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Article

The Evaluation of Quality of the Co-Firing Process of Glycerine Fraction with Coal in the High Power Boiler

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Abstract: The article presents the test results of the co-firing process of a glycerine fraction derived from the production of liquid biofuels (fatty acid methyl esters) with coal. The test was performed in industrial conditions using a steam boiler with a capacity of approx. 2 MW in one of the building materials manufacturing facilities. The process of co-firing a mixture of a 3% glycerine fraction and eco-pea coal was evaluated. The reference fuel was eco-pea coal. The combustion process, composition and temperature of exhaust gases were analyzed. Incorrect combustion of glycerine fraction may result in the emission of toxic, mutagenic, and carcinogenic substances, including polycyclic aromatic hydrocarbons. During the test of the combustion process of a mixture of glycerine fraction and eco-pea coal, a decrease in the content of O_2, CO, and NO_x was observed as well as an increase in the content of H_2, CO_2, and SO_2 in the fumes and growth of temperature of exhaust gases in relation to the results of combustion to eco-pea coal. Reduced content of carbon monoxide in exhaust gases produced in the combustion could be caused by the high temperature of the grate or by an excessive amount of oxygen in the grate. The higher content of oxygen in glycerine changes the value of excess air coefficient and the combustion process is more effective. The bigger content of sulfur dioxide in burnt fuels containing the glycerine fraction could be caused by the presence of reactive ingredients contained in the glycerine fraction. The reduced content of nitrogen oxides in exhaust gases originating from the combustion of a fuel mixture containing a fraction of glycerine could be caused by lower content of nitrogen in the glycerine fraction submitted to co-firing with coal and also higher combustion temperature and amount of air in the combustion chamber. The increased content of carbon dioxide in exhaust gases originating from the combustion of fuel mixture containing glycerine fraction could be caused by the influence of glycerine on the combustion process. The increase of hydrogen in the glycerine fraction causes the flame temperature to grow and makes the combustion process more efficient.

Keywords: glycerine fraction; combustion; co-firing of fuels; steam boiler; nitrogen oxides; sulfur dioxide; carbon monoxide; carbon dioxide

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1. Introduction

According to the Act on Renewable Energy Sources of 2011 and Directive 2009/28/EC, the term "biofuels" refers to liquid fuels that are produced from biomass and are used for energy-related purposes, i.e., to generate electricity and heat. According to the Act on biofuels and bio-components, liquid biofuels cannot be classified as biomass, whose burning in the process of electricity production requires certificates confirming that the energy comes from renewable sources [1–3]. Given the existing regulations, it is assumed that pure raw vegetable oil can be classified as fuel for energy-related purposes, while methyl and ethyl esters, which are pure fuels, cannot be used for energy-related purposes [4,5]. Taking the legal criteria into consideration, it can be argued that fuels used for energy-related purposes include fuels produced from biomass in the form of crude vegetable oils and their mixtures; crude glycerine, which is a side product of the transesterification process of rapeseed oil; and used vegetable oils or animal fats which are products of the disposal of slaughterhouse waste [6]. Growth in the production of such fuels increases the number of waste products of the esterification process, including glycerine fraction. The quality of glycerine fraction changes with the development of technology and raw material used [7]. The glycerine fraction of complex chemical composition, wherein crude glycerine accounts for 40–55%, is generated during the production of methyl esters of fatty acids [8,9]. Apart from glycerine, the fraction includes soaps, methanol, esters, catalyst residues, water, and solid pollution. Glycerine can also include the glycerine fraction, containing 10–15% of methanol, technical glycerine containing 3–5% of water, and trace amounts of salts and pharmaceutical grade glycerine, which is an important raw material in cosmetic, food, pharmaceutical, tobacco and leather industry, and is used for the production of dyes and cooling liquid cooling [10–12]. Recently, a considerable increase in this type of waste, and consequently a decrease in prices, have been observed. The global demand for glycerine is 1–1.2 million tons (2012) [13–15]. One of the ideas of how to dispose of the glycerine fraction is to use it as fuel for power boilers. That is why research into the use of co-firing of the glycerin fraction with coal or biomass has begun to develop recently [16–18]. The use of glycerine for energy-related purposes has been observed, among others, in the USA and Poland [19,20]. The availability of glycerine fraction is closely related to the production of bioesters [21–23]. Taking into account its different quality, which depends on its origin, parameters, and the method of transesterification process, its manufacturers should always provide quality certificates [24,25]. Co-firing of liquid fuel in the form of glycerine fraction will result in the change of chemical composition and a stream of exhaust fumes, and consequently, a change in their properties such as emissivity and absorbability [6,15,26–29]. In addition, their speed and viscosity will change. This, in turn, will affect the intensity of convective heat transfer [21,22]. Use of glycerine fraction for energy-related purposes is connected with a change in combustion conditions, which may involve a risk of high-temperature corrosion [24,30]. Sulfur, potassium, and sodium contained in the ash pose a risk of sulfate corrosion. Another threat associated with co-firing of glycerine fraction with conventional fuel or biomass may be chloride corrosion [31,32]. There are two main chemical factors that may contribute to corrosion, i.e., the content of gaseous components in the exhaust gases, in particular, of sulfur compounds, chlorine, and CO, and a sediment aeriform ash gathering on the surfaces of heat exchangers. The corrosive properties of exhaust gases significantly affect the failure-free operation of boilers. For this reason, risk indicators of chloride corrosion in the combustion process were introduced [33,34]. Therefore, the use of glycerine fraction as fuel for energy-related purposes requires continuous monitoring of quality and energy parameters since the chemical composition as well as chemical and physical properties of this type of waste differ considerably from those of typical solid and liquid fuels used in boilers of medium and high power for heating purposes [35–37].

For years, tests have been carried out on the energetic use of waste glycerine fraction. In the article [30], the authors presented the results of physical–chemical properties of waste glycerin (glycerin fraction from biodiesel), derived from fatty acid methyl ester. The physical-chemical properties having a significant impact on the process of combustion of waste glycerine were analyzed in comparison with the analogous properties of conventional fuel oils. The paper contains test results of the elemental composition of exhaust fumes created in the combustion process on a test bench furnace equipped with a gas-dynamic burner for light and heavy liquid fuels.

The authors present the results of the combustion of glycerine fraction with conventional fuel on a retort boiler [28]. This article presented the results of the evaluation process of the combustion of coal and coal mixture with glycerine on the retort boiler with a capacity of 100 kW. Evaluated the content of carbon dioxide, carbon monoxide, oxygen, nitrogen oxides, and sulfur dioxide in the flue gas after combustion caused the above fuels. It was found that the differential process of combustion depends on the composition of the fuel. Improving the quality of the co-firing process of glycerine with conventional fuels requires proper selection of the composition of the fuel composition and regulation of the working boiler.

In the article [27], the authors present the results of the combustion of glycerine with conventional fuel using a KJ-WD grate boiler with a capacity of 14 kW. They evaluated the content of CO_2, CO, O_2, H_2, NO_x, and SO_2, and the value of the coefficient excess air in the exhaust gases produced by burning fuel above depending on the amount of air supplied to the combustion chamber.

In article [38], the author presented the results of research on selected environmental aspects of co-incineration of glycerin phase with coal in grate furnaces. The research which was carried out included the study of the incineration of compounds with the mass fraction of the glycerol phase ranging from 5 to 20%. The paper presents the methodology of the study and the outcomes of the resulting emissions of CO and NO.

In this article [39], the authors presented the effect of waste glycerol on the rheological properties of coal-water fuel (CWS). The addition of glycerol to CWS increases the viscosity and density of these suspensions. Due to the fact that CWS is dosed to a heated chamber, its modification with glycerol results in easier nebulization into the combustion chamber, lowering of the solidification temperature and increasing the calorific value of the resulting fuel.

In the review paper [40], the research scope for areas where crude glycerol could be utilized as a feedstock or co-feedstock in thermochemical conversion technology is highlighted. Various thermochemical conversion processes, namely, gasification, pyrolysis, combustion, catalytic steam reforming, liquefaction, and supercritical water reforming, are discussed and shown to be highly suitable for the use of crude glycerol as an economical feedstock. It is found that the integration of crude glycerol with other thermochemical conversion processes for energy production is a promising option to overcome the challenges related to biodiesel production costs. Hence, this paper provides all the necessary information on the present utilization status of crude glycerol in thermochemical conversion processes, as well as identifying possible research gaps that could be filled by future research studies.

In article [41], the authors present the use of glycerol as a flammable additive to the coal-water fuel is environmentally friendly and leads to reducing the ignition time and threshold temperature of that composition fuel. Generally accepted approximation of the dependence of the main combustion parameters includes the ignition temperature and the time delay before ignition on the glycerol content of the fuel composition does not correspond to the physical nature of the process and does not reflect the real nature of the change. To approximate the experimental data in the case of complex two-component fuel based on the coal-water slurry and glycerol, a more suitable and physically correct inverse sigmoid function is proposed. The applicability of the proposed function has been confirmed by experimental studies.

In article [42], the authors tried to answer the fundamental question that arises: What can be done with glycerol? This is one of the main reasons current research is aimed at developing technologies for the conversion and/or use of glycerol in order to enhance the biodiesel industry and dramatically improve its profitability. This study evaluates and quantifies the environmental impact of glycerol combustion in biodiesel production plants that utilize boilers to produce thermal energy for the process. The concept of ecological efficiency mainly evaluates the environmental impact caused by CO_2, SO_2, NO_x, and particulate matter (PM) emissions.

After analyzing the available literature, the authors made an attempt to expand the existing knowledge by using the waste glycerin fraction in energy processes with coal. Co-firing of such fuel will help in the management of waste glycerin and will expand the current knowledge on fuel combustion processes.

2. Materials and Methods

The process of co-firing of a mixture of a 5% glycerine fraction and eco-pea coal was evaluated. The reference fuel was eco-pea coal. The combustion process, composition, and temperature of exhaust gases were analyzed. The co-firing process was evaluated using a steam boiler with a capacity of approx. 2 MW installed in a clay building materials manufacturing plant. The test was performed according to the user's manual and operating instructions for the boiler provided by the company. Figure 1 presents a steam boiler with a capacity of 2 MW, used for testing the co-firing of liquid waste produced in biofuel production with coal.

(**a**) (**b**)

Figure 1. Steam boiler with a capacity of 2 MW in a silicate manufacturing plant in Żytkowice used for testing of the co-firing of coal with glycerine fraction; (**a**) view from the loading side, (**b**) view of the flue duct from the exhaust with a tube of gas analyzer.

The fuel mixture was prepared by immersing coal of the eco-pea assortment in a known amount of glycerin fraction. The contact time between coal and glycerin was 40 min. The fuel mixture was then placed in the combustion chamber of the boiler, after which the coal soaked in glycerin was subjected to the combustion process in the steam boiler.

Generally, a steam boiler is a type of closed container, designed using steel, for heating the water to generate steam by some energy source like burning of fuel. The vapor generated may be delivered at low pressure for industrial work in many industries.

The main function of a steam boiler is to produce, store and trouble the vapor. The liquid containing boiler is nothing but a shell and the heat energy produced while burning of fuel will be moved to the water and then converted into steam at the required pressure and temperature.

The main conditions of this boiler mainly include the water container should lock very carefully. The vapor of water should be supplied in the preferred conditions namely, quality, rate, pressure, and temperature.

The main working principle of a steam boiler is easy. This boiler is one type of closed device in the shape of a cylindrical. The capacity of the boiler to have steam, as well as water, is sufficient.

Generally, the liquids are stored in the boiler for generating steam by burning the fuels or applying the heat energy at different conditions of pressure based on the size of the vessel as well as specifications. Finally, the steam in the boiler supplies using a pipe and flows into various industries like plants.

The main components of this boiler mainly include a shell, furnace, grate, mountings, water space, accessories, refectory, level of water, scale, foaming, lagging, and blowing off. The tests were carried out using the fire tube boiler. The fuel consumption of this type of boiler is 500 kg of coal per hour. To start up the steam boiler, it is necessary to fill the combustion chamber with 3 tons of fuel. This type of boiler can be built with a number of tubes for supplying hot gases. These tubes are absorbed into the water in a closed container; actually, this type of boiler consists of a single closed container to pass the hot tubes. These tubes heat up the water to convert it into vapor, and the vapor remains in the same container. When both the water as well as vapor is in a similar container, then a fire-tube boiler cannot generate vapor at high force.

To evaluate the composition of exhaust gases, two flue gas analyzers were used, namely Testo 350 XL and Madur 21. The probes of exhaust gas analyzers were placed in the boiler flue.

3. Results and Discussion

In the results of the test, combustion of reference fuel, i.e., eco-pea with a 5% glycerine fraction, was analyzed. The composition of exhaust gases (CO, CO_2, O_2, NO_x, SO_2, H_2) and exhaust gas temperatures were assessed. Table 1 shows the physical and chemical properties of eco-pea coal which were tested, while Table 2 shows the same parameters of glycerine fraction.

Table 1. Physical and chemical properties of coal.

Test Parameter	Eco-Pea Coal
Sulfur content [%]	0.6
Calorific value [MJ/kg]	26
Grain size [mm]	8–24
Volatile parts content [%]	34–38
Sintering ability [–]	14–16
Total humidity [%]	5–8
Ash content [%]	7

Table 2. Physical and chemical properties of glycerine fraction [7,8].

Parameter	Glycerine Fraction
Kinematic viscosity [mm^2/s] at 20 °C	339.86
Flash point in open cup [°C]	198
Density [g/cm^3] at 15 °C	1.2737
Sulfur content [ppm]	14.85
Pour point [°C]	−37
Incinerated residue [%]	0.9951
Surface tension [mN/m]	32.41
Calorific value [MJ/kg]	27.9

According to the analysis of data contained in Tables 1 and 2, the calorific value of glycerine fraction was higher by 1.9 MJ/kg than that of eco-pea coal. The sulfur content in coal is many times higher than the value of this parameter in the glycerine fraction. The combustion process was carried out according to the user's manual of the boiler. Changes in the composition of exhaust gases and temperature were recorded during the 2-h test. The averaged results of the composition and exhaust gas temperature during the test of the reference fuel and the mixture of glycerine fraction with eco-pea coal are presented in Table 3.

During the test, higher values of carbon dioxide and hydrogen in exhaust gases than those for coal were recorded. They were generated as a result of the combustion of fuel and glycerine fraction. An increase in the amount of oxygen (O_2), carbon monoxide (CO) and nitrogen oxides (NO_x) were also observed in the case of coal rather than in the case of the fuel mixture.

A comparison of exhaust gas temperature for reference fuel and for a mixture of eco-pea coal with glycerine fraction is shown in Figure 2.

Table 3. The averaged results of composition and temperature of exhaust gases during the combustion of coal and coal with glycerine fraction.

Component Emissions (the Average Results of Measurements)	Eco-Pea Coal	Eco-Pea Coal with Glycerine Fraction
Oxygen content [%]	15.87 ± 2.87	15.10 ± 2.71
Carbon dioxide content [%]	3.99 ± 0.64	4.97 ± 0.80
Carbon oxide content [ppm]	651.83 ± 136.88	537.58 ± 118.27
Sulphur dioxide content [ppm]	13.08 ± 1.83	72.01 ± 10.08
Nitrogen dioxide content [ppm]	57.05 ± 10.84	50.94 ± 9.68
Exhaust gases temperature [°C]	183.52 ± 14.68	211.11 ± 16.89
Hydrogen content [ppm]	340.31 ± 78.27	502.81 ± 115.65

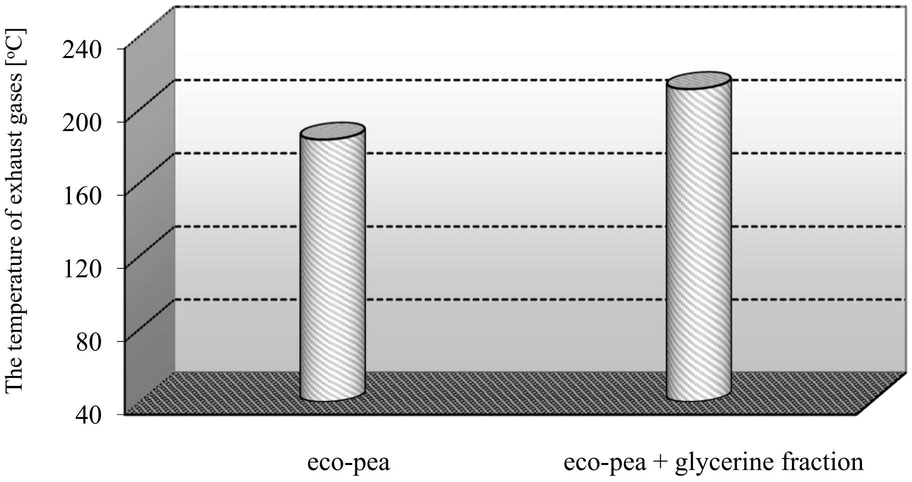


Figure 2. The average temperature of exhaust gases during the test of combustion of coal and fuel composition consisting of coal and glycerine fraction.

The higher mean temperature of the exhaust gases for a mixture of coal and glycerine fraction (211.11 °C) than for reference eco-pea fuel was observed during the test (183.52 °C). A mixture of coal and waste liquid deriving from the production of biofuels, i.e., glycerine fraction, caused an increase in the average temperature of exhaust gases in comparison with the combustion of eco-pea coal. The increase in the average temperature of exhaust gases in the combusted fuel mixtures was caused by the change of composition of the fuel mixture.

Figure 3 shows changes in the content of carbon monoxide in exhaust gases produced during the process of co-firing of coal and waste liquid (glycerine fraction) produced in the production of biofuels and during the combustion process of eco-pea reference fuel.

Analysis of the results presented in Figure 3 showed a variable amount of carbon monoxide in the exhaust gas during the verification tests. A lower average content of carbon monoxide in exhaust gases was observed for the mixture of glycerine fraction and coal (Table 3: 537.58 ppm) than in the case of the reference fuel. The reduced content of carbon monoxide in exhaust gases produced in the combustion of a fuel mixture containing glycerine fraction could be caused by the high temperature of the grate, the fact that the fuel was kept in the combustion chamber for a long time, or by an excessive amount of oxygen in the grate. A significant increase in the content of carbon monoxide in exhaust gases was observed each time a new batch of fuel was loaded into the combustion chamber of the boiler (maximum to 3723 ppm for a mixture of eco-pea and glycerine fraction). On the basis of the results obtained, it can be concluded that setting the air inflow to the combustion chamber in accordance with the user's manual is not effective in terms of efficiency of the combustion process, and it has a negative impact on the environment (higher content of carbon oxides). The temperature of the exhaust gases obtained as a result of eco-pea combustion was lower as compared to the temperature of exhaust gases measured during the combustion of eco-pea with glycerine fraction. An increase in temperature is caused by the presence of hydrogen in glycerine, which has a higher calorific value than coal. Moreover, the presence of oxygen in glycerine changes the coefficient of excess air. Therefore, a better outcome of the combustion process results in a bigger share of carbon dioxide for the composition of eco-pea and glycerine waste.

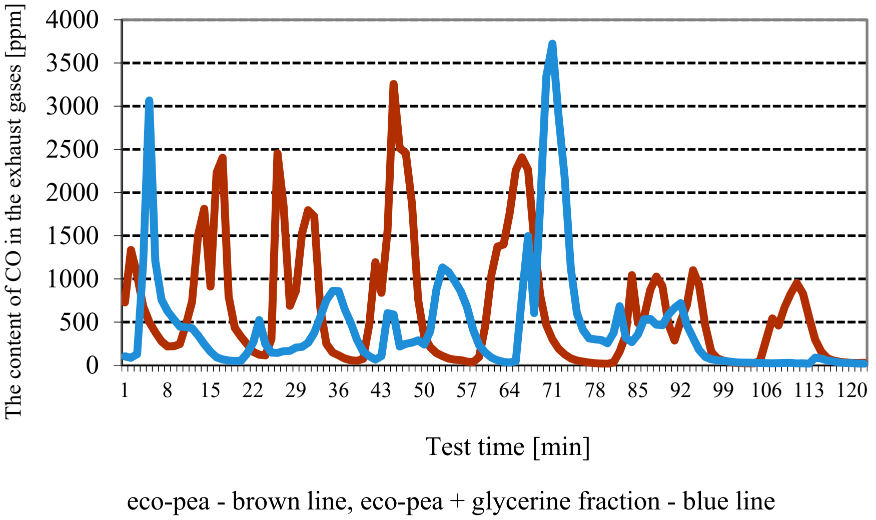


Figure 3. Comparison of changes in the content of the carbon monoxide in exhaust gases produced during the test of the process of co-firing of coal and liquid waste (glycerine fraction) produced in biofuel production and combustion of eco-pea reference fuel.

It seems that the changes in the content of carbon monoxide in the fuel mixture supplied for combustion depended on the combustion conditions and the qualitative and quantitative composition of the fuel mixture. The chemical composition of the glycerine fraction had a significant influence on the quality of combustion and the formation of additional amounts of carbon monoxide.

Figure 4 presents changes in the content of sulfur dioxide in exhaust gases produced during the process of co-firing of coal and glycerine fraction and combustion eco-pea reference fuel.

Analysis of the results presented in Figure 4 showed a variable content of sulfur dioxide in exhaust gases during the test in a steam boiler with a capacity of 2 MW. Changes in the content of sulfur dioxide in exhaust gases from 2 ppm to 206 ppm were observed during the test of reference fuel. A greater content of sulfur dioxide was observed in the first 10 min from the moment a new batch of reference fuel was loaded. Then the concentration of sulfur dioxide stabilized at the level of a few ppm units. A significantly higher (more than five times) average content of sulfur dioxide in exhaust gases was observed for a mixture of glycerine fraction and coal (Table 3—72.01 ppm) than in the case of reference fuel. The increased content of sulfur dioxide in exhaust gases produced in the combustion of fuel mixture containing glycerine fraction could have been caused by the presence of reactive ingredients in the glycerine fraction. A significant increase in the content of sulfur dioxide in exhaust gases was observed each time when a new batch of fuel was loaded into the combustion chamber of the boiler (maximum up to 126 ppm for mixtures of eco-pea and glycerine fraction).

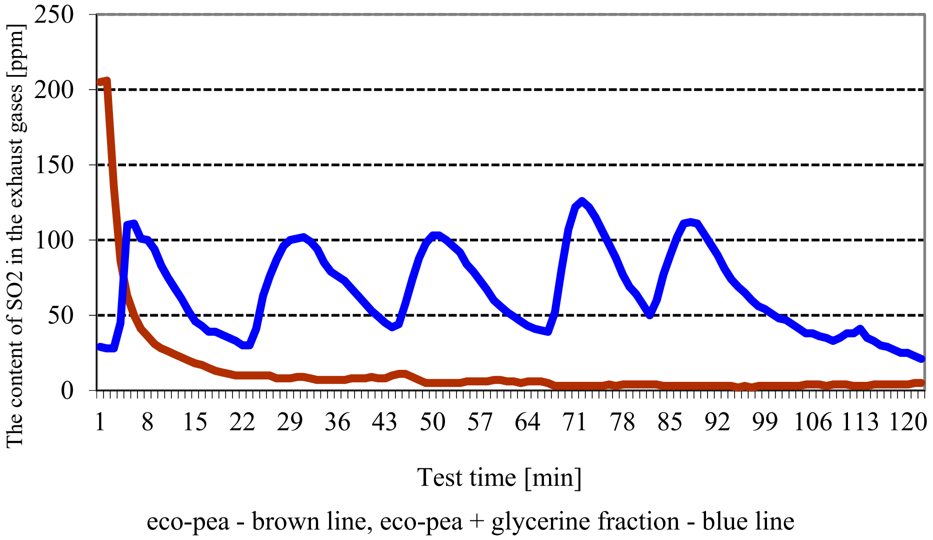


Figure 4. Comparison of changes in the content of the sulfur dioxide in exhaust gases produced during the test of co-firing of coal and liquid waste (glycerine fraction) of biofuel production and the test of combustion of eco-pea reference fuel.

Such variable values of sulfur dioxide during combustion of a fuel mixture containing glycerin fractions may be caused by a high content of sulfur in the composition of glycerin. Inadequate aeration of the combustion chamber can significantly increase the concentration of this parameter.

Figure 5 presents changes in the content of nitrogen oxides in exhaust gases produced during the process of co-firing coal and liquid waste (glycerine fraction) produced in the production of biofuels and combustion of eco-pea reference fuel.

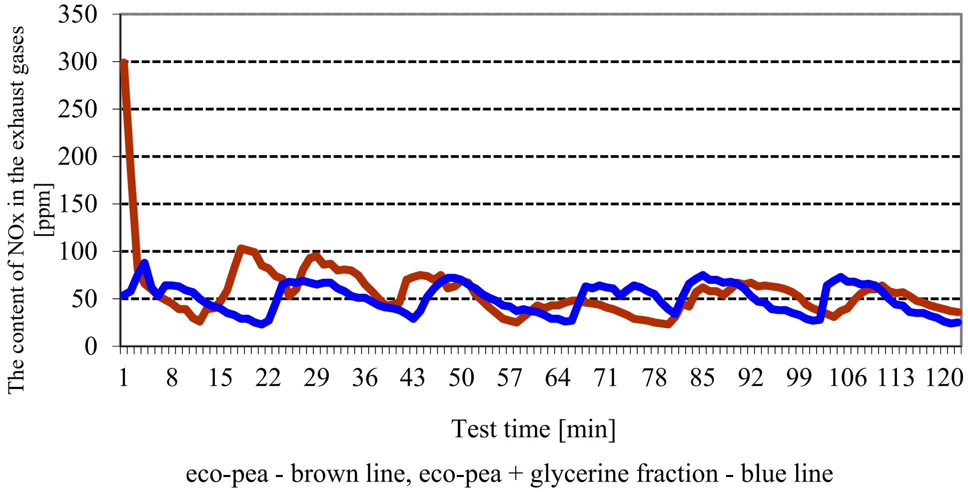


Figure 5. Comparison of changes in the content of nitrogen oxides in exhaust gases produced during the test of co-firing of coal and liquid waste (glycerine fraction) produced in biofuel production and of combustion of eco-coal reference fuel.

Analysis of the results presented in Figure 5 showed variable content of nitrogen oxides in exhaust gases during the test in a steam boiler with a capacity of 2 MW. Changes in the content of nitrogen oxides in exhaust gases from 25 ppm to 299 ppm were observed during the test of reference fuel. The increased content of nitrogen oxides was observed in the first 5 min from the moment a new batch of the reference fuel was loaded. Then, the concentration of nitrogen oxides stabilized at 25–100 ppm. A lower (over 10.7%) average content of nitrogen oxides in exhaust gases was recorded for the mixture of glycerine fraction and coal (Table 3—50.94 ppm) than for the reference fuel. During the test of the mixture of glycerine fraction and eco-pea, it was observed that the content of nitrogen oxides was stable during all the test cycles. A significant increase or decrease in the content of NO_x each time a new batch of fuel was loaded into the combustion chamber of the steam boiler was not recorded. Probably, this phenomenon was due to a more even penetration of the lower layers of the composition of fuel by the gases produced. As a result of gasification, fuel-generated gases can freely flow between the grained fuel. Therefore, the change in the amount of generated NO_x is quite small. Reduced content of nitrogen oxides in exhaust gases produced in the combustion of a fuel mixture containing a fraction of glycerine could be caused by lower content of nitrogen in the glycerine fraction submitted to co-firing with coal and also by increased combustion temperature and amount of air in the combustion chamber. On the basis of the results obtained, it can be concluded that additional glycerine caused a decrease in the content of NO_x. During the combustion of coal, oxides of nitrogen are formed as a result of the heat and flame mechanisms. The coal contains nitrogen, and therefore during the combustion, the so-called fuel nitrogen oxides are emitted as well as those which are produced as a result of oxidation of nitrogen contained in the air. The mechanism of NO_x formation depends on the conditions of combustion. It is possible that higher temperature was a factor determining the elimination of nitrogen oxides.

Figure 6 shows changes in the content of oxygen in exhaust gases produced during the test of the process of co-firing of coal and glycerine fraction and during the test of combustion eco-pea reference fuel.

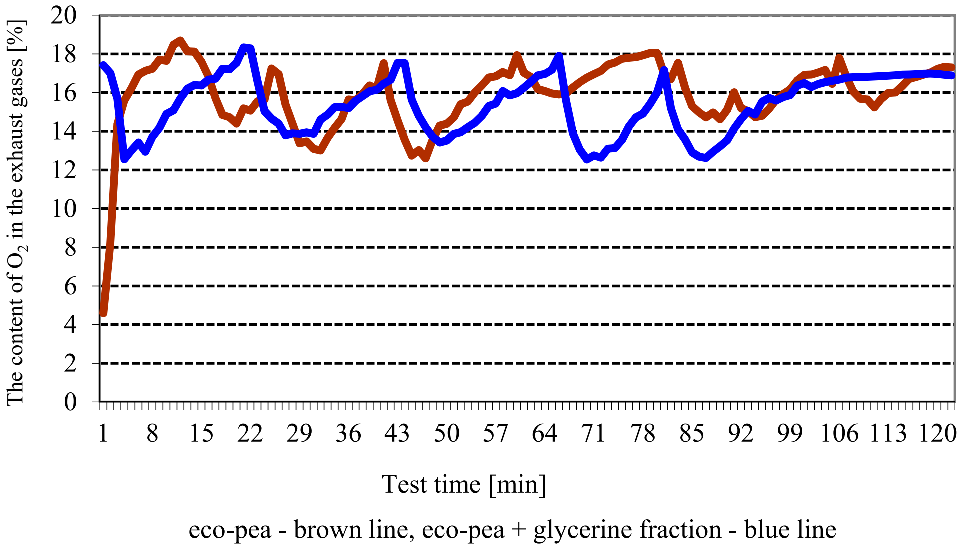


Figure 6. Comparison of changes in the content the oxygen in exhaust gases produced during the test of the process co-firing of eco-pea coal and liquid waste (glycerine fraction) produced in biofuel production and the process of combustion of eco-pea reference fuel.

Analysis of the results presented in Figure 6 has shown variable content of oxygen in exhaust gases during the test in a steam boiler with a capacity of 2MW. Changes in the content of O_2 in the exhaust gases from 4.60% to 18.70% were observed during the test of reference fuel. The increased content of oxygen was observed in the first 15 min from the moment a new batch of reference fuel was loaded. Then, the concentration of oxygen increased each time when a new batch of fuel was loaded into the combustion chamber of the steam boiler. A similar average content of oxygen was observed in exhaust gases for the mixture of glycerine fraction and coal (Table 3—15.10%) and for the reference fuel (Table 3—15.87%). During the test of mixtures of eco-pea and glycerine fraction, an increase in the content of oxygen in exhaust gases was observed each time when a new batch of fuel was loaded into the combustion chamber of the steam boiler (maximum up to 18.33%). Adding glycerine increased the amount of oxygen in the combustion chamber, which was recorded on the device monitoring the qualitative and quantitative composition of exhaust gases produced.

The decrease of oxygen value in the combustion chamber may be related to the increasingly weaker oxygenation conditions in the combustion chamber, which in turn leads to an increase in the content of sulfur oxides and nitrogen oxides during the combustion process of the fuel mixture containing the glycerine fraction.

Figure 7 shows changes in the content of carbon dioxide in exhaust gases produced during the test of the process of co-firing of coal and liquid waste (glycerine fraction) produced in the production of biofuels and the test of combustion of the eco-pea reference fuel.

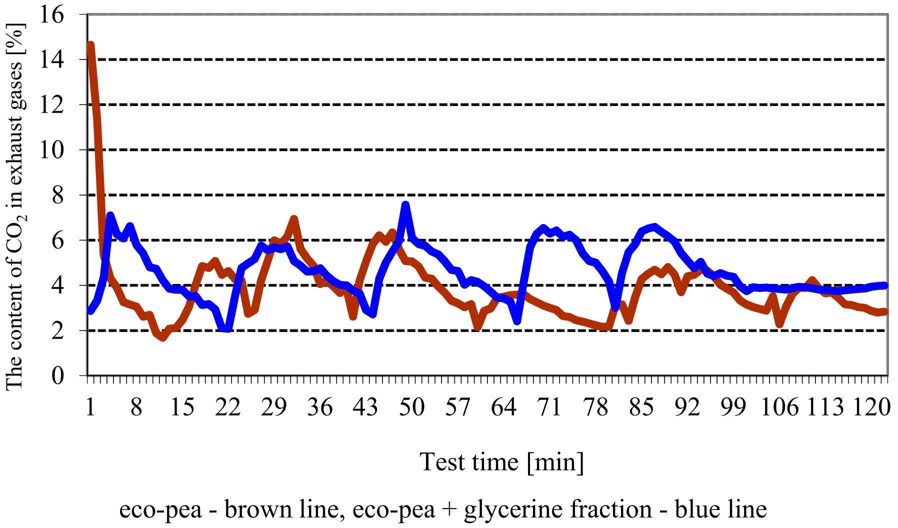
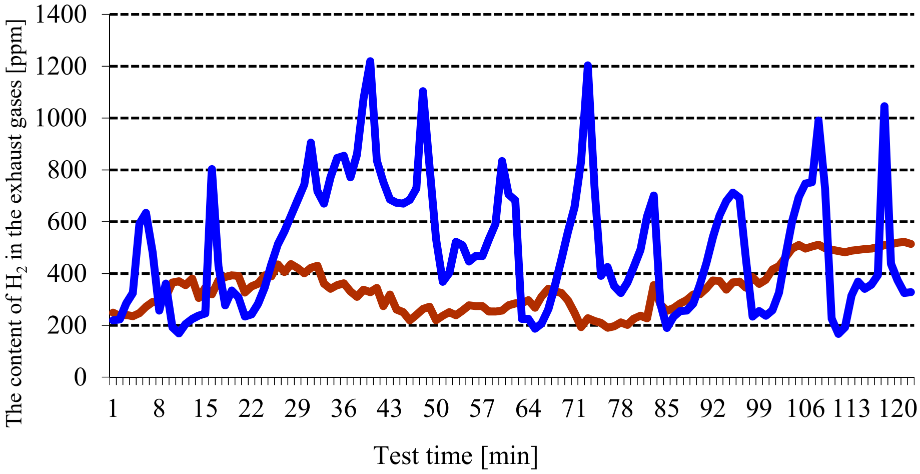


Figure 7. Comparison of changes in the content of carbon dioxide in exhaust gases produced during the test ofthe process of co-firing of coal and liquid waste (glycerine fraction) produced in biofuel production and the test of combustion of eco-pea reference fuel.

Analysis of the results presented in Figure 7 shows the variable content of carbon dioxide in exhaust gases during the test in a steam boiler with a capacity of 2 MW. Changes in the content of CO_2 in exhaust gases from 1.68 to 14.65% were observed during the test of reference fuel. The increased content of carbon dioxide was observed in the first 5 min from the moment a new batch of the reference fuel was loaded. Then, the concentration of carbon dioxide oscillated between 1.68 and 6.94%. The increased content of carbon dioxide in exhaust gases was registered each time when a new batch of fuel was loaded into the combustion chamber of the steam boiler. A higher (by approx.24.5%) average content of carbon dioxide in exhaust gases was observed for a mixture of glycerine fraction and coal (Table 3—4.97%) in respect of reference fuel. During the test of a mixture of eco-pea and glycerine fractions, a marked increase in the content of carbon dioxide in exhaust gases was observed each time a new batch of fuel was loaded into the combustion chamber of the steam boiler (maximum up to 7.57%). The increased content of carbon dioxide in exhaust gases from the combustion of fuel mixture containing glycerine fraction could have been caused by the influence of glycerine on the combustion process. Glycerine contains oxygen atoms which, from the chemical point of view, are involved in the oxidation of carbon. At the same time, hydrogen present in glycerine causes the flame temperature to grow and makes the combustion process more efficient. Each time when a fuel mixture was loaded into the boiler in the initial phase, the carbon dioxide amount increased. On the other hand, when glycerine fraction is burned, parameters of the combustion process deteriorate, and the content of carbon dioxide decreases while the content of carbon monoxide increases.

Figure 8 shows changes in the content of hydrogen in exhaust gases produced during the test of the process of co-firing of coal and liquid waste (glycerine fraction) produced in the production of biofuels and the test of combustion of the eco-pea reference fuel.



eco-pea - brown line, eco-pea + glycerine fraction - blue line

Figure 8. Comparison of changes in the content of hydrogen in exhaust gases produced during the test of the process co-firing of coal and liquid waste (glycerine fraction) produced in biofuel production and the test of combustion of eco-pea reference fuel.

Analysis of the results presented in Figure 8 shows the variable content of hydrogen in exhaust gases during the test in a steam boiler with a capacity of 2 MW. Changes in the content of H_2 were observed in exhaust gases from 193 ppm to 522 ppm during the test of reference fuel. The concentration of hydrogen during the test was stable. No significant increase or decrease in the concentration of hydrogen during the combustion of coal was observed. A higher (by approx. 47.8%) average content of hydrogen in exhaust gases was observed for the mixture of glycerine fraction and coal (Table 3—502.81 ppm) than in respect of reference fuel. During the test, a mixture of glycerine fraction with eco-pea, a marked increase in the content of hydrogen in exhaust gases was observed each time when a new batch of fuel was loaded into the combustion chamber of the steam boiler (maximum up to 1219 ppm).

An increase in the hydrogen content in the fuel mixture containing the glycerine fraction is due to the presence of this element in the waste glycerine. During the combustion of a mixture of glycerin and carbon, the concentration of hydrogen increases because the chemical composition of the mixture is high content of hydrogen.

4. Conclusions

During the test of the combustion process of the mixture of eco-pea and glycerine fraction, a decrease in the content of O_2, CO, and NO_x was observed, while the content of H_2, CO_2, and SO_2 in the exhaust gases increased, and the temperature of exhaust gases decreased as compared to the results of the combustion process of eco-pea.

The test results indicate that it is necessary to optimize the parameters of the boiler and to change the system of air supplied for combustion. The combustion process heavily relies on the amount of air supplied to the boiler. Too high a coefficient of air excess may lead to incomplete combustion and the formation of carbon oxide. Incomplete combustion is caused by one of the two factors, i.e., Wilk (2000):

- inadequate mixing of fuel and air, which makes mixtures too rich (mostly) or excessive impoverishment of the mixture; in both cases, the rate of fuel combustion decreases,
- very fast cooling of the combustion products in the cold coating boundary in the devices where the ratio of the surface of the chamber to its volume is big.

Reduced content of carbon monoxide in exhaust gases produced in the combustion of fuel mixture containing glycerine fraction could be caused by the high temperature of the grate, the fact that fuel remains in the combustion chamber for a long time, or by an excessive amount of oxygen in the grate. An increase in temperature is caused by the presence of hydrogen in glycerine, which has a higher calorific value than coal. Moreover, the content of oxygen in glycerine changes the value of the excess air coefficient. Therefore, better results of the combustion process are obtained, which are then translated into a bigger share of carbon dioxide in the case of the composition of eco-pea and glycerine fraction.

The bigger content of sulfur dioxide in burnt fuels containing glycerine fraction could be caused by the presence of reactive ingredients contained in the glycerine fraction.

Reduced content of nitrogen oxides in exhaust gases originating from the combustion of a fuel mixture containing a fraction of glycerine could be caused by lower content of nitrogen in the glycerine fraction submitted to co-firing with coal and also higher combustion temperature and amount of air in the combustion chamber. On the basis of the results obtained, it can be concluded that adding glycerine causes a decrease in the content of NO_x. The mechanism of NO_x formation depends on the conditions of combustion. It is possible that higher temperature was a factor determining the elimination of nitrogen oxides.

The increased content of carbon dioxide in exhaust gases originating from the combustion of fuel mixture containing glycerine fraction could be caused by the influence of glycerine on the combustion process. Glycerine contains oxygen atoms which, from a chemical point of view, are involved in the oxidation of carbon. At the same time, hydrogen present in glycerine causes the flame temperature to grow and makes the combustion process more efficient.

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