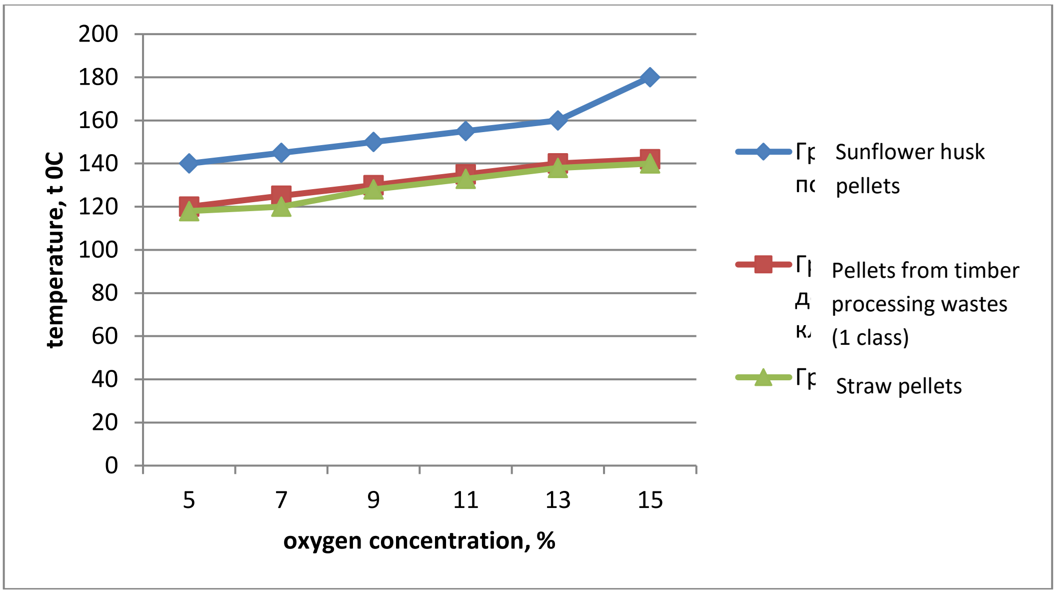


**Figure 3. Oxygen concentration affecting the combustion temperature of various fuels.**

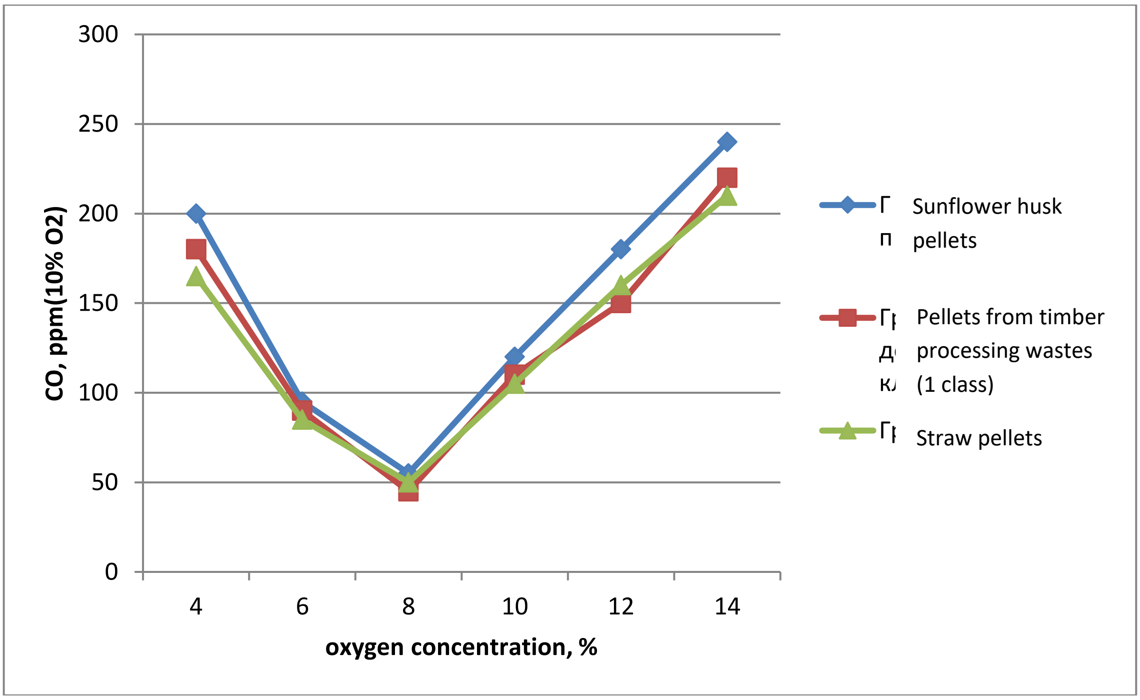


**Figure 4. Oxygen concentration affecting the CO concentration in combustion of various fuels.**

The results show that the method of burning various types of pelleted fuel with varied oxygen concentrations yielded positive outcomes. The highest value of CO emissions corresponds to the oxygen concentration of 8%, with the CO emissions decreasing for higher $O_2$ concentration.

## CONCLUSION

The experiment results allow concluding that changing the air supply to the burner and correspondingly changing the oxygen concentration in combustion gases play an important role in the combustion process of pelleted biofuel. The maximum efficiency of the burner and minimal CO emission appear when the oxygen concentration in the combustion gas is about 8%. Increased and decreased oxygen concentration results in decreased efficiency and increased emissions of harmful substances to the atmosphere. Mixing fuel with air becomes poorer with increased flow of combustion gases. This is testified by the increased CO emissions in case of high oxygen concentration.

The heat is lost both with combustion gases and through building envelopes. The highest heat losses with combustion gases occur with increased temperature and oxygen concentration. Heat losses occur due to incomplete combustion of fuel when the oxygen concentration in combustion gases is high. This is caused by high speed of the combustion gas. It has been established that the speed of combustion gases will increase from 0.65 m/s for $O_2$ concentration in exhaust gases of 5% to 1.3 m/s for $O_2$ concentration in exhaust gases of 14%.

Based on the experimental studies, it has been established that the pelleted biofuel shows specific advantages over conventional types of fuel and, when made of agricultural wastes, it is comparable to fuel pellets made of wood feedstock.

The publication was made with the financial support of the project of applied scientific studies and experimental developments by the Ministry of Education and Science of the Russian Federation under the agreement No. 14.578.21.0091 dated 28.11.2014, unique ID RFMEFI57814X0091.

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