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Experimental study on optimisation of the burning process in a small scale pellet boiler due to air supply improvement

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Abstract. The specific weight of biomass and pellets in thermal energy production has recently started to increase rapidly. The continually growing price of fossil fuels and European Union requirements to increase the share of renewable energy in thermal energy production are the main reasons of the biomass specific weight increase. Unfortunately, Latvia uses only a small part of the country's existing biomass potential for the time being. A growth of the amount of biomass utilisation for energy production can be foreseen in the future, because such type of energy production has a number of advantages, one of which is the lesser amount of emissions that arise during the combustion process. However, the amount of emissions that arise during the combustion of wood pellets can get lower due to optimisation of the combustion process. Air supply is one of the main factors which have effect on the heat loss, boiler efficiency, and emissions levels.

The main goal of this study is to optimise the pellet combustion process in a small scale pellet boiler due to the air supply improvement. Experimental research of the combustion process of a pellet boiler with nominal capacity 25 kW was carried out during the work. First at all, the effect of changes in the amount of air supplied to the boiler combustion process was determined. Then, approbation of two methods for combustion process improvement was made.

The first method was based on flame dissipation, but the second method included the opposite method – flame concentrating. However, the main task of both methods applied was to improve the process of mixing air and fuel. It was important to reduce the rate of air supplied, too. Four different gratings were used for dissipation of the flame. Cylinders without and with a spiral for flow swirl were used for flame concentration. The results of the study show that both methods, in general, have a positive impact on the combustion process.

Key words: pellet boiler, air supply, flame dissipation, flame concentrating.

Nomenclature

C	Carbon content of test fuel (as fired basis), % of mass
CO	Carbon monoxide content in dry flue gases, % of volume
H	Hydrogen content of test fuel (as fired basis), % of mass
NO_x	Nitric oxides content in dry flue gases, % of volume
O_2	Oxygen content of dry flue gases, % of volume
PM	Dust content of dry flue gases, % of volume
T_{fg}	Temperature of flue gas, °C

INTRODUCTION

Combustion process is a complicated process where exothermic chemical reaction between the fuel and the oxidant happens and some amount of the heat gets free. The emission from the combustion process can be divided into two groups – unburned pollutants and pollutants that are produced by combustion. CO, hydrocarbons, polycyclic aromatic hydrocarbons, and tar form the unburned pollutants. Ash, particulate matter, different nitrogen, and sulphur emissions make the second group. The amount of the emission from the first group can be decreased if optimal combustion parameters are organised (Khan et al., 2009). It is important to minimize the amount of CO in flue gas to have high combustion efficiency. A specific condition must be organised in the pellet boiler furnace to reduce the amount of CO (Hansen et al., 2009).

Nowadays, utilisation of the renewable energy from agro biomass for heat production is becoming more and more popular in the world and, especially, in the Northeast European countries (Mikkola & Ahokas, 2011; Beloborodko et al., 2013). Biomass has high potential, because it is an environmentally friendly heat production method with low amount of harmful emission (Jasinskas et al., 2011). Pellet is one of the most popular kinds of agro biomass. There is a wide range of heating devices available for pellet combustion.

Pellet combustion efficiency varies highly for different pellet boilers. Combustion process efficiency in a pellet boiler can vary highly and depends on many factors. Pellet boiler construction is one of the main parameters which have a dominant effect on the combustion process. There are three main burner types available for pellet boilers – underfed, horizontally fed, and top fed burners. Each of the burner types has some specific characteristic and differences in the air supply and ash removal (Haapa-Aho et al., 2011). In the study done by Verma et al. (2011a), a pellet boiler with different burner types was tested. The results show that top fed boilers have higher CO concentrations and lower efficiencies. The properties of the pellets that are used have an important role on the combustion process (Verma et al., 2012). The fuel with high ash content has a negative effect on the air supply and combustion process in general (Stahl & Wikström, 2009). The ash content has an impact on the dust content in flue gas (State of the art …). There are pellets with different properties available in Latvia, thus it is important to check pellet quality (Kirsanovs et al., 2012).

Air supply has one of the dominant roles on the combustion process in a pellet boiler. Air supply must be organized in such a way so as to reach a qualitative air and fuel mixing process. Air must be left in the burner and furnace for a sufficient time to achieve complete combustion. The amount of CO largely depends on the air supply organisation (Johanssona et al., 2004). The amount of air supply affects the temperature in the furnace, but temperature in the furnace influences all chemical reactions and emission formatting. A study done by Verma et al. (2011b) shows that CO has an effect on the amount of dust in flue gas. The higher the concentration of CO, the higher the amount of the particulate matter in flue gas. The losses due to unburned combustibles in flue gas depend on the dust content. The work done by Fernandes & Casta (2011) presents a similar connection between CO and the dust content in flue gas. The results also show that the amount of emissions depends on the boiler capacity. The closer the boiler capacity is to nominal, the lower amount of emissions.

There are different methods to improve the combustion process in a pellet boiler and some of them are based on air supply optimisation. Firstly, the optimal amount of oxygen in flue gas must be determined. This optimal value can vary depending on the boiler's technological properties. If air supply is too high, the amount of CO increases. Heat losses with outlet gases grow up too, and this is the main problem. Flue gas flow rises as well. The heat transfer to water goes down, because the time during which the hot gas is placed in the heat exchanger decreases (Loo et al., 2008). Nowadays, lambda sondes have become more and more popular for oxygen concentration regulation in flue gas. A study done by L. Carvalho (2008) shows the advantages of lambda sondes. The experimental research was done using different boilers with and without lambda sondes. There are other methods for combustion process control (Biomass combustion …, 2008; Haapa-aho et al., 2011).

Air staging is one of the commonly used methods to improve the combustion process. Primary air was used for lighting and fuel drying, but secondary air was used to burn out the combustible volatiles. Sometimes tertiary air was used as well. The required amount of air in different parts of a boiler furnace can be organised if air staging is used (Eskilsson et al., 2004). It is important to calculate the optimal ratio between primary and secondary air supply to reduce the amount of emissions and increase combustion efficiency (Žandeckis et al., 2013a). The location of secondary air and distance from primary air injection and the burner have important roles as well (Chaney et al., 2012). There are many other studies where the advantages, main details, and specific features of the air staging utilisation are described (Nussbaumer et al., 2003; Klason & Bai, 2007; Liu et al., 2013).

Different pellet boiler burner design modifications can be used for combustion process improvement and emission reduction. The main part of the goal of design optimisation is to make air and fuel mix better. One of such methods is continual or periodical fuel mixing. Different technological solutions exist. A study done by L. Terrazzano et al. describes one of such burner design improvements (Terrazzano et al.).

METHODS AND MATERIALS

Description of the experimental stand

To achieve the goal of the research, a set of experiments were conducted using an experimental stand which is intended for biomass boiler testing according to the standard LVS EN 303-5 'Heating boilers - Part 5: Heating boilers for solid fuels, manually and automatically stocked, nominal heat output of up to 300 kW – Terminology, requirements, testing and marking' (2012). The experimental stand is shown in Fig. 1. The laboratory stand consisted of a 25 kW pellet boiler, monitoring equipment, a heat accumulation tank, and a heat exchanger for boiler cooling.

For determination of flue gas chemical composition (NO_x, CO, O_2), the flue gas analyser Testo 350XL was used. All concentrations were calculated under equal conditions – at 10% of O_2. Flue gas temperature, chemical composition, amount of dust content in flue gas flow rate, chimney draught, fuel consumption, and thermal performance of the boiler were monitored during the test. The K-type thermocouples were used for the flue gas measuring.

The water flow rate was measured using a magnetic flow meter. PT 100 temperature sensors were used for water temperature measuring. The pressure into the flue gas stack was regulated manually and was determined using the differential manometer DPT ± 100-R2-Az-D-Span. For determination of fuel consumption, the pellet boiler was put onto the industrial weighing platform Svenska Vag HCPS-4 and changes in the weight were recorded automatically.

All data was gathered scientifically using Campbell data and was transferred to a PC for data processing.

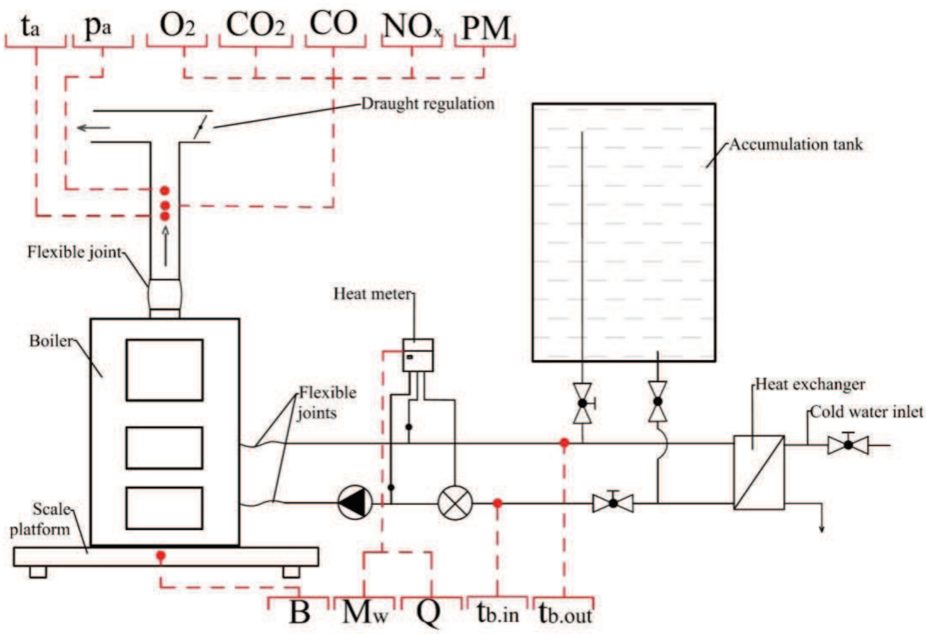

Figure 1. The principal scheme of the boiler stand (Žandeckis et al., 2013b).

The nomenclature used in Fig. 1: B – mass of the test fuel (kg h^{-1}), M_w – water flow rate (kg h^{-1}), Q – heat output (kW), B – heat input (kW), Q_b – chemical heat losses in the flue gases, referred to the unit of mass of the test fuel, (kJ kg^{-1}) t_a – flue gas temperature (°C), p_a – draught in the chimney (Pa), $t_{b.in}$ – boiler input temperature (°C), $t_{b.out}$ – boiler output temperature (°C).

The boiler efficiency was calculated according to the standard EN 303-5:2001 using the direct method. The amount of the fuel used, produced heat, and the net calorific value were taken into account for the boiler efficiency calculations. The heat losses with outlet gases and heat losses by incomplete burning from chemical causes were calculated according to the standard LVS EN 13240:2002 'Roomheaters fired by solid fuel – Requirements and test methods' (2002). For the flue gas flow rate determination, direct and indirect methods were used. It was done to increase the veracity of the acquired data. The Vortex VA40 ZG7 flow meter was used for direct the method. The indirect method is the calculation of the flow rate using the data about the fuel chemical composition, moisture content, and calorific value.

Description of the pellet boiler

The experiments were done using a 25 kW pellet boiler (see Fig. 2). The burning process happens in the automatic regime, the amount of pellets supplied and the control of on/off sequences is the function of the water temperature in the boiler. Pellets from a container next to the boiler are fed through a horizontal screw type conveyor into a vertical, bottom fed burner. The amount of the fuel supply was constant for each test. The required amount of combustion air was supplied with a fan which was controlled by manually changing the ON/OFF intervals of the air blower. The amount of air supplied was different to get different values of oxygen concentration in the flue gas in the range from 5% to 13%.

Figure 2. The pellet boiler Grandeg GD_BIO 25.

Description of the fuel used for tests

Three different types of pellets were used for combustion tests. It was done to make three series of combustion test with changed oxygen concentrations in the flue gas in the range from 5% to 13%, and to increase the veracity of the acquired results. The physical and chemical parameters of the pellets used for the tests are described in the Table XX. The laboratory analysis was based on the methodology given in the CEN/TS standards, see Table 1.

Table 1. The chemical and physical parameters of the pellets

Parameter	Pellet A	Pellet B	Pellet C	Method
Ash content, %	1.23	1.39	0.56	CEN/TS 14775 (EN, 2009)
Moisture content, %	6.71	11.84	8.56	CEN/TS 14774-3 (EN, 2009)
Net calorific value, MJ kg^{-1}	17.7	16.4	17.4	CEN/TS 14918 (EN, 2009)
Gross calorific value, MJ kg^{-1}	20.5	20.2	20.5	CEN/TS 14918 (EN, 2009)
C, %	45.7	43.2	44.8	
H, %	5.79	5.47	5.67	

Description of the methods for flame dissipation and concentration

A grate made of steel pipes with outside diameter 2.4 cm and wall thickness 2.2. mm was used for flame dissipation (see Fig. 3). In general, the construction was made of the more than 90 tubes. The length of the tubes was 12 cm. The diameter of the grate was about 22–23 cm. The height of the construction could be regulated with legs. The grate was installed over the boiler burner and the flame that reached the bottom part of the grate dissipated and went through pipes. The resistance of flue gas grew and the process of air and volatiles blending was improved.

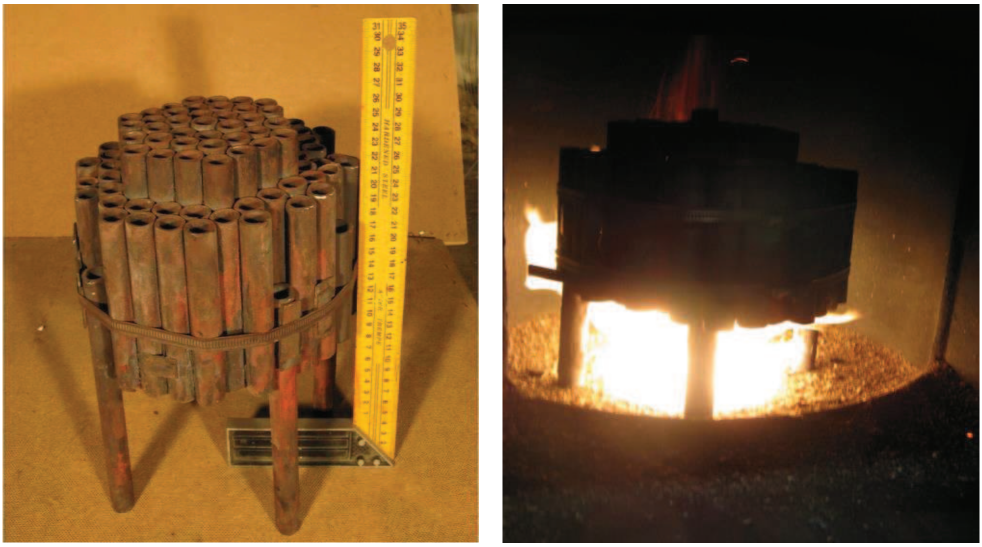

Figure 3. The grate for flame dissipation.

The second method to improve the combustion process was based on the opposite method. A steel cylinder with a spiral for flow swirl was used for flame concentration (see Fig. 4). The diameter of the cylinder was 18 cm and the height 30 cm. The cylinder was installed over the burner and the flame went through it. An increase of the reaction time between oxygen and volatiles was reached. It promoted a more complete combustion process.

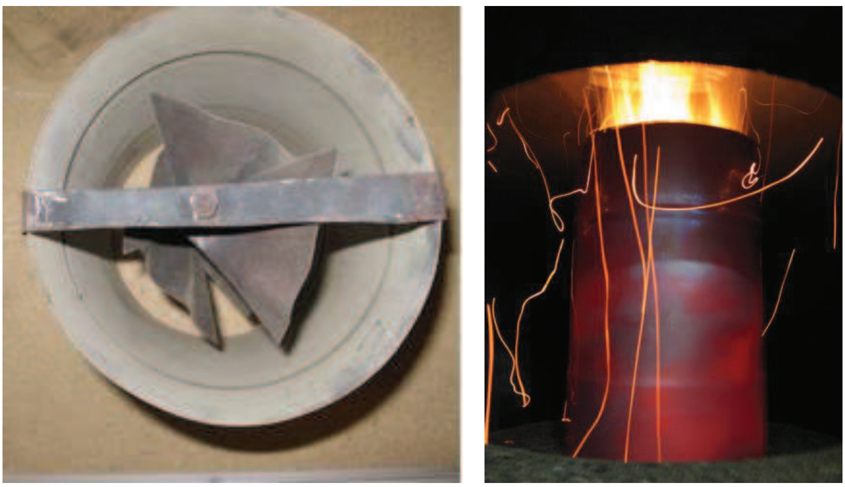

Figure 4. The cylinder for flame concentrating with a spiral for flow swirl.

RESULTS

Oxygen concentration changes the influence on the combustion process

The results of the tests carried out during the research show that changing the oxygen concentration in flue gases from 5 to 13%, changes the flue gas temperature from 125°C to 170 °C (see Fig. 5). The flue gas temperature grows with oxygen concentration increase. NO_x concentration also grows, but not so sharply. The minimum amount of CO is 30–50 ppm calculated under normal conditions with the oxygen concentrations of the flue gas of 6–7%. The amount of CO was up to 25 times higher in the flue gas with oxygen concentration 13%. The heat losses with outlet gases average from 5% to 14% depending on the oxygen concentration in flue gases. The heat losses by incomplete burning from chemical causes were significantly lower – only 0.1% with the oxygen concentration of exhaust gas of 6–7% and 1.5% with high concentrations of oxygen when the CO concentration in flue gas is high. The heat losses with outlet gases and by incomplete burning from chemical causes have a dominant effect on the combustion efficiency. Boiler efficiency varies in the range of 76 to 90%. The maximum efficiency was established at the oxygen concentration of the flue gas of 6.5%.

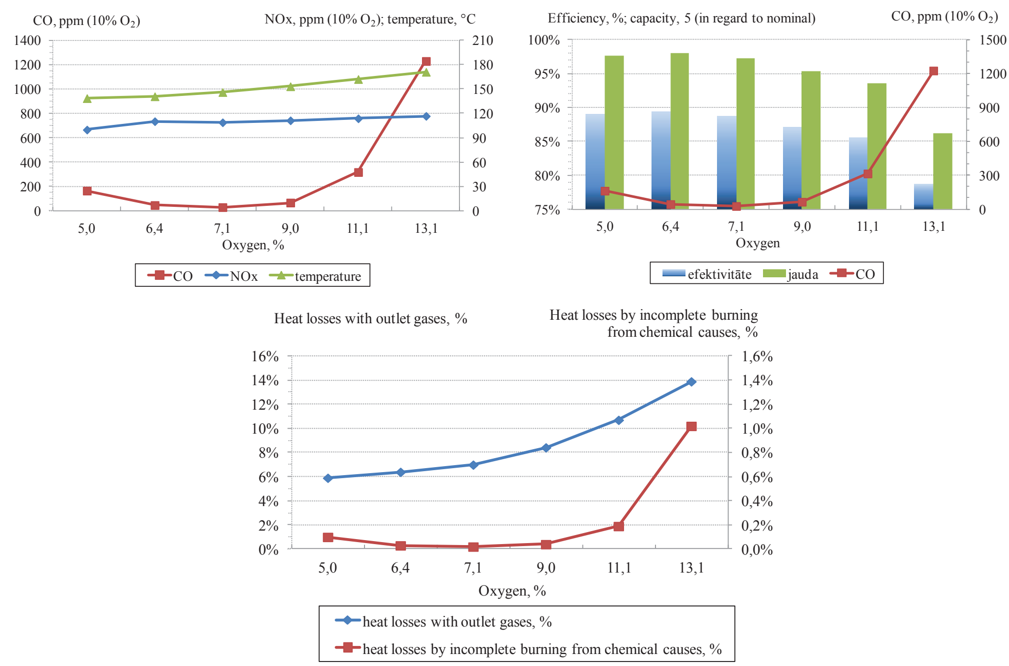

Figure 5. The influence of changes in oxygen concentration on the combustion process.

Fig. 6 presents the changes of the flue gas velocity depending on the oxygen content in the flue gas. The flue gas velocity was determined directly using a flow meter and an indirect method was used too. The flue gas velocity was measured in a chimney with a diameter of 16 cm. The results show that the calculated data was similar to the measured data. The flue gas velocity increases sharply from 0.7 m s^{-1} at the oxygen concentration of exhaust gas of 5% to 1.4 m s^{-1} at the oxygen concentration of exhaust gas of 13%. An increase in flue gas velocity has a negative impact on combustion efficiency, because the time during which the hot gas is in the heat exchanger decreases.

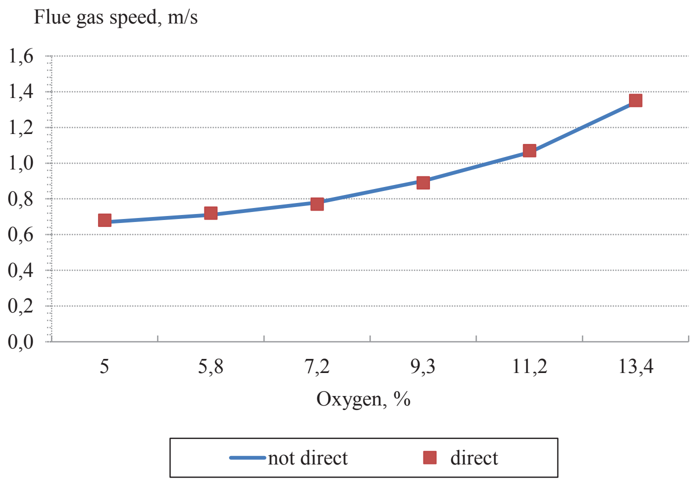

Figure 6. The flue gas velocity depending on oxygen content.

Data verification using a different fuel

Two additional series of tests were made using pellet B and pellet C to ensure that the acquired results were not accidental and to increase the veracity of the data. The received data about flue gas temperature, CO concentration, heat losses, dust content, and total efficiency show similar results in general (see Fig. 7). The flue gas temperature using pellet A was a little bit higher, but the reason for this was that pellet A has higher calorific value. The amount of CO using pellet B was slightly higher and therefore the heat losses by incomplete burning from chemical causes were higher too. The main reason for this can be explained considering that pellet B has higher ash content. The heat losses with outlet gases were higher with pellet A, because the flue gas temperature was higher using this pellet. The efficiency in all three test series was similar. The dust content in flue gas was determined using pellets A and B. The results of the utilisation of different pellets were similar as well. The dust content was minimal at the oxygen concentration of the flue gas of 6.5%, but higher at the oxygen concentration of 13%. These results prove that CO concentration has an important role on particulate matter.

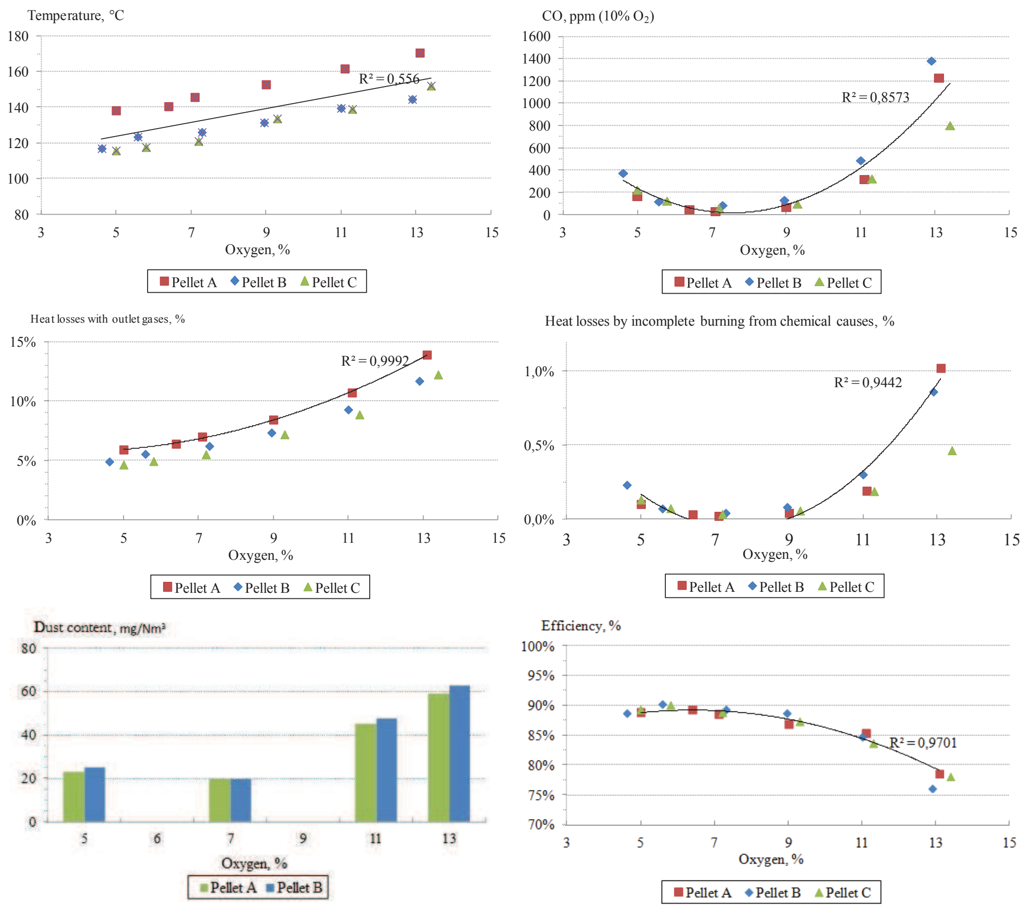

Figure 7. The influence of oxygen concentration changes on the combustion process used with different types of the fuel.

Air supply optimisation. Flame dissipation and concentration

The tests with flame dissipation and concentration were carried out using pellet A; therefore the results from the first testing series were used as reference data to determine the effect of both methods. The results show that both approbation methods have a positive effect (see Fig. 8). The biggest CO emission value decrease was achieved using the flame concentration method. An especially high decrease was achieved at a high oxygen concentration. The temperature drops by 10°C at a low oxygen concentration and by 20 °C at a high concentration were achieved using the concentration method as well. The temperature decrease promotes the heat losses with outlet gases to go down too, but the CO concentration drop affects the decrease of heat losses by incomplete burning from chemical causes. An efficiency rise was obtained using both methods, but comparing the two methods, the biggest effect belongs to the flame concentration method, especially at a high temperature.

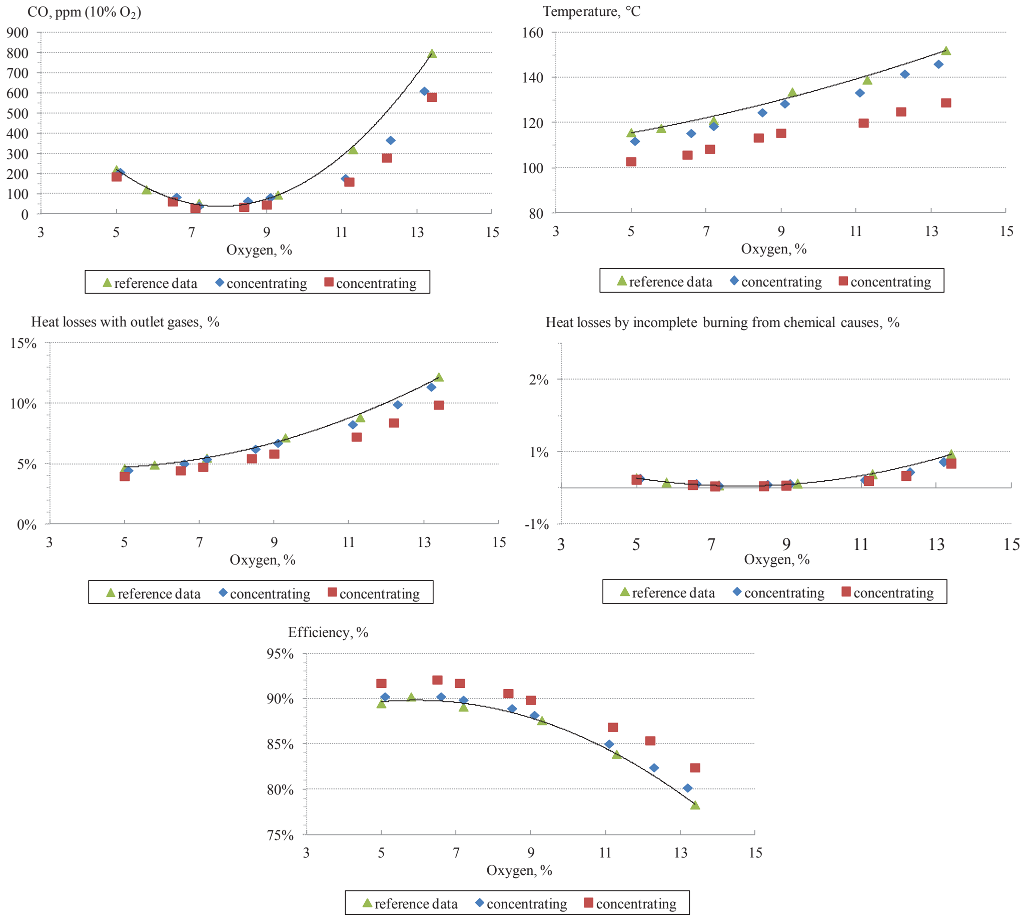

Figure 8. The effect of flame dissipation and concentration on the combustion process.

CONCLUSIONS

Experimental studies showed that air supply and oxygen concentration changes in flue gas have an important role in the combustion process. The minimum amount of CO and the highest efficiency of the boiler were achieved at the concentration of oxygen in the flue gas of 6–7%. Increasing or decreasing the concentration of oxygen in the flue gases promotes growth of the CO concentration and a decrease in the efficiency of the pellet boiler or vice versa.

The largest heat loss formed with outlet gases – an average from 5% to 14% depending on the oxygen concentration in the flue gases. The rise of the temperature during the increase in the oxygen concentration is the main reason of high heat losses with outlet gases. Heat loss due to mechanically incomplete combustion is generally higher at a high concentration of oxygen in the flue gas. The main reason for this is the flue gas velocity increase.

It was determined that the flue gas flow rate increases from 0.68 m s^{-1} at low concentrations of oxygen in the flue gas to 1.35 m s^{-1} at the oxygen content in the flue gas of 13%. The air and fuel mixing process deteriorates with an increase in the flue gas flow. This is evidenced by a growth of the amount of CO at high oxygen content.

An increase in the flue gas velocity promotes a decrease in the time spent by the flue gas in the heat exchanger. Therefore, the smaller the amount of heat transfers from the flue gas to water, which circulates through the boiler. This is evidenced by reduction of the efficiency of the boiler and the flue gas temperature rise with increasing the amount of oxygen in the flue gas.

Two methods for the boiler combustion process improvement and better air and fuel mixing were validated: flame dissipation and concentration. If we compare the two methods, concentration of the flame shows better results. A CO reduction of about 20 to 40 ppm was achieved at low concentrations of oxygen and 170 to 240 ppm at high concentrations of oxygen in the flue gas utilisation. The largest boiler efficiency improvement was achieved by using a cylinder with a spiral for flow swirl. The boiler efficiency increased by around 2% at low concentration of oxygen in exhaust gases and around 4% at high oxygen content. The efficiency improvement was achieved thanks to better air and fuel mixing and flue gas flow rate reduction, due to fuel combustion time increase, improved boiler heat exchange process, and decrease of the flue gas temperature.

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