Chemical and Process Engineering 2012, 33 (2), 231-242
DOI: 10.2478/v10176-012-0020-3

POLLUTANT EMISSION FROM A HEAT STATION SUPPLIED WITH AGRICULTURE BIOMASS AND WOOD PELLET MIXTURE

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Tests for combustion of hay and sunflower husk pellets mixed with wood pellets were performed in a horizontal-feed as well as under-feed (retort) wood pellet furnace installed in boilers with a nominal heat output of 15 and 20 kW, located in a heat station. During the combustion a slagging phenomenon was observed in the furnaces. In order to lower the temperature in the furnace, fuel feeding rate was reduced with unaltered air stream rate. The higher the proportion of wood pellets in the mixture the lower carbon monoxide concentration. The following results of carbon monoxide concentration (in mg/m^3 presented for 10% O_2 content in flue gas) for different furnaces and fuel mixtures (proportion in wt%) were obtained: horizontal-feed furnace supplied with hay/wood: 0/100 - 326; 30/70 - 157; 50/50 - 301; 100/0 - 3300; horizontal-feed furnace supplied with sunflower husk/wood: 50/50 - 1062; 67/33 - 1721; 100/0 - 3775; under-feed (retort) furnace supplied with hay/wood: 0/100 - 90; 15/85 - 157; 30/70 - 135; 50/50 - 5179; under-feed furnace supplied with sunflower husk/wood: 67/33 - 2498; 100/0 - 3128. Boiler heat output and heat efficiency was low: 7 to 13 kW and about 55%, respectively, for the boiler with horizontal-feed furnace and 9 to 14 kW and 64%, respectively, for the boiler with under-feed furnace.

Keywords: agricultural residue, wood, combustion, emission, heat station

1. INTRODUCTION

Biomass is a renewable and CO_2 neutral energy source. There are few furnaces in Poland designed specifically for firing agricultural residue pellets. Therefore, some customers try firing agricultural residue pellets in residential boilers equipped with wood pellet furnaces. The experimental study presented below examines the emission of pollutants during firing of pellets made from hay and sunflower husk separately and in co-combustion with wood pellets in two most known types of wood pellet furnaces with horizontal and under-feed (retort) fuel supply.

It is widely known that pollutant emission and boiler heat efficiency values measured by accredited laboratories for boiler producers are performed in stable conditions (Olsson et al., 2003; Venkataraman et al., 2001) and differ significantly from the ones measured in full scale heat stations during operation (Juszczak, 2010; Juszczak, 2011). This is why it is essential to perform experiments in full scale heat stations in real conditions.

Out of different biomass types, wood constitutes the most precious one, as it contains small amounts of ash, nitrogen and sulfur. In terms of different wood products for combustion, wood pellets for residential heating provide a possibility of using automated systems with higher burning efficiency and

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lower emission of incomplete combustion products as compared to wood log firing (Johanson et al., 2004).

Ash related problems such as slagging and deposit formation on the grate of residential wood pellet furnaces has been sometimes observed (Öhman et al., 2004). The quality of wood pellets used in all types of furnaces is very important, especially in case of residential heating because of slag formation on the grate. Some experiments made during wood pellet combustion in residential furnaces indicated initial sintering temperatures of wood pellet ash between 850 and 1025°C and for coniferous wood bark 866 ±7°C (Öhman et al., 2004). During wood pellet combustion very low concentration of hydrocarbons, especially CH_4 (only a few mg/m^3) was observed (Kjällstrand et al., 2004).

Considering limited availability of good quality wood pellets for residential combustion purposes, some European producers introduced other kinds of biomass within their commercial offers, namely pellets made from wood residues i.e. coniferous wood bark, as well as agricultural residues such as hay or sunflower husk.

Agricultural residues, which are the topic of this study, present a much higher content of ash, nitrogen and sulfur when compared to wood (Gible et al., 2008; Demirbas, 2004). The amount of ash and inorganic compounds, such as K_2O, Na_2O and SiO_2 in agricultural residue pellet raw material can result in ash related problems (Gible et al., 2008; Rybak, 2006). K_2O and SiO_2 content in ash are important parameters as these compounds can form eutectics lowering the sintering temperature of ash. The increased SiO_2 content most probably originates from contamination in form of quartz, sand or silicates during production, handling or storage of pellet raw material (Öhman et al., 2004). Also chlorine content is an important factor in biomass combustion as it can form KCl that melts at a low temperature. Therefore, it is recommendable to use additives, such as $Ca(OH)_2$ or dolomite that react with chlorine and impede KCl formation (Poskrobko et al., 2010a; 2010b; 2012).

Lower melting point of ash in case of agricultural residues, as compared to wood, requires periodical removal of ash and slag from the grate or /and burning at much lower temperatures (Werther et al., 2000). Obviously, it is possible to obtain low furnace temperature if air excess is higher than in case of wood pellet combustion but boiler heat efficiency is much lower. On the other hand, it is well known that unoxidized gaseous compounds, i.e. CO and hydrocarbons, are produced as a consequence of imperfect combustion conditions, which can be explained by commonly known criteria of good-quality firing: high temperature in the combustion chamber, proper mixing of air and combustible gases and long residence time (Colannino, 2006; Nussbaumer, 2003). Elevated air excess can contribute to the cooling of the combustion chamber, resulting in high CO emission and some authors (Johanson et al., 2004) indicate that there is a linear correlation between the concentrations of carbon monoxide (CO) and total organic carbon (TOC) for wood boilers, pellet furnaces and oil burners. Dust emission for poor combustion conditions of biomass is mainly due to carbonaceous particles (Wiinikka et al.,2006). Incomplete biomass combustion is a significant source of pollutants such as PAH (Verma et al., 2011), which presents a much higher global warming potential than carbon dioxide. Pollutant emission from combustion of some agricultural residue pellets i.e. tomato and cardoon residue pellets in a residential boiler was investigated and gave relatively good results for a mixture with wood pellets (González et al., 2004).

It is worth mentioning that the aforementioned problem of slagging during biomass combustion can be managed by using an additive which causes an increase in ash sintering temperature. There are several studies that address this issue. Such method was successfully performed e.g. during sunflower husk pellet firing in a boiler with high nominal heat output, where adding approx. 2 wt% of halloysite ($Al_4(OH)_8/Si_4O_{10}$ x 10 H_2O) caused an increase in ash sintering temperature from 800 to approx. 1050°C (Mroczek et al., 2011).

2. MATERIAL

The study examined hay and sunflower husk pellets of 8 mm in diameter and 15 to 40 mm in length. The chemical composition analysis gave the following results for the mentioned biomass types (Table 1):

Table 1. Ultimate analysis [wt %] and lower heating value of hay, sunflower husk and wood pellets determined on the dry basis

Parameters / Fuel	C	H	N	Ash	S	Cl	Moisture [%]**	Lower heating value [MJ/kg]*
Hay pellets	45.1	5.9	1.3	7.1	0.01	0.18	9.0	16.0
Sunflower husk pellets	51.4	5.0	0.6	1.9	0.60	0.10	8.5	18.5
Wood pellets	51.5	7.6	0.35	0.8	0.08	0.03	7.6	19.0

* measured in a laboratory belonging to Poznan University of Technology
** determined according to EN 12048, 1999

Potassium content in the examined pellets and their ash was not measured. Different studies show however that K_2O and SiO_2 content in ash for wood pellets is 0.065 and 0.125 wt%, dry basis, respectively (Öhman et al., 2004). As shown in other studies for sunflower husk pellets, potassium content in ash is 17.3 wt% and Si content is 26.2 wt% (Mroczek et al., 2011). In case of hay, the average value of K_2O and SiO_2 content in ash is 2459 ppm and 46.18 wt%, dry basis, respectively (Vassilev et al., 2010).

3. EXPERIMENTAL SET UP AND PROCEDURE

Experiments were carried out in two boilers in a heat station (Fig.1) located in a laboratory belonging to the Poznan University of Technology (Division of Heating, Air Conditioning and Air Protection, Institute of Environmental Engineering) in conditions resembling the ones existing in domestic boilers.

The boilers work alternately and cooperate with a 900 l water heat storage equipped with a special mixing device. This device enables water flow in the boiler only after reaching the temperature of 64°C. In the wood combustion process, this is crucial for minimizing soot formation by keeping the combustion chamber walls hot. During the experiments, heat was transferred to the atmosphere with a fan cooler located on the roof of the heating station. Usually it is recommended that boilers are equipped with a ceramic combustion chamber, which helps to maintain high combustion temperature during the entire burning cycle, resulting in decreasing emissions during the gas combustion phase and an increased energy yield (Johanson et al., 2004). None of the two boilers however possesses additional ceramic elements inside the combustion chamber and thus none is adjusted for proper wood pellet combustion.

Pellets were fired in two types of wood pellet furnaces frequently used in residential boilers: horizontal–feed (Fig.2) and under-feed (retort) furnace (Fig.3).

The horizontal-feed furnace (Fig. 2) was installed in a down-draft wood log boiler with a nominal heat output of 15 kW, replacing a fixed grate. The under-feed furnace (Fig.3) was installed in a pellet boiler with a nominal heat output of 20 kW. This furnace was equipped with a special slag removing device, however, in case of agricultural residue combustion it often turns out to not to be sufficient. Pellets are supplied from the hopper by means of a fixed-speed screw feeder and gravitationally fall into a small chamber. Subsequently, a horizontal fixed-speed screw pellet dispenser of each furnace introduces pellets to the burning region. Both devices are synchronized and always work simultaneously. In case of the horizontally-feed furnace, pellets are delivered through the front of the furnace, and in case of the under-feed furnace - under the fuel bed. In both furnaces fuel stream can be regulated manually by modifying operation and stand-by time of the screw pellet dispenser. Both pellet furnaces were equipped with their own electrically heated automatic ignition device.

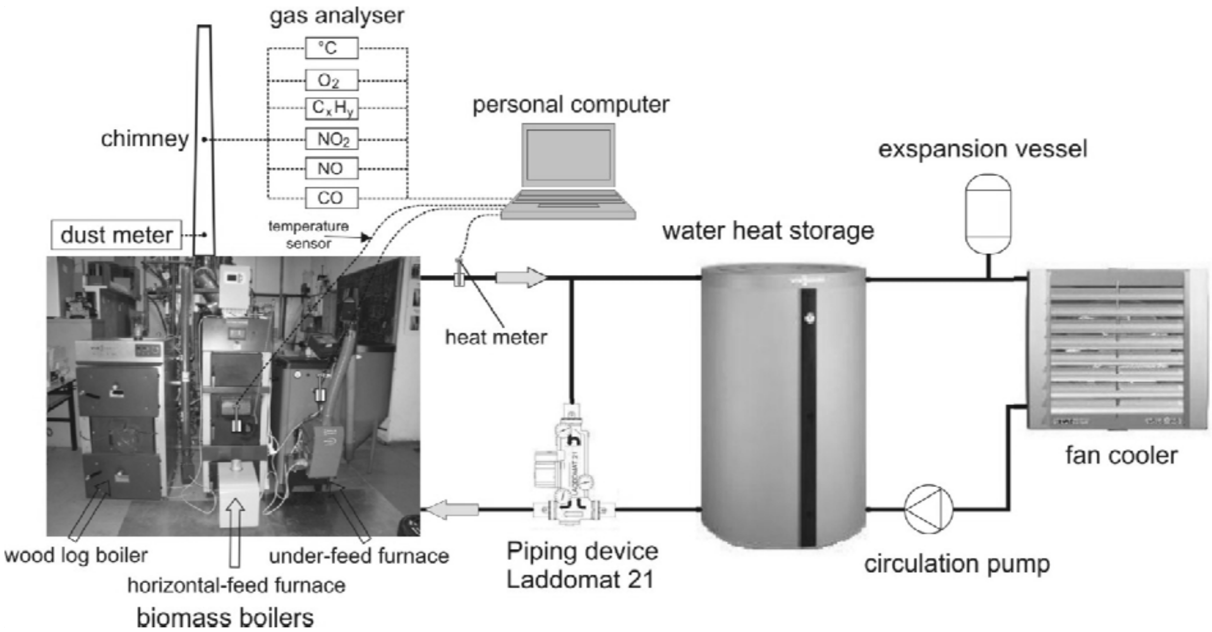

Fig. 1. Schematic layout of experimental set up

Fig. 2. Horizontal-feed wood pellet furnace, slag appears during hay pellet combustion

Air supply in both furnaces was provided by a fan integrated with the furnace. The boilers lack an automatic device with an oxygen probe (lambda sensor) that would measure oxygen concentration in the flue gas downstream the boiler. Air stream can be modified manually by fan speed regulation, ranging from 10 to 100% of its maximum value.

Fig. 3. Under-feed (retort) wood pellet furnace, slag can be observed during hay pellet combustion

Primary air enters the furnace through a perforated plate located at the bottom of both pellet furnaces. Secondary air is inserted above the grate at one level with flow direction optimized to ensure stable combustion. The fan stops operating when boiler water temperature reaches its maximum value of 85°C and reinitiates after the temperature decreases 5°C below this maximum value.

The conditions created for research purposes were favorable for slagging phenomenon reduction. In order to reduce the temperature in the combustion chamber and therefore limit the ash melting, sintering and slagging phenomenon that contributes to the increased CO and C_xH_y concentrations, the stream of agricultural residue pellets was being reduced with constant air supply, while observing the pellet firing process inside the furnace through a sight glass, measuring the temperature in the combustion chamber and monitoring the CO concentration indications of the flue gas analyzer.

The experiments lasted for ten continuous hours for each combustion device (boiler with a pellet furnace) and for each fuel type (a mixture of agricultural residues and wood) with uninterrupted furnace operation. However, for mean parameter value calculation, duration time of the experiment was divided into one-hour measurement cycles (test runs) - because of the slagging phenomenon significant parameter value differences were expected. All the obtained data (measured continuously) were transmitted to a personal computer via a data acquisition system. For each test run, parameter values were collected every 5 seconds, averaged and mean values were calculated. This time interval of data gathering was optimal as the measured values were not changing very quickly. Mean values for several consecutive test runs were used to obtain the overall mean value for each type of experiment. Uncertainty intervals were calculated for all measurement results with a 0.95 probability.

Gas pollutant concentrations in the flue gas downstream the boiler as well as flue gas temperature were measured using Vario Plus (MRU) flue gas analyzer (Germany). CO and C_xH_y concentrations were measured using the infrared procedure. Oxygen (O_2), nitric oxide (NO) nitrogen dioxide (NO_2) concentrations were measured with electrochemical cells. Gas analyzer calculated NO_x concentration as a total of NO (transformed to NO_2) and NO_2 concentration. The flue gas analyzer also calculated air excess ratio and chimney loss (needed for boiler heat efficiency estimation). Dust concentration in the chimney was measured several times using a gravimetric dust meter equipped with isokinetic aspiration. Fuel stream was measured several times using a weighing device. Temperature in the combustion chamber was measured about 0.20 m above the flame with a radiation shielded thermocouple PtRhPt connected additionally with a temperature meter for value comparison. Heat received by the boiler water and boiler heat output were measured with an ultrasonic heat meter.

4. RESULTS AND DISCUSSION

In the attempt to reduce the temperature in the combustion chamber, fuel stream was decreased until reaching the value of approx. 5.0 kg/h or lower (Table 2) with constant air supply. Therefore, air excess ratio was elevated with different values for different tests, chimney loss was high and boiler heat efficiency was low as compared to wood pellet combustion. Throughout the course of the experiments, the concentration of hydrocarbons (calculated to CH_4) was negligible and dust concentration did not exceed 50 mg/m^3 (presented for 10% O_2 content in flue gas), which is why these values are not subjected to further analysis. Boiler heat efficiency during wood pellet firing was not satisfactory due to excessive air stream supplied for combustion, reaching 55% in case of horizontal-feed pellet furnace and 64% in case of under-feed pellet furnace.

A bigger variation of CO concentration was observed for agricultural residue pellet combustion than for wood pellet combustion (Fig. 4-7). This is most probably caused by the generated slag that limits air access to the fuel. The amount of slag is correlated with the proportion of agricultural residues in the mixture. This phenomenon was observed in the furnace through the sight glass. Figures 4 - 7 show that CO concentration increased as hay and sunflower husk content increased in the mixture with wood.

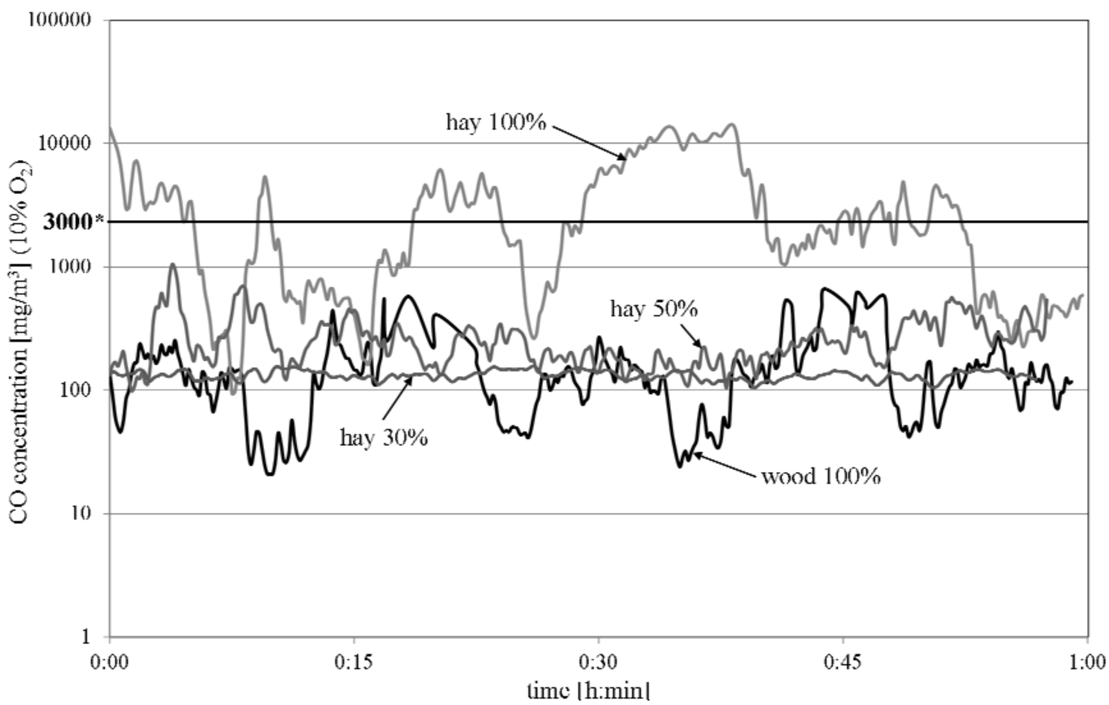

Fig. 4. Time-dependent CO concentration in the flue gas, relative to the proportion of hay pellets in the mixture with wood pellets for the horizontal-feed pellet furnace (selected representative test run);
* permitted CO concentration value 3000 mg/m^3, presented for 10% O_2 content in flue gas (PN-EN 303-5, 2004)

Mean parameter values obtained during the selected representative test runs and visualized in Figures 4 - 7 are presented in Table 2 and 3. As presented in Table 2, flue gas temperature values are very high, which results from the fact that an old construction downdraft boiler for wood logs with very low heat efficiency was used. Dust concentration in case of both furnaces was low (slightly higher for the horizontal-feed furnace than for the under-feed furnace) and was correlated with ash content in the fuel. In case of the horizontal-feed furnace air stream was relatively high as compared to the under-feed furnace (see oxygen concentration in Table 2 and Table 3). Additionally the horizontal-feed furnace construction in form of a rectangular channel favors a higher emission of dust from the furnace than in case of the under-feed furnace.

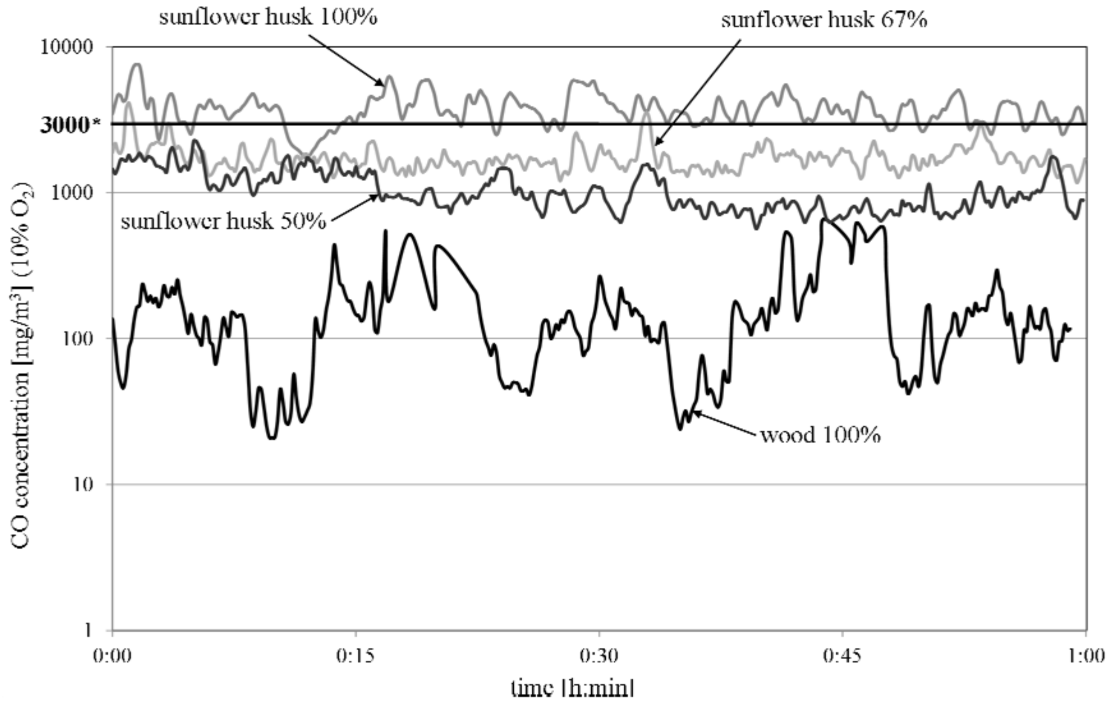

Fig. 5. Time-dependent CO concentration in the flue gas, relative to the proportion of sunflower husk pellets in the mixture with wood pellets for horizontal-feed pellet furnace (selected representative test run);
* permitted CO concentration value 3000 mg/m^3, presented for 10% O_2 content in flue gas (PN-EN 303-5, 2004)

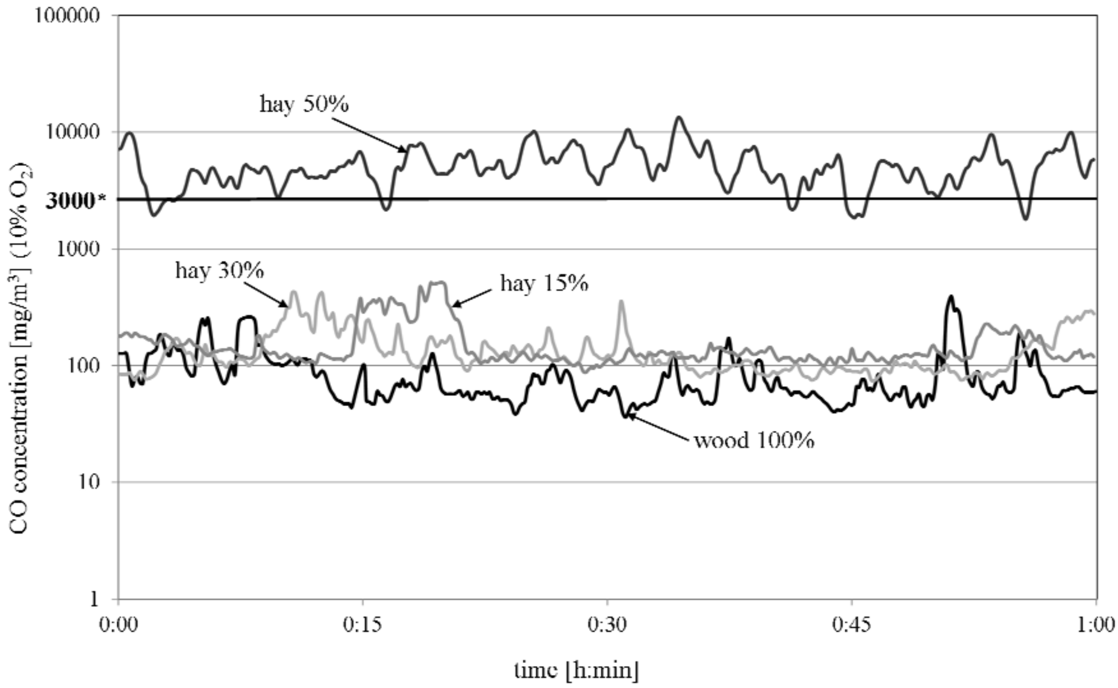

Fig. 6. Time-dependent CO concentration in the flue gas, relative to the proportion of hay pellets in the mixture with wood pellets for under-feed pellet furnace (selected representative test run)
* permitted CO concentration value 3000 mg/m^3, presented for 10% O_2 content in flue gas (PN-EN 303-5, 2004)

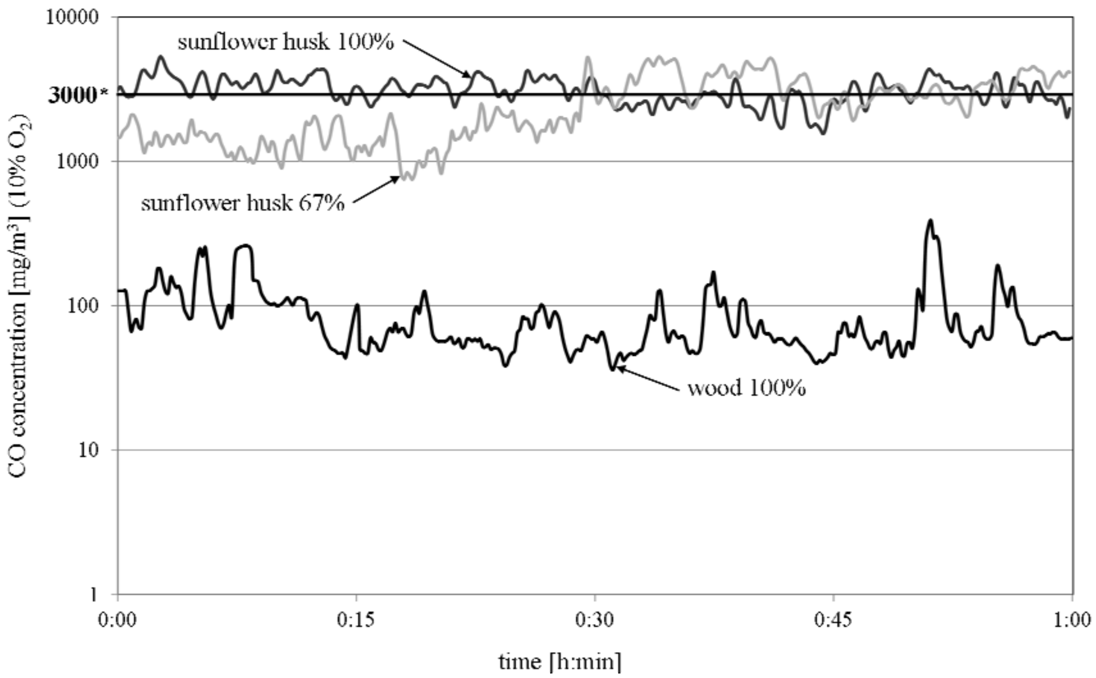

Fig. 7. Time-dependent CO concentration in the flue gas, relative to the proportion of sunflower husk pellets in the mixture with wood pellets for under-feed pellet furnace (selected representative test run);
* permitted CO concentration value 3000 mg/m^3, presented for 10% O_2 content in flue gas (PN-EN 303-5, 2004)

Table 2. Horizontal-feed furnace. Mean parameter values from selected representative test runs presented in Figures 4-5 (a mixture of hay/sunflower husk pellets and wood pellets as compared to wood pellets)

Horizontal-feed furnace parameters	Hay / wood [wt %]				Sunflower husk / wood [wt %]		
	0/100	30/70	50/50	100/0	50/50	67/33	100/0
Combustion chamber temperature in [°C]*	781	762	750	776	535	685	531
Flue gas temperature [°C]	273	265	287	270	275	258	235
Boiler heat output [kW]	13.1	12.1	10.3	12.7	8.7	8.2	7.1
O_2 [%]	9	16	17	14	12	14	16
CO concentration (10% O_2) [mg/m^3]	326	157	301	3300	1062	1721	3777
NO_x concentration (10% O_2) [mg/m^3]	36	47	63	123	226	209	221
Dust concentration (10% O_2) [mg/m^3]	8	27	32	45	15	21	25
Fuel mass stream [kg/h]	4.2	3.9	3.5	5.1	3.1	3.5	2.9
Boiler heat efficiency [%]	59	62	61	56	54	45	48

* measured about 0.20 m above flame

During the experiments significant amount of deposits appeared on heat exchange surfaces. Low boiler heat efficiency was caused by excessive air stream and low temperature in the combustion chamber. Fuel feeding rate was being changed with unaltered air stream in order to obtain the lowest possible carbon monoxide concentration, which is why oxygen concentration varies significantly for different test runs.

Table 3. Under-feed furnace. Mean parameter values from selected representative test runs presented in Figures 6-7 (a mixture of hay/sunflower husk pellets and wood pellets as compared to wood pellets)

Under-feed furnace parameters	Hay / wood [wt %]				Sunflower husk/wood [wt %]	
	0/100	15/85	30/70	50/50	67/33	100/0
Combustion chamber temperature [°C]*	548	575	588	694	529	551
Flue gas temperature [°C]	153	182	175	166	159	162
Boiler heat output [kW]	11.1	13.1	14.0	14.2	9.8	12.1
O_2 [%]	6	8	7	8	14	15
CO concentration (10% O_2) [mg/m^3]	90	157	135	5179	2498	3128
NO_x concentration (10% O_2) [mg/m^3]	57	196	381	289	277	292
Dust concentration (10% O_2) [mg/m^3]	5	12	15	16	13	18
Fuel mass stream [kg/h]	3.1	4.2	4.4	4.7	3.0	3.6
Boiler heat efficiency [%]	68	61	63	62	63	65

* measured about 0.20 m above the flame

Un-burnt coal was examined in the slag and did not exceed 1 wt% of dry basis, both for sunflower husk and hay pellets. Also, SiO_2, CaO, MgO i K_2O content in bottom ash was determined with the following results (wt% of dry basis): wood pellets 11.9; 45.9; 1.1; 0.7; sunflower husk pellets 18.2;14.5; 7.8; 19.3; hay pellets 19.3; 12.1; 6.3; 14.2, respectively.

Significant oscillations of CO concentration for hay alone (100 wt%) in Fig.4 and for wood alone (100 wt%) in Figure 4, 5 and 7 are due to the application of long intervals in fuel feeding cycles (of approx. 8-10 seconds) for low fuel feeding rate.

In under-feed pellet furnace, firing of hay pellets alone (without mixing them with wood pellets) was not successful as after several hours the amount of slag was so big that the temperature in the furnaces decreased to less than 200°C and combustion got hampered.

Mean values of carbon monoxide and nitrogen oxides NO_x concentration from 10 one-hour test runs for each type of fuel mixture and both furnace types were shown in Figures 8 and 9.

Figure 8 shows a notable increase of carbon monoxide concentration in relation to the proportion of hay and sunflower husk pellets in the mixture with wood pellets for both studied furnaces. Figure 9 demonstrates that the NO_x concentration increase is caused by the increase of agricultural residue pellet proportion in the mixture with wood pellets, due to the fact that hay and sunflower husk contain much more nitrogen than wood. The temperature in the combustion chamber in all experiments that analyzed different fuel mixtures did not vary significantly and the oxygen concentration was excessive in all cases. Therefore, the influence of temperature and oxygen concentration on the concentration increase of nitrogen oxides is very low.

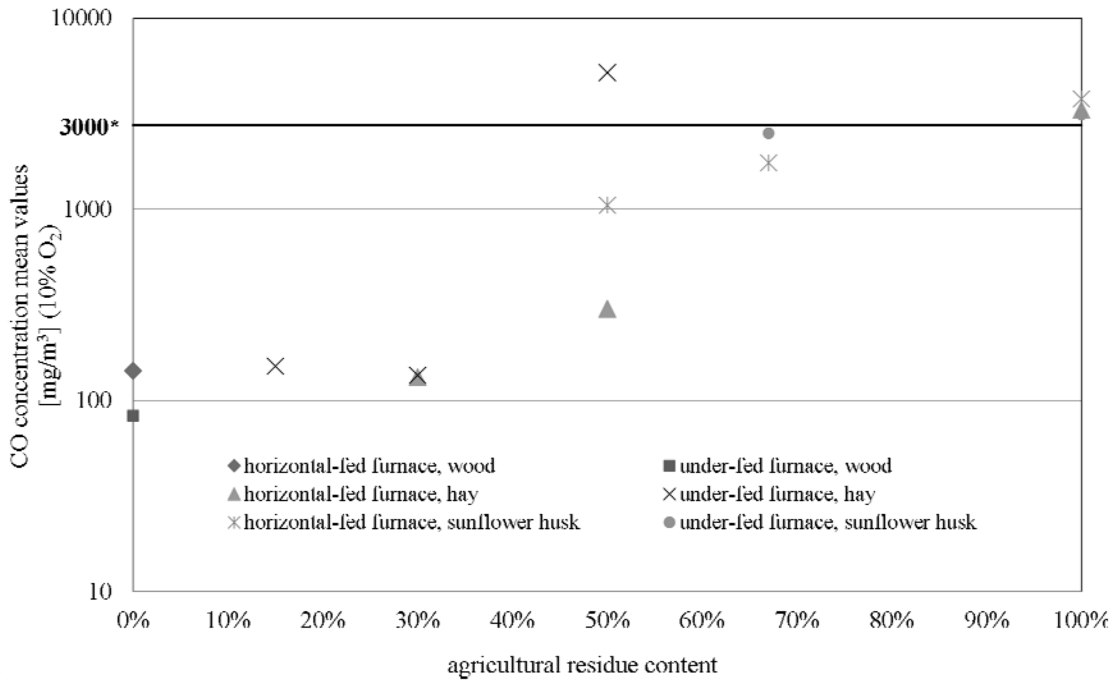

Fig. 8. Mean values of CO concentration in the flue gas from 10 one-hour test runs for each type of fuel mixture and for both furnaces (horizontal-feed and under-feed) in relation to hay and sunflower husk pellets content in the mixture with wood pellets

* permitted CO concentration value 3000 mg/m^3, presented for 10% O_2 content in flue gas (PN-EN 303-5, 2004)

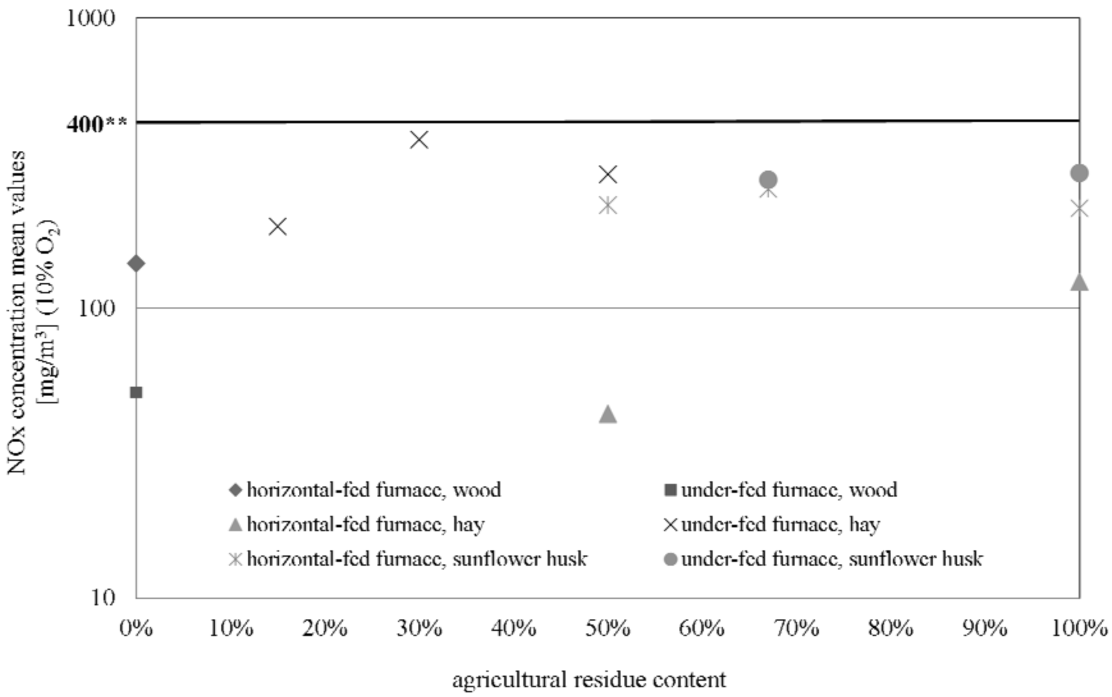

Fig. 9. Mean values of NO_x concentration in the flue gas from 10 one-hour test runs for each type of fuel mixture and for both furnaces (horizontal-feed and under-feed) in relation to hay and sunflower husk pellets content in the mixture with wood pellets;

** NO_x concentration value 400 mg/m^3 (presented for 10% O_2 content in flue gas) required to obtain the Polish ecological certificate

Some researchers also noticed a positive influence on the combustion process when adding wood materials to agricultural residues, namely in a mixture of vine shoots and industrial cork residue (Mediavilla et al., 2009). The best results were obtained with a fuel mixture composition of 30 wt% vine shoots and 70 wt% industrial cork residue, in which case carbon monoxide concentration was 1700 mg/m^3 (presented for 10% O_2 content in flue gas). For comparison purposes, it is worth indicating that carbon monoxide concentration while firing cork residue pellets or vine shoots alone was higher (3100 and 9000 mg/m^3, respectively). Similar conclusions were drawn for combining tomato residues, olive stones and cardoon with wood pellets (González et al., 2004). The lowest carbon monoxide concentration was obtained for the following mixtures: tomato residues/wood (75/25 wt%) 5159 ppm, tomato residues/ olive stones (50/50 wt%) 2013 ppm, cardoon/wood (50/50 wt%) 437 ppm, olive stones/ wood (25/75 wt%) 4157 ppm. In general terms, the higher the proportion of wood pellets in the mixture, the lower carbon monoxide concentration in the flue gas.

One should remember that firing agricultural residues is much more difficult than firing wood due to the necessity of applying lower combustion temperature. Even when applying special furnaces designer for a specific biomass type (González et al., 2004; Verma et al., 2011) it is hard to obtain carbon monoxide concentration as low as in case of wood pellets.

5. CONCLUSION

Having analyzed the study results, it can be concluded that hay and sunflower husk pellets can be fired in the studied wood pellet furnaces with some difficulties. However, to ensure relatively low carbon monoxide concentration, they need to be fired in a mixture with wood pellets. It can also be stated that the higher the proportion of wood pellets in the mixture the lesser slag production and the lower carbon monoxide concentration in the flue gas. The concentration of nitrogen oxides NO_x (mostly NO), for combustion chamber temperature below 1000°C, mainly depends on nitrogen content in the fuel, which in the analyzed case translates to the proportion of agriculture biomass (hay and sunflower husks) pellets in the mixture. The magnitude of carbon monoxide concentration constitutes an important indicator of the feasibility of firing agriculture biomass pellets in wood pellet furnaces. Also, the author has an impression that the significant increase of carbon monoxide concentration value is caused mainly by the increasing amount of slag generated in the furnace.

I would like to thank the technical workers and students of Poznan University of Technology for their help during the research. This work was carried out as a part of the research project PB-13/615/08BW sponsored by Poznan University of Technology.

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Received 16 January 2012
Received in revised form 01 March 2012
Accepted 26 March 2012