

## SPECIFIC EMISSIONS FROM BIOMASS COMBUSTION

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**ABSTRACT.** This paper deals with determining the specific emissions from the combustion of two kinds of biomass fuels in a small-scale boiler. The tested fuels were pellets made of wood and pellets made of rape plant straw. In order to evaluate the specific emissions, several combustion experiments were carried out using a commercial 25 kW pellet-fired boiler. The specific emissions of CO, SO<sub>2</sub> and NO<sub>x</sub> were evaluated in relation to a unit of burned fuel, a unit of calorific value and a unit of produced heat. The specific emissions were compared with some data acquired from the reference literature, with relatively different results. The differences depend mainly on the procedure used for determining the values, and references provide no information about this. Although some of our experimental results may fit with one of the reference sources, they do not fit with the other. The reliability of the references is therefore disputable.

**KEYWORDS:** specific emissions, biomass combustion, small-scale boilers.

### 1. INTRODUCTION

Renewable energy sources have recently received a high level of support, mainly because the EU has a commitment to produce 20 % of its primary energy from renewable energy sources by 2020. In 2010, the ratio of renewable energy sources in primary energy sources (PES) in the Czech Republic was 6.4 % [1]. The mostly widely-used renewable energy source is biomass, which forms almost 70 % of PES, and is the most promising renewable energy source for the future. The amount of energy produced from biomass does not provide major competition for other primary energy sources. However, it is taking a more and more important position in the energy mix. Most of the biomass used for heating purposes is consumed for domestic heating (almost 60 %). This amounts to about 30.7 PJ annually in Czech households [2].

Typical biomass boilers for domestic purposes are in the small-scale power capacity range, usually not exceeding 50 kW of nominal power output. Until the end of 2012, no limits were set on the levels of gaseous pollutants released during the operation of boilers of this size. In 2012, an amended Air Protection Act [3] was passed, which for the first time introduced emission limits for heat sources with nominal power capacity below 300 kW. This law specifies new limits for carbon monoxide (CO), total organic carbon and particulate matter. Although it is not fully clear from the law whether emissions monitoring is also obligatory for households, it is necessary to know the levels of gaseous pollutants when evaluating local air pollution models. Monitoring the emissions in domestic boilers is technically complicated and also expensive. It is therefore important to look for other ways to determine the emission levels. One option is to determine so-called specific emissions. A specific

emission is a unit that expresses the mean amount of monitored pollutants released from a combustion process, related to a certain variable connected with the fuel and the specific operating conditions of a boiler of a certain type [4]. Generally, the specific emission can be related to any unit connected with the measured value. In this paper, emissions of CO, SO<sub>2</sub> and NO<sub>x</sub> are related to a unit of burned biomass mass ( $SE_{\text{mass}}$ ), a unit of low heating value of burned fuel ( $SE_{LHV}$ ), and a unit of produced heat.

### 2. EXPERIMENTAL PROCEDURE

The main goal of this work was to evaluate specific emissions from representative fuels based on wood and agricultural biomass, and to compare the results with previously published data. The main difference compared to the data obtained from the literature is that the experiments were performed in a boiler that had already been in operation for several years, and therefore represents real-life operating conditions. This approach avoids the typical “laboratory” conditions that are widely used in testing procedures for small-scale biomass boilers.

A commercially available automatic hot water boiler for biomass pellets with front fuel loading was used for the experiments. The fuel is loaded from a container located next to the boiler, using a screw conveyor. There are individual inputs of primary and secondary air. The nominal capacity of the boiler specified by the manufacturer is 25 kW for wood pellets. The nominal capacity for pellets made of agricultural fuels is 18.5 kW. To compare these two kinds of fuels, the boiler output was set to 18.5 kW for both fuels. The power capacity of the boiler was controlled by adjusting the fuel loading interval. The primary and

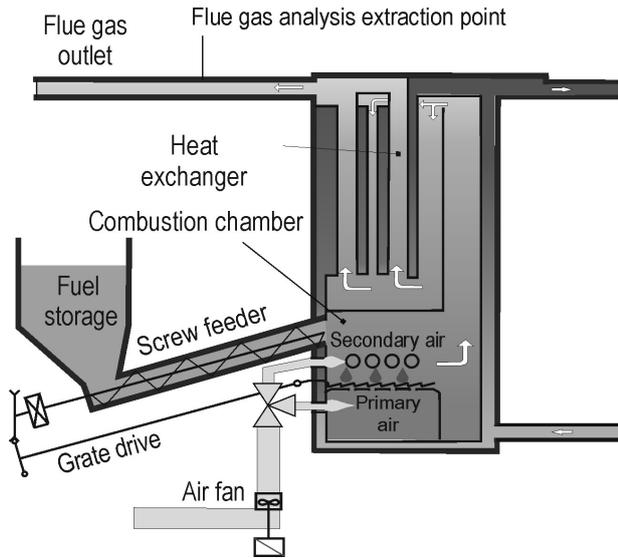


FIGURE 1. Simplified scheme of the boiler.

secondary airflow are dependent on each other, because they are provided by a single ventilator that cannot be directly controlled. Flaps can control the primary and secondary combustion air. The boiler is also equipped with a flue gas recirculation system that is controlled by the revolutions of the recirculation fan. A simplified scheme of the boiler is shown in Figure 1. The properties of the tested fuel samples are summarized in Table 1.

The key point of the evaluation of specific emissions is to make an analysis of the composition of the flue gases. The sampling point for online emissions analysis is located in the exhaust tube, before the extraction point for flue gas recirculation, as shown in Figure 1. Each experiment lasted for two hours under stable operating conditions of the boiler. The composition of the flue gas was continuously analysed during this period, and some other operating parameters of the boiler were also monitored. The mean concentrations of  $O_2$ ,  $CO_2$ ,  $CO$ ,  $NO_x$  and  $SO_2$  were evaluated after the experiment, and also the standard deviations of the time series. The values were measured in volume fraction concentration, and were converted to mass concentrations that are related to dry flue gas at normal pressure and temperature and reference oxygen content, using the equation

$$C_m^X = C_V^X \frac{M_X p_{ref}}{RT_{ref}} \frac{21 - O_{2,ref}}{21 - O_{2,meas}}, \quad (1)$$

where  $C_V^X$  is the measured volume concentration of the given component X in the volume ppm,  $M_X$  is the molar mass in g/mol,  $p_{ref}$  is reference pressure 101.325 kPa,  $R$  is a universal gas constant equal to 8.3143 J/(K mol),  $T_{ref}$  is the reference temperature 273.15 K,  $O_{2,ref}$  is the reference oxygen content (for this purpose 10 %, which is set by law), and  $O_{2,meas}$  is the measured oxygen content in volume %. The final unit of mass concentration of the flue gas component is mg/(Nm<sup>3</sup>). Nitrogen oxides are calculated as NO<sub>2</sub> [5].

	Wood pellets	Rape plant straw pellets
$LHV$ [MJ/kg]	16.35	15.13
$W^r$ [%]	7.8	9.3
$A^r$ [%]	1.5	8.4
$C^{daf}$ [%]	51	54.5
$H^{daf}$ [%]	6.9	7.1
$N^{daf}$ [%]	0.3	1
$S^{daf}$ [%]	0.003	0.06

TABLE 1. Basic fuel properties.

First, it is necessary to calculate the theoretical volume of the flue gas from the elemental composition of the fuel. Using oxygen concentration, the theoretical volume of the flue gas is converted to the real volume of flue gas. Finally, the specific emission, which is related to the mass of the fuel  $SE_{mass}$ , is obtained by multiplying by the recalculated mass concentration of a flue gas component:

$$SE_{mass}^X = V_{FG}^{real} C_m^X, \quad (2)$$

where  $V_{FG}^{real}$  is the real volume of flue gas and  $C_m^X$  is the mass concentration of component X. The calculation of  $SE_{LHV}$  is based on converting the weight of the fuel to the recoverable energy stored in it:

$$SE_{LHV}^X = \frac{SE_{mass}^X}{LHV}, \quad (3)$$

where  $LHV$  is the low heating value in MJ/kg. This provides a different way to compare fuels. In this case, the differences are not fully apparent due to the quite similar low heating values of the two fuels.

$SE_{output}$  is related to a produced kilowatt-hour of heat energy:

$$SE_{output}^X = \frac{SE_{mass}^X \eta_K}{LHV}, \quad (4)$$

where  $\eta_K$  is the efficiency of the boiler and  $LHV$  is the low heating value in kWh/kg. It incorporates the boiler efficiency, and thus includes the type of combustion equipment and the real operation conditions of the boiler. The efficiency of the boiler was obtained by balancing the power output in hot water and the power input in the fuel.

### 3. RESULTS AND DISCUSSION

Time series of emissions of  $CO$ ,  $NO_x$  and  $O_2$  from combustion experiments with wood pellets and rape plant straw pellets are shown in Figures 2 and 3. The average volume emission concentration values from the measurements, and the values converted to the mass concentration at standard conditions and the reference concentration of oxygen are presented

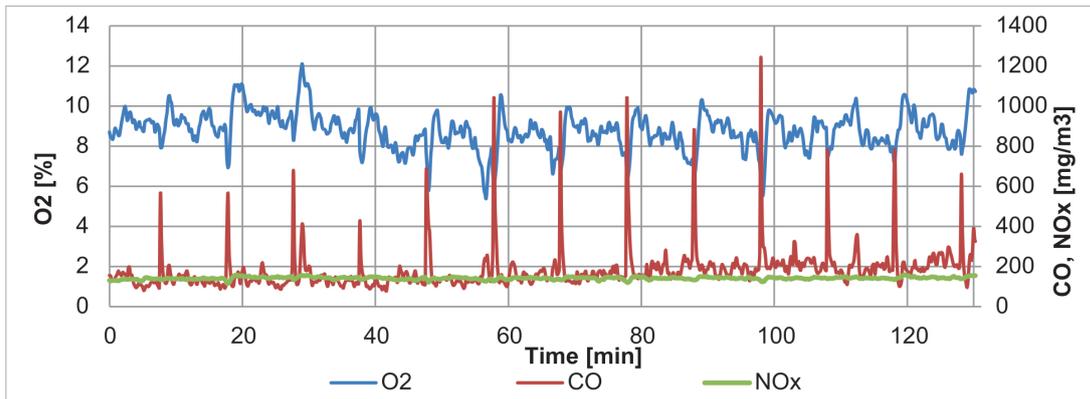


FIGURE 2. Time series of emissions from the combustion experiment with wood pellets.

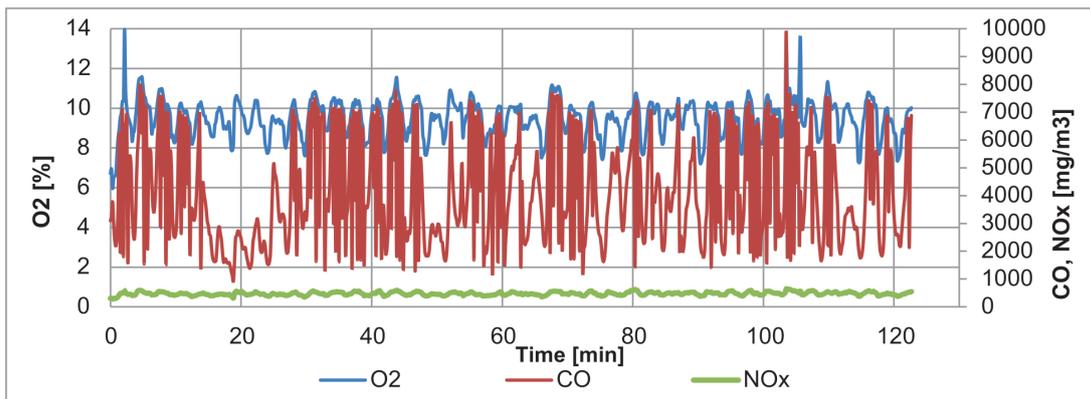


FIGURE 3. Time series of emissions from the combustion experiments with rape plant straw pellets.

in Table 2. Recently, only the CO emission limit (3000 mg/Nm<sup>3</sup>) was valid for biomass combustion in a boiler with automatic fuel loading up to a capacity of 65 kW. A comparison between the measured values and the emission limits shows that the combustion of rape plant straw pellets in this boiler does not comply with the CO emission limit.

Three kinds of specific emissions were evaluated from the measured data: the specific emission related to the mass of the fuel ( $SE_{mass}$ ), related to the low heating value of the fuel ( $SE_{LHV}$ ), and related to the produced quantity of heat ( $SE_{output}$ ). The calculated emission factors are given in Table 3.

The data in Tables 2 and 3 and in Figures 2 and 3 shows that the wood pellets generally produce lower amounts of pollutants than the rape straw pellets. The biggest difference between the fuels is in CO emissions, which are indicators of the quality of the combustion process. When wood pellets were combusted, there was much better combustion stability, and the boiler output was at the set value. The peaks of the CO emissions, as shown in Figure 2, are given by the grating period, which was set to 10 minutes. Combustion of the rape plant straw pellets produced worse characteristics. The performance fluctuated greatly, and it was necessary to set a lower grating period (2 minutes), due to the higher ash content, and due to the lower softening temperature of the ash and its

tendency to sinter. The boiler efficiency was lower when these pellets were used (about 59 %; whereas for wood pellet combustion the efficiency was 71 %).

The SO<sub>2</sub> emissions for both fuels were very low due to the low content of combustible sulphur. Emissions of nitrogen oxides are partly dependent on the nitrogen content in the fuel. It is noticeable that the NO<sub>x</sub> emissions from the rape plant straw pellets are more than three times higher than the emissions from the wood pellets, and this corresponds to the nitrogen content in the fuels, as shown in Table 1.

The measured specific emissions were compared with specific emissions taken from the EMEP/EEA Emission Inventory Guidebook 2009 – part B – 1.A.4. small combustion (EEA) [6], and with specific emissions supplied by the Czech Hydrometeorological Institute [7] (CHMI) [4]. The EEA values are for small boilers burning wood and similar wood wastes, with a nominal capacity lower than 50 kW. The CHMI values are for wood combustion. A comparison is shown in Table 4. Neither of the published sources contains data for agricultural biomass fuels.

As shown in Table 4, the comparison with previously published data on specific emissions is very interesting. Two reference sources were taken for comparison. One was published in 2003 (CHMI), and the other in 2009 (EEA). Unfortunately, details of the testing procedure are unknown. The EEA source published

Fuel		Volume emission concentration (measured) [ppm]			Mass emission concentration (converted) [mg/Nm <sup>3</sup> ]		
		CO	NO <sub>x</sub>	SO <sub>2</sub>	CO	NO <sub>x</sub>	SO <sub>2</sub>
		<b>Wood pellets</b>	AM	165	77	0.32*	183
	SD	112	4	0.52*	106	6	1.25*
<b>Rape plant straw pellets</b>	AM	3381	240	0.43*	4121	475	1.15*
	SD	1426	16	1.62*	1906	58	4.42*

TABLE 2. Measured concentrations of flue gas components. AM – Arithmetic mean; SD – standard deviation; \* – value affected by inaccuracy of the measurement technique, which was not sufficiently precise when measuring in the low concentration range.

Fuel		$SE_{mass}$			$SE_{LHV}$			$SE_{output}$		
		CO	NO <sub>x</sub>	SO <sub>2</sub>	CO	NO <sub>x</sub>	SO <sub>2</sub>	CO	NO <sub>x</sub>	SO <sub>2</sub>
		[ $\frac{g}{kg}$ ]	[ $\frac{mg}{kg}$ ]	[ $\frac{mg}{kg}$ ]	[ $\frac{g}{MJ}$ ]	[ $\frac{mg}{MJ}$ ]	[ $\frac{mg}{MJ}$ ]	[ $\frac{g}{kWh}$ ]	[ $\frac{mg}{kWh}$ ]	[ $\frac{mg}{kWh}$ ]
<b>Wood pellets</b>	AM	1.57	1223	6.70*	0.10	75	0.41*	0.25	191	1*
	SD	0.917	52.2	10.7*	0.056	3.192	0.66*	0.14	8.16	1.7*
<b>Rape plant straw pellets</b>	AM	37.3	4292	10.42*	2.46	284	0.69*	5.17	595	1.5*
	SD	17.2	520	39.9*	1.139	34	2.65*	2.39	72.2	5.55*

TABLE 3. Evaluated specific emissions. AM – Arithmetic mean; SD – standard deviation; \* – value affected by inaccuracy of the measurement technique, which was not sufficiently precise when measuring in the low concentration range.

Pollutant	EEA	CHMI	Wood pellets	Rape plant straw pellets
CO	4000	68,5	100	2460
NO <sub>x</sub>	120	205.5	75	284
SO <sub>2</sub>	30	68.5	0.41	0.69

TABLE 4. Comparison between measured  $SE$  and  $SE$  available from EEA and CHMI, values in g/GJ.

extremely high specific emissions for carbon monoxide. This value seems to be unreliable, since our experimental results indicate much lower values. Even for the case of rape plant straw pellets, which were found to be very difficult to burn (ash deformation) and which produced very high CO concentration levels, the specific emission is about one half of the published value. From this point of view, the CHMI source, which corresponds well with the measured specific emission for wood, seems to be a more reliable value. However, the NO<sub>x</sub> specific emissions from the EEA source seem to be more reliable. The specific emission from CHMI is closer to the value for rape plant straw, which is extremely rich in fuel nitrogen. The EEA value corresponds better with the measured value for wood, which was also a tested fuel in the publication. However, there is an important question regarding the experimental boiler, which is also not specified in the reference books. Developments in boilers between 2003 and 2009 resulted in a significant improvement in efficiency and in reduced emission levels. The specific

emissions should therefore generally be lower in the data from EEA (2009) than in the data from CHMI (2003). However, this is true only for NO<sub>x</sub>.

Finally, the specific emissions for SO<sub>2</sub> in both sources are completely different from the measured data. There is no apparent explanation for this big difference. The electrochemical cell measurement technique that was applied for SO<sub>2</sub> is not sufficiently accurate when measuring in the low concentration range, and may therefore have been a source of some errors in the measured concentrations.

#### 4. CONCLUSIONS

Two types of biofuels, wood pellets and rape plant straw pellets, were examined. Combustion experiments were performed in an automatic pellet boiler, and the emissions were measured. The specific emissions related to the weight of the fuel, the calorific value of the fuel and the amount of produced heat were determined on the basis of the emission concentration measurements and stoichiometric calculations.

The wood pellets generally show much lower emission concentrations of harmful pollutants than the rape plant straw pellets. Rape plant straw pellets are a typical representative of agricultural biomass with a relatively high nitrogen content. They produce several times higher specific emissions of NO<sub>x</sub> than wood. Both fuels have a very low combustible sulphur content, so the SO<sub>2</sub> emission factors are negligible.

A comparison between the calculated specific emissions and the data taken from the reference literature provided inconsistent results. The specific emissions for CO correspond better with the CHMI data, while the values for NO<sub>x</sub> correspond better with the EEA data. Moreover, there are some uncertainties regarding the experimental procedure and the boiler used in the published results. Developments in boiler construction leading to better efficiency and lower emissions should have been reflected in lower specific emissions in the EEA data, which was gathered six years later than the CHMI data. However, this did not happen for carbon monoxide. Verification of this value favours the older value provided by CHMI, and the more recent EEA data may be considered as unreliable.

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