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Effect of coal and biomass co-combustion on the concentrations of selected gaseous pollutants

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Abstract. One of the main environmental problems is the protection of atmospheric air from pollution, which is a result of increase the cover needs of the energy. This problem is particularly important in Poland, where the heat market is one of the largest in Europe and is based in 75% on the use of fossil fuels. The amount of fuel, its type and quality directly affect boiler operation, heat generation capacity, combustion process and thus emissions. The change of the pollutant emission factor also results in a variable load on the boiler room dependent on external conditions. Reduction of emissions pollutants in the energy production process is possible, for example, by increasing the share of renewable fuels in the overall energy balance. One of the possibilities to increase the share of these fuels in the energy sector is co-firing hard coal and biomass. The paper presents results of measurement of concentrations of selected air pollutants in the exhaust gases from co-firing of hard coal and biomassin the form woodchips coming from furniture companies. Based on experimental research, has been created statistical models on the influence of co-combustion of hard coal and biomass in WR water boilers during unstable conditions on the concentration of selected gaseous pollutants.

1. Introduction

One of the main issues concerning environmental protection is protection of atmospheric air against pollutants. Significant amounts of emitted pollutants are the effect of a progressing increase of society's demand for power. It is especially essential in the processes of energy production during combustion of solid fuels. Highest emissions of atmospheric air pollutants (mainly dusts, CO_2, SO_2 and NO_X) per unit of produced energy is achieved during combustion of hard and brown coal. A high level of pollutants is emitted both during normal operation of boilers and under conditions which are different from normal ones during imperfect and incomplete combustion, when, additionally, pollutants such as CO, HF, HCl, CH4, NH_3 and VOC are created. Such problem turns out to be especially important in Poland as approx. 75% of the country's demand for electrical power is met by solid fuels, including mainly hard coal. That results, inter alia, from the availability and price of the source material and the fact that the straight majority of the existing heat-generating plants was designed and built in the seventies and eighties of the previous century as coal-fired plants [1-4].

In connection with the progressing degradation of the environment and negative climatic changes, one of the main elements of Polish power policy is to increase the efficiency of using fuels and energy

[5-8]. Great possibilities of reducing fossil fuel consumption can be seen in heating systems, from production, transmission and distribution to consumers streamlining their heat consumption [9]. Also, obligations assumed by Poland concern also the increase of renewable fuel participation in the energy balance [10]. One of the technological solutions for using such fuels is co-combustion of hard coal and biomass in power boilers. The increased participation of renewable energy in the fuel structure, mainly by co-combustion, results, above all, in the reduction of greenhouse gas emission. Additionally, the usage of biomass in the co-combustion process is connected with low capital outlays on adjusting the boilers and is significant for improving the energy supply safety and for supporting technological development. The co-combustion of conventional fuels and biomass is also extremely essential in social terms as it affects the increase of employment and local development [11, 12].

2. Co-combustion of hard coal and biomass in the existing heat boilers

The task of boiler room devices is to change chemical energy of fuel into thermal energy and to transfer it to the working medium. Boilers often used in the Polish power industry are WR type boilers, which means a grate type water boilers. WR boilers are fired with hard coal and obtain the highest design efficiency of 82% during operation with the optimal boiler rating, i.e. 85-95% of the nominal power. A change of the boiler rating is strongly correlated with the external air temperature. In the summer season the demand for hot tap water is at a constant level but to meet the demand for central heating in the heating season, the operation of a wide range of heat sources is required.

The process of direct co-combustion of biomass and hard coal may take place in WR boilers. Such solution seems to be the quickest way leading to using biomass in power generating facilities having large powers and also ensuring a high efficiency of conversion of chemical energy contained in fired fuel [13-17].

From the cognitive point of view, it was interesting to examine the correlation between the concentrations of particular gas pollutants, boiler power and the amount of biomass in fuel in the process of combustion of the mixture of biomass and conventional fuels in water power boilers operating below their minimal heat rating.

3. Tests and compilation of results

The measurements of gas pollutants were performed in a heat-generating plant equipped with a WR-10 boiler. The process of direct co-combustion of the mixture of hard coal and woodchips coming from furniture companies took place in the said heat-generating plant. The mass fraction of biomass in fuel was 35%, 45%, 60% or 70%. The heat-generating plant used to supply heat to council flats and the municipal industrial zone. Such operating conditions enabled to achieve the optimal boiler rating. Presently, due to economic reasons, only the municipal industrial zone is supplied with heat; and therefore, the hot water boiler operates significantly below the optimal rating which depends on the actual consumers' demand for heat.

The measurement of the composition of combustion gases was conducted on a section behind the boiler in specially prepared measuring holes. A single measurement was carried out in a continuous way and lasted from 2 to 8 hours.

The performed measurements served for determining the probable causality of co-combustion of biomass with hard coal during unstable operation of the boiler and the concentration of particular pollutants.

The composition of combustion gases was determined using the method of spectroscopy and a GASMET DX-4000 analyser. The measurement of the composition of combustion gases was carried out according to the norm PN-ISO 10396:2001 Stationary source emissions - Sampling for the automated determination of gas concentrations. The measuring point was located near the middle of the gauging section, approx. 1/3 of the canal length, thanks to which it was possible to obtain most representative concentration values.

The devices enabled to carry out automatic measurements of volume fractions of the following compounds: carbon dioxide CO_2, %, nitrogen oxides NO_X, mg/Nm^3, sulphur dioxide SO_2, mg/Nm^3, hydrogen chloride HCl, mg/Nm^3, hydrogen fluoride HF, mg/Nm^3, methane CH_4, mg/Nm^3.

On the basis of the received data, the analysis of the correlation between independent variables, i.e. the amount of biomass in fuel and boiler power, and dependant variables, i.e. changes in values of particular concentrations, was carried out, and a numerical model was prepared applying the Statistica program package for each analysed concentration by using multiple regression.   Particular models differ from one another in the participation of two exogenies, i.e. mass fraction (X_1) and boiler power (X_2). A diagram of a demonstration heat-generating plant with a section of WR boiler were presented in figure 1.
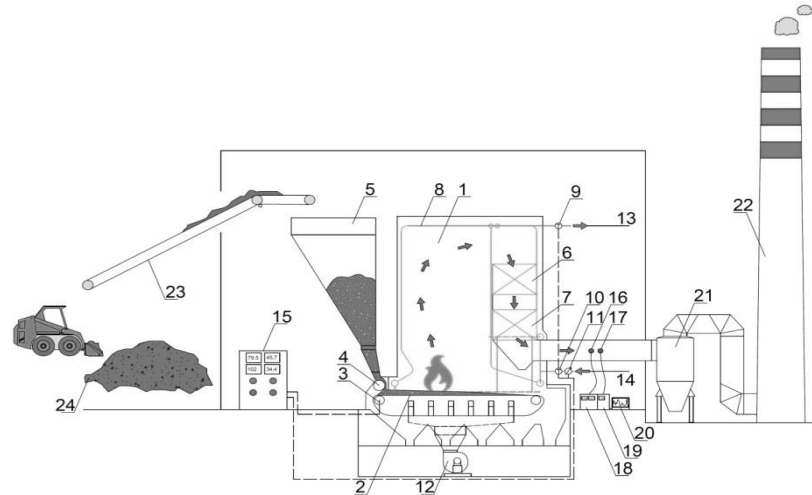

Figure 1. Diagram of heat-generating plant [25]: 1-furnance chamber, 2–grate, 3–grate drive, 4-rotary vane feeder, 5– boiler bunker, 6 I feedwater heater bank, 7–II feedwater heater bank, 8–feedwater heaters, 9–discharge water temperature detector, 10–entering water temperature detector, 11–flowmeter, 12–air flow fan, 13–heated water spout, 14–cold water inflow, 15–boiler control unit, 16–GASMET DX-4000analyzer sampling probe, 17– J.U.M. OVF 3000 analyzer sampling probe, 18–GASMET DX-4000analyzer, 19–J.U.M. OVF 3000analyzer, 20–computer, 21–gas extractor–cyclone, 22–chimney, 23–belt conveyor, 24–hard coal yard.

3.1. Carbon dioxide - CO_2

Figure2 shows a chart of carbon dioxide concentration as a function of boiler power with different participation of biomass with the fitted power trend line.
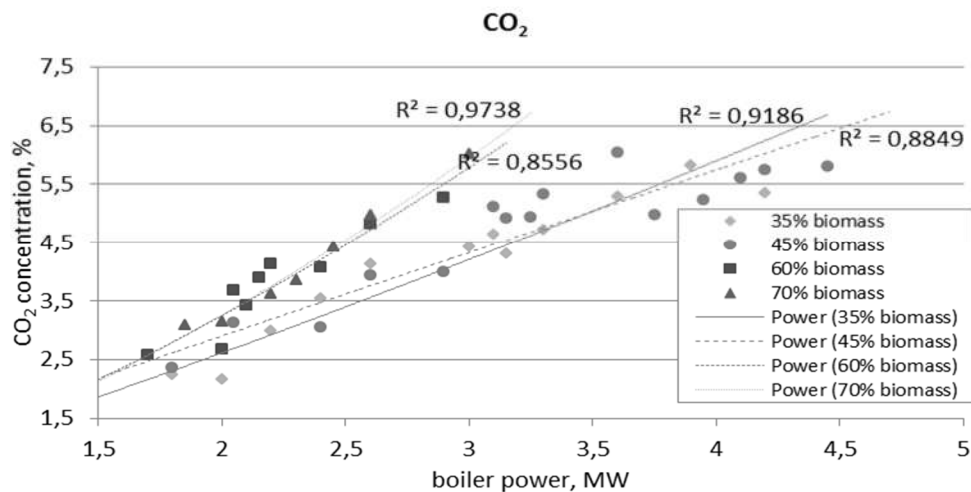

Figure 2. Chart of CO_2 concentrations as a function of boiler power with different participation of biomass.

From the chart it appears that with the increase of boiler power and participation of biomass, the amount of carbon dioxide in combustion gases increases. The nature of such change is retained for all the participation levels of biomass. Small variations may result from unstable boiler's operation which is significantly below its nominal power. The highest CO_2 concentration was observed during the co-combustion of hard coal and 70% participation of biomass in the whole boiler power range. A comparable concentration was achieved with 60% participation of biomass. Evidently lower concentrations of CO_2 were noted with 35% and 45% participation of biomass.

The multiple regression model is as follows:

$$Y_{CO2} = 0.03\,X_1 + 1.46X_2 - 1.21$$
$$\quad(0.01)\quad(0.10)\quad(0.48)$$

(1)

where: Y_{CO2} – equasion for CO_2 concentration, %; X_1 – amount of biomass, %; X_2 – boiler power, MW.

If the amount of biomass is increased by 1%, the CO_2 concentration will increase by 0.03%. If the boiler power is increased by 1 MW, the CO2 concentration will increase by 1.46%. The standard error is: 0.01 for participation of biomass, 0.1 for boiler power and 0.48 for the free term. The coefficient of determination R_2 shows 84.02% fit of the model to the data.

3.2. Nitrogen oxides –NO_X

Figure 3 shows a chart of carbon dioxide concentration as a function of boiler power with different participation of biomass with the fitted power trend line.
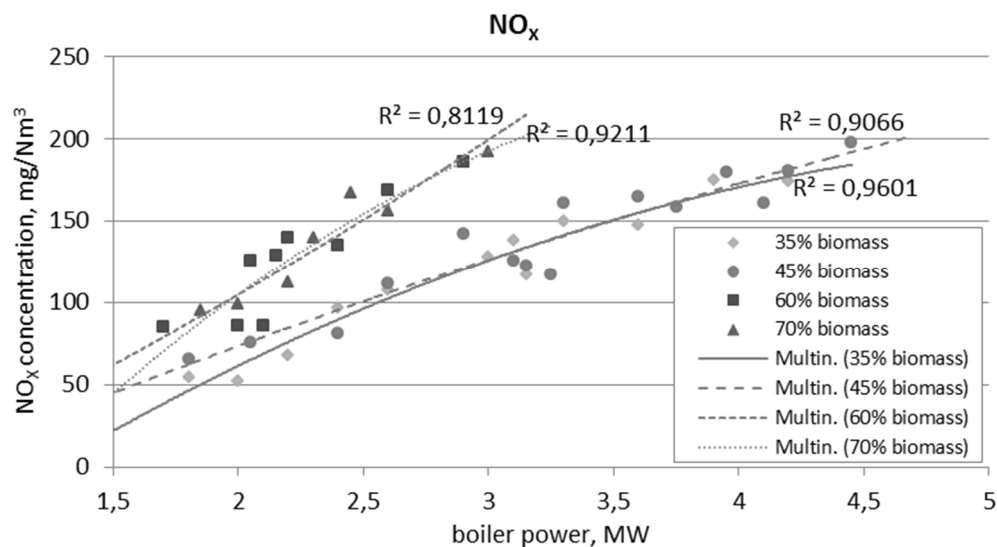

Figure 3. Chart of NO_X concentrations as a function of boiler power with different participation of biomass.

From the chart it appears that with the increase of boiler power and participation of biomass, the amount of nitrogen oxides in combustion gases rises. The nature of such change is retained for all the participation levels of biomass. Small variations may result from unstable boiler's operation which is significantly below its nominal power. The highest NO_X concentrations were observed during the co-combustion of hard coal and 60% and 70% participation of biomass in the whole boiler power range. Evidently lower NO_X concentrations in combustion gases were noted with 35% and 45% participation of biomass. With the increase of boiler power, the temperature in the combustion chamber rises, which contributes to the creation of nitrogen oxides through thermal and quick mechanisms. The amount of burnt fuel is also greater, therefore, oxidation of fuel organic compounds containing nitrogen takes place (fuel mechanism).

The multiple regression equation is as follows:

$$Y_{NOx} = 1.68\,X_1 + 51.66\,X_2 - 98.20$$
$$(0.22) \quad (3.76) \quad (18.54)$$

(2)

where: Y_{NOx} – equation for NO_X emission standard, mg/Nm³; X_1 – amount of biomass, %; X_2 – boiler power, MW.

If the amount of biomass is increased by 1%, the NO_X emission standard will increase by 1.68 mg/Nm³. If the boiler power is increased by 1 MW, the NO_X emission standard will increase by 51.66 mg/Nm³. The standard error is: 0.22 for participation of biomass, 3.76 for boiler power and 18.54 for the free term. The coefficient of determination R^2 shows 81.81% fit of the model to the data.

3.3. Sulphur dioxide – SO₂

Figure4 shows sulphur dioxide concentrations as a function of boiler power with different participation levels of biomass with the fitted power trend line.
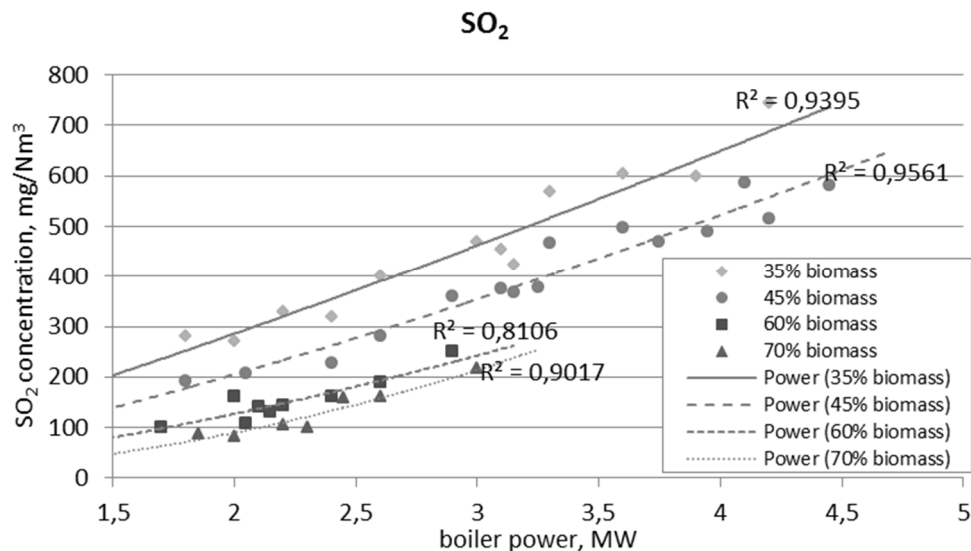

Figure 4. Chart of SO₂ concentrations as a function of boiler power with different participation of biomass.

From the chart it appears that with the increase of boiler power and participation of biomass, the amount of sulphur dioxide in combustion gases rises. The nature of such change is retained for all the participation levels of biomass. The content of sulphur in burnt hard coal was approx. 0.55%, whereas it was 0.21% in biomass, so the amount of SO₂ emission is strictly connected the content of sulphur in fuel and the amount of burnt fuel. Highest SO₂ concentrations were observed during the co-combustion of hard coal and 35% participation of biomass.

The regression equation is as follows:

$$Y_{SO2} = -7.32X_1 + 151.77X_2 + 252.39$$
$$(0.63) \quad (10.48) \quad (51.59)$$

(3)

where: Y_{SO2} – equation for SO₂ emission standard, mg/Nm³; X_1 – amount of biomass, %; X_2 – boiler power, MW.

If the amount of biomass is increased by 1%, the SO₂ emission standard will decrease by 7.32 mg/Nm³. If the boiler power is increased by 1 MW, the SO₂ emission standard will increase by 151.77 mg/Nm³. The standard error is: 0.63 for participation of biomass, 10.48 for boiler power and 51.59 for the free term. The coefficient of determination R^2 shows 93.4% fit of the model to the data.

3.4. Hydrogen chloride - HCl

Figure 5 shows hydrogen chloride emission standards as a function of boiler power with different participation levels of biomass with the fitted power trend line.
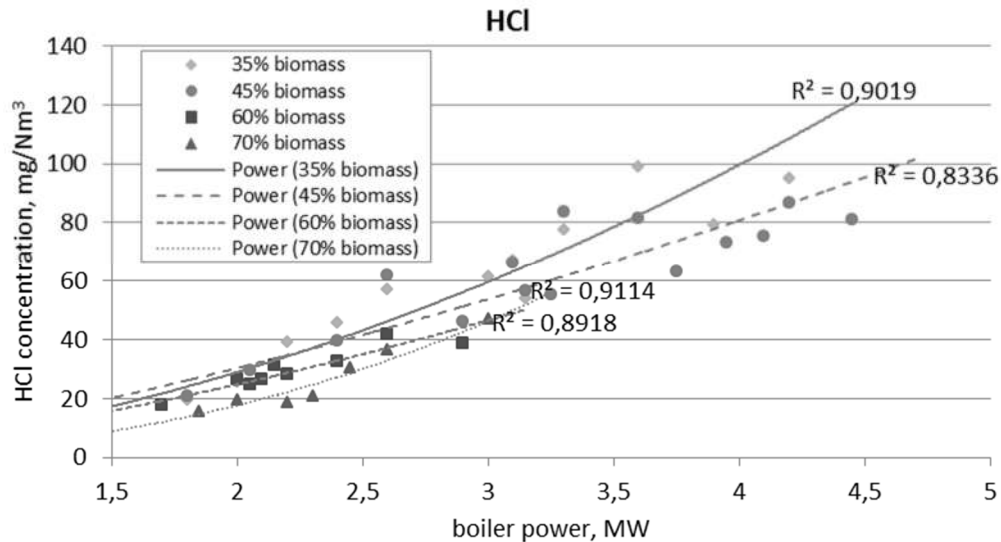

Figure 5. Chart of HCl concentrations as a function of boiler power with different participation of biomass.

From the chart it appears that with the increase of boiler power and participation of biomass in the fuel mixture, the content of hydrogen chloride in combustion gases rises. Chloride is a natural element present in fossil fuels. It is probable that higher hydrogen chloride concentrations and smaller participation of biomass result from the presence of a greater amount of chloride compounds in hard coal than in biomass. The nature of such change is retained for all the examined cases. Small variations may result from unstable boiler's operation which is significantly below its nominal power. The regression equation is as follows:

$$Y_{HCl} = -0.49X_1 + 25.52X_2$$
$$(0.11) \qquad (1.79)$$

(4)

where: Y_{HCl} – equation for HCl emission standard, mg/Nm^3; X_1 – amount of biomass, %; X_2 – boiler power, MW.

If the amount of biomass is increased by 1%, the HCl emission standard will decrease by 0.49 mg/Nm^3. If the boiler power is increased by 1 MW, the HCl emission standard will increase by 25.52 mg/Nm^3. The standard error is: 0.11 for participation of biomass and 1.79 for boiler power. The coefficient of determination R^2 shows 89.04% fit of the model to the data.

3.5. Hydrogen fluoride - HF

Figure6 shows hydrogen fluoride concentrations as a function of boiler power with different participation levels of biomass with the fitted multinomial trend line.

From the chart it appears that with the increase of boiler power and participation of biomass in the fuel mixture, the content of hydrogen chloride in combustion gases increases. Just like chlorine, fluoride is a natural element present in fossil fuels. It is probable that a higher hydrogen fluoride concentration and smaller participation levels of hard coal result from the presence of a greater amount of fluoride compounds in biomass than in hard coal. The nature of such change is retained for all the examined cases. Small variations may result from unstable boiler's operation which is significantly below its nominal power.
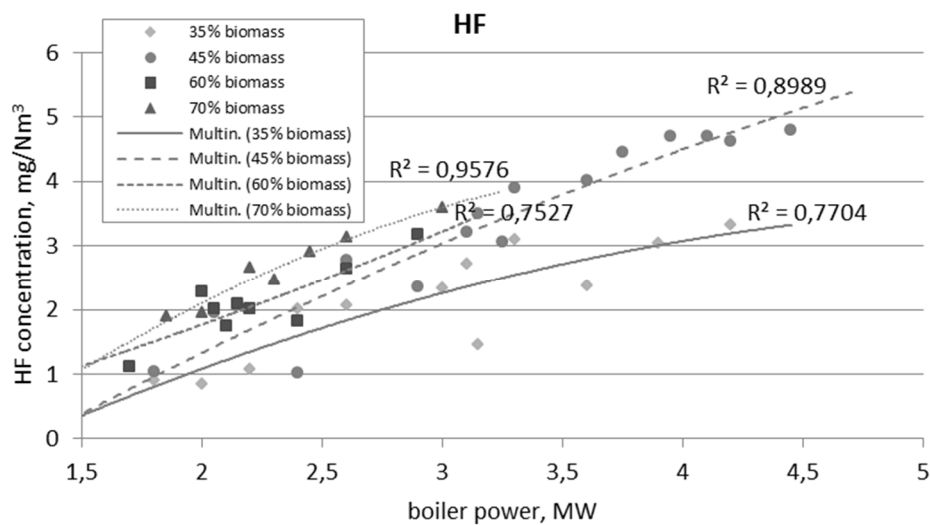
Figure 6. Chart of HF concentrations as a function of boiler power with different participation of biomass.

The regression equation is as follows:

$$Y_{HF} = 0.04X_1 + 1.45X_2 - 3.27$$
$$(0.01) \quad (0.10) \quad (0.49)$$

(5)

where: Y_{HF} – equation for HF emission standard, mg/Nm^3; X_1 – amount of biomass, %; X_2 – boiler power, MW.

If the amount of biomass is increased by 1%, the HF emission standard will increase by 0.04 mg/Nm^3. If the boiler power is increased by 1 MW, the HF emission standard will increase by 1.45 mg/Nm^3. The standard error is 0.01 for participation of biomass, 0.10 for boiler power and 0.49 for the free term. The coefficient of determination R^2 shows 83.23% fit of the model to the data.

3.6. Methane - CH$_4$

Figure 7 shows methane concentrations as a function of boiler power with different participation levels of biomass with the fitted exponential trend line.
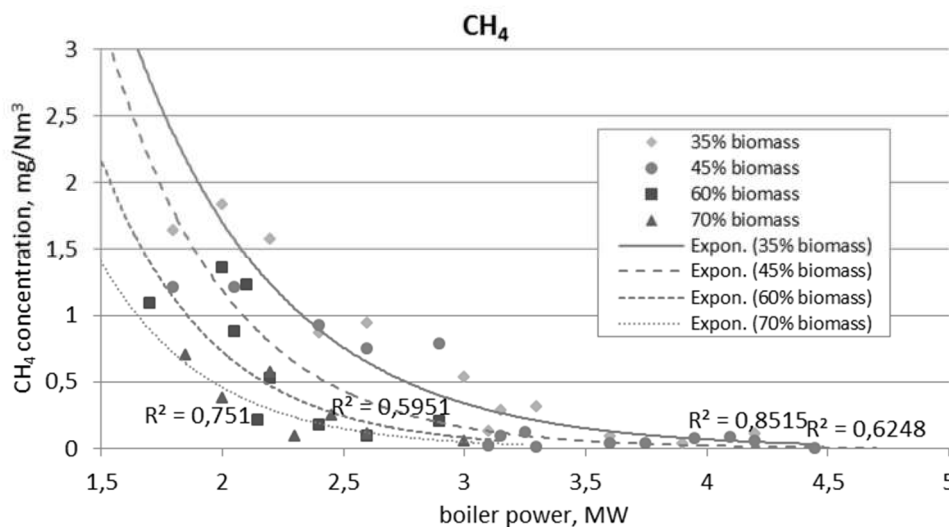

Figure 7. Chart of CH$_4$ concentrations as a function of boiler power with different participation levels of biomass.

From the chart it appears that with the increase of boiler power and participation of biomass in the fuel mixture, the methane concentration decreases. A high content of CH_4 and a low boiler rating may be connected with a lack of optimization of the combustion process. When boiler power is increased and, thus, the furnace operation is stabilized, the methane level falls to zero. The nature of such change is retained for all the examined cases. Small variations may result from unstable boiler's operation which is significantly below its nominal power.

The regression equation is as follows:

$$Y_{CH4} = -0.02X_1 - 0.65X_2 + 3.40$$
$$(0.00) \quad (0.06) \quad (0.31)$$

(6)

where: Y_{CH4} – equation for CH_4 emission standard, mg/Nm³; X_1 – amount of biomass, %; X_2 – boiler power, MW.

If the amount of biomass is increased by 1%, the CH_4 emission standard will decrease by 0.02 mg/ Nm³. If the boiler power is increased by 1 MW, the CH_4 emission standard will decrease by 0.65 mg/ Nm³. The standard error is: 0.00 for participation of biomass, 0.06 for boiler power and 0.31 for the free term. The coefficient of determination R^2 shows 71.3% fit of the model to the data.

4. Conclusions

The co-combustion of hard coal and biomass in the form woodchips coming from furniture companies affects concentrations of particular gas pollutants in water power boilers during operation under unstable conditions. With the increase of the participation of woodchips in fuel, the contents of nitrogen oxides, hydrogen fluoride and carbon dioxide increase. Biomass has a zero balance of carbon dioxide emission, therefore, the increase of such emission may be ultimately passed over. A positive effect of co-combustion is a decreased emission of sulphur dioxide, hydrogen fluoride and methane.

Using a STATISTICA program package, models describing concentrations of particular gas pollutants under unstable conditions of boiler operation depending on its power and participation of biomass in burnt fuel were created through the analysis of multiple regression. High coefficients of determination were achieved, which confirms an essential influence of independent variables, i.e. the amount of biomass in fuel and boiler power, on dependant variables, i.e. changes in values of particular concentrations.

The compiled models are characterized by a qualitative trend so on their basis it is possible to determine the change of efficiency, concentrations or emission of pollutants. On that basis we may optimize the process of co-combustion of hard coal and biomass in WR stocker-fired water boilers.

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