MIDDLE POMERANIAN SCIENTIFIC SOCIETY OF THE ENVIRONMENT PROTECTION

Rocznik Ochrona Środowiska

Volume 21. Year 2019 ISSN 1506-218X 378-394

Comparison and Assessment of Emission Factors for Toxic Exhaust Components During Combustion of Biomass Fuels

*Grzegorz Zając, Joanna Szyszlak-Bargłowicz, Tomasz Słowik**
University Life Sciences of Lublin, Poland
**corresponding author's e-mail: tomasz.slowik@up.lublin.pl*

1. Introduction

One of the basic factors determining the state of the environment, and thus significantly affecting the quality of life, is air cleanliness. Among the anthropogenic sources of pollutant emissions the most significant are fuel combustion processes, in which power industry plays the main role, including small power industry. The types of pollutants introduced into the air during combustion of fuels depend mainly on the type of fuel burned. The dominating role in the energy sector is played by conventional fuels: hard and brown coal, natural gas and crude oil. These fuels contribute to significant environmental pollution and the increase of greenhouse effect.

The European Union pays special attention to the broadly understood protection of the environment, as a result of which member states focus on ecological education, promotion of new energy sources, reclamation of post-mining areas, nature protection and rational waste management (Grudziński & Stala-Szlugaj, 2016). The desired sources of energy in the energy and ecological policy of Poland and the European Union are the renewable ones, in particular biomass, understood as any organic substance of plant or animal origin, as well as all the derived substances obtained from the transformation of such raw materials (Borycka, 2009).

Biomass is a renewable energy source, the use of which has recently grown worldwide. It is mainly used for heating households, as an alternative to fossil fuels (Lasek et al., 2018; Pastorello et al., 2011). However, the combustion of biomass, like fossil fuels, releases pollutants into the air, such as: carbon monoxide, nitrogen oxides, sulfur oxides, as well as organic and inorganic particulates (Gonçalves et al., 2012). They have a significant impact on the climate (Chen &

Bond, 2010), air quality (Zielinska & Samburova, 2011) and human health (Lewtas, 2007, Lighty et al., 2000).

The use of small boilers and furnaces (<50 kW) as a source of heat in households (home heating, CWU preparation) is widespread throughout the world (Lasek et al., 2018). Automatic pellet boilers powered by various types of biomass fuels are used for this purpose more and more commonly (Dołżyńska & Obidziński, 2017; Stolarski et al., 2015). The use of pellets allows automation and easier control of the combustion process.

The assessment of environmental benefits resulting from biomass combustion is a complex issue. It is the most reliable when there is a possibility of empirical emissions evaluation using various fuels in energy installations. If no specific emissions data are available, they should be estimated using appropriate factors (Borycka, 2008, Kowalczyk-Juśko, 2010, Maj 2017). Some studies have shown that emissions from various types of pellet burning systems can vary considerably, depending on many factors, e.g. the type and quality of equipment, technical conditions of its operation, fuel properties (Boman et al., 2011; Evtyugina et al., 2014).

There is still considerable uncertainty in the assessment of the impact of pollutant emissions during the combustion of biomass on air quality on a local and global scale (Pastorello et al., 2011). This is caused not only by the lack of data on the amount of biomass burned but also by the lack of emission factors that would characterize real combustion. In this context, it is extremely important to expand knowledge on environmental aspects resulting from the use of energy biomass. Biomass is a very diverse fuel in terms of physical-chemical properties (Maj 2015), and its combustion in inappropriate installations may entail serious environmental costs associated with excessive emissions of toxic exhaust components.

The determination of emission factors is a way to assess the levels of pollutants emitted from a fuel combustion source. The emission factor is usually defined as the amount of a given pollutant emitted per one unit of the burned fuel mass or per a specific task performed. It is often presented in the form of an emission factor referring to the mass and expressed, for example, in g of pollutant per kg of fuel burned. An alternative representation is the mass of the pollutant per one unit of energy obtained. The determination of emission factors can be performed using two basic methods: the index one and the direct measurements one. The best source of information on the emission of pollutants into the atmosphere are measurements performed on real objects and in conditions similar to real conditions. The emission factors determined on the basis of such measurements reflect their real levels and allow a comparison between different combustion systems. However, it should be borne in mind that the measurements are technically and legally complex, and also expensive.

Periodic measurements of emissions into the air are carried out for fuel combustion installations requiring a permit to introduce gases or dusts into the air or an integrated permit, involving combustion units for fuels for which emission standards are defined. For other installations, not covered by the measurements, for which there is no obligation to carry them out, emission factors developed in the literature should be used (Niemczewska, 2017). This is the case with domestic low-power boilers. The main idea of the index method of calculating the emission of pollutants is based on the use of tabulated values of drift factors and/or emissions estimated for a given pollutant and the type and power of the boiler (installation) used, or other technological and technical data developed for typical processes and technological devices. It is the simplest and cheapest method, but charged with a rather large error.

The values of air pollution emission factors calculated using the index method often differ from the ones based on direct measurements, as they are either overestimated or lowered. This usually occurs in the case of modern devices characterized by low real emissions or in the case of devices with a significant degree of depletion, so that the regulation of their working conditions is not possible or very limited, which results in high real emissions of pollutants (Niemczewska, 2017).

The aim of the work was to compare and assess the emission factors of toxic exhaust components obtained on the basis of direct measurements as well as the factors estimated using the index method, calculated on the basis of relevant drift factors available in the literature. A commercially available automatic pellet boiler with the capacity of 10 kW was used in the study . Combustion tests were carried out for five different materials, including wood pellets, energy plant pellets and agricultural waste. The emission factors were determined for CO, NOx and SO_2 with reference to the unit of fuel mass and calorific value of fuel.

2. Material and methods of research

An empirical evaluation of the emission of toxic exhaust components was made during combustion tests of pellets from various types of biomass in an automatic 10 kW boiler (EG-PELLET Greń), adapted to the combustion of wood pellets. The installation used in the tests was a typical installation used for heating detached houses.

Wood pellets available on the market were obtained, as well as pellets from sunflower husks and rape straw from a local distributor (Zamość distric in Poland) and pellets made from Virginia mallow (*Sida hermaphrodita*) and Miscanthus (*Miscanthus giganteus*), produced in the own laboratory (SJ 25 Brikol) for research purposes.

The boiler used in the tests was equipped with a retort burner, which was fed with fuel from the tank by means of a screw-conveyor feeder. The combustion air was supplied by the fan to the nozzle system in the burner. Boiler operation was controlled by means of a programmed electronic controller. During the combustion tests, the boiler's nominal settings have not been interfered with. Combustion tests were carried out at the set boiler operating conditions at nominal settings. During the test, the boiler worked with rated power. Before starting the measurements the boiler was heated for a period of 1 hour, the combustion tests for individual types of pellets lasted 3 hours. The fuel mass flow was approx. 4 $kg \cdot h^{-1}$. The combustion tests were carried out in triplicate and the arithmetic mean of the three measurements was used for further calculations.

The composition of exhaust gases at the boiler outlet was measured using the SIEMENS analyzer system. The system includes ULTRAMAT 23 type analyzers enabling CO measurement in the ranges of 0-5% and 0-50%, SO_2 in the range of 0-2500 ppm and two NO analyzers with ranges of 0-1000 ppm, including one cooperating with the NO_2 to NO converter. These analyzers use the IR reference method. The gas concentration was measured using the OXYMAT 5 type analyzer, allowing the measurement of O_2 in the 0-25% range, operating on the basis of the reference method using the phenomenon of paramagnetism. The exhaust gases were sampled continuously using a heated probe system with a ceramic filter, a heated hose and a gas-conditioning system. The gas sampling probe was located on a vertical, straight and free of flow disturbances duct of chimney of a constant diameter (the requirement of $L \geq 5$ DH for the measuring cross-section was fulfilled).

To determine the emission factors using the index method, it is necessary to know the physical-chemical characteristics of the biomass used, thus a technical and elementary analysis of the biomass was carried out. The research material was prepared in accordance with the PN-EN 14778 standard. The elemental composition of the combustible substance was determined in the samples in the analytical state. Carbon, hydrogen, nitrogen and sulfur were determined using the CHN628 Elemental Analyzer with the LECO S module. The oxygen content in the fuel was calculated as a supplement to 100%. Moisture determination was performed in accordance with the requirements of the PN-EN ISO 18134 standard, volatile compounds PN-EN ISO 18123 and ash PN-EN ISO 18122. The measurements were carried out with the LECO TGA 701 thermogravimeter. The combustion heat was determined in samples in working condition. The determinations were made in accordance with the PN-ISO 1928 standard, the LECO AC600 calorimeter was used for the measurements.

The emissions of particular chemical compounds were estimated in relation to the mass of fuel burned and energy value.

Estimation of emissions from unconventional energy sources is still an unresolved problem, as there are no unambiguous guidelines in this regard, especially for biomass sources. To estimate the emission levels of individual gaseous pollutants, the method of emission factors was used based on the IPCC/OECD methodology (IPCC/OECD, 1995, Radović, 1997, Borycka, 2008, Zwoździak & Walawska, 2008). The method proposed by the IPCC is a simple and transparent way to determine CO, NOx and SO_2 emissions from the combustion of traditional biomass as fuel. It is based on the estimation of an amount of chemically pure coal separated in the combustion process and appropriate ratios of emission of other gases to carbon emissions. The emission per one unit of biomass combusted (emission factor) was determined according to the following formulas:

CO emission factor

$$WE_{CO}=\frac{28}{12}\cdot WE_{C}\cdot(C\_CO/C),\ [kg\cdot kg^{-1}] \tag{1}$$

where:
WE_{CO} – CO emission factor,
$\frac{28}{12}$ – the molar ratio of carbon monoxide and carbon,
C_CO/C – part of the carbon emitted as CO – the average value assumed – 0,06 (Radović, 1997),
WE_C – emission factor of chemically pure coal,

$$WE_C=c\cdot u_c,\ [kg\cdot kg^{-1}] \tag{2}$$

where:
c – carbon content in biomass in working condition,
u_c – part of carbon oxidized in the combustion process – the overall value assumed – 0,88 (Radović, 1997)).

NOx emission factor

In the method used, the NOx emission factor is a summary factor for nitrogen dioxide (NO_2) and nitrogen oxide (NO). The emission per unit of fuel burned was determined according to the following formula:

$$WE_{NO_X}=\frac{46}{14}\cdot WE_{C}\cdot(N/C)\cdot(N\_NO_X/N),\ [kg\cdot kg^{-1}] \tag{3}$$

where:
WE_{NOx} – nitrogen oxide emission factor,
$\frac{46}{14}$ – the molar mass ratio of nitrogen dioxide and nitrogen, the molar mass of nitrogen dioxide is taken into account because nitrogen oxide in the air oxidizes very quickly to nitrogen dioxide

N/C – nitrogen to carbon ratio in biomass,
N_NO$_X$/N – part of the nitrogen emitted as NO$_X$ (the average value assumed – 0,122 (Radović, 1997)).

SO_2 emission factor

In exhaust gases over 90% of sulfur is in the form of SO_2. The sulfur oxide emission factor was calculated by to the following dependence:

$$WE_{SO_2} = \frac{2S}{100}, \text{ [kg·kg}^{-1}\text{]} \tag{4}$$

where:
WE_{SO_2} – sulfur dioxide emission factor,
2 – molar mass ratio of SO_2 and sulfur,
S – sulfur content in the fuel.

Emission factors obtained during direct measurements were calculated on the basis of formulas 5-7 (Janka, 2014; Warych, 1999)

The value of excess air coefficient λ was calculated based on the measurement of the oxygen concentration in the exhaust gas using the formula:

$$\lambda = \frac{21}{21\text{-}O_{2\,sp}}, \text{ [-]} \tag{5}$$

where:
λ – excess air coefficient,
O_{2sp} – oxygen concentration in the exhaust gas [%].

The emission factors (E_i) of CO, NO$_X$ SO_2 were calculated by the dependence:

$$E_i = V_s^j \cdot \dot{B} \cdot S_i, \text{ [kg·kg}^{-1}\text{]} \tag{6}$$

where:
V_s^j – volume of dry exhaust gases arising from the combustion of 1 kg of solid fuel,
$\dot{B}$ – consumption of solid and liquid fuel,
Si – concentration of the ith pollution in gas,

The conversion into the value of factors in relation to the calorific value of fuel was obtained by the following dependence:

$$E_{Ei}=\frac{E_i}{W_o},\ [kg \cdot GJ^{-1}] \quad (7)$$

where:
E_{Ei} – emission of pollution,
W_o – calorific value of fuel.

3. Results and discussion

The results of tests on the physical-chemical properties of the biomass studied are summarized in Table 1.

Table 1. Physical-chemical properties of the pellets studied [own research]

Parameter	Symbol	Unit	Wood pellets	Pellets from rape straw	Pellets from Virginia mallow	Pellets from Miscanthus	Pellets from sunflower husks
Moisture	W_t^r	%	6.3	9.4	6.4	7.1	9.4
Ash	A^a	%	0.32	10.4	3.8	3.16	9.9
Volatile Matter	V^a	%	73.5	64.7	73.3	72.5	69.3
Carbon	C^a	%	46.8	40.1	44.6	46.3	43.6
Hydrogen	H^a	%	6.2	5.8	6.4	6.4	6.4
Nitrogen	N^a	%	4.3	0.8	0.52	0.49	1.7
Sulfur	S^a_A	%	0.01	0.31	0.07	0.056	0.17
HHV	Q_s^r	$kJ \cdot kg^{-1}$	18 235	15 972	17 956	17 975	17 956
LHV	Q_i^r	$kJ \cdot kg^{-1}$	16 741	14 476	16 402	16 440	16 457

The results of tests on toxic components emissions during the combustion of the pellets studied are presented in Table 2.

The lowest CO emission was found during the combustion of wood pellets and pellets from Virginia mallow*,* while the highest NO_X emissions were recorded for these fuels. The highest CO emission took place during the combustion of pellets from sunflower husk and Miscanthus, slightly lower during the combustion of rape straw pellets, the NO_X emission during the combustion tests of these fuels was the lowest (Table 2). SO_2 emission is closely related to sulfur content in fuel (Table 1) (a higher sulfur content in fuel translated into higher SO_2 charge introduced into the atmosphere), the highest emission occurred during the combustion of rape straw pellets, the lowest when burning wood pellets (Table 2).

Table 2. Emission of toxic components of exhaust gases during the test's combustion [own research]

The type of pellets	λ	CO	NO_X	SO_2	CO	NO_X	SO_2
	–	$mg \cdot m^{-3}$			$mg \cdot m^{-3}$ (10% O_2)		
Wood	1.47	87.50	338.89	0.081	70.16	271.73	0.065
Rape straw	1.73	447.50	151.02	0.741	405.21	136.76	0.310
Virginia mallow	1.78	241.25	238.04	0.244	118.85	248.31	0.120
Miscanthus	1.69	613.75	170.00	0.197	273.65	75.79	0.088
Sunflower husks	1.85	983.75	122.65	0.289	470.21	58.62	0.138

The emission factors determined by means of direct measurements and the index method, calculated according to the relationship (1-7) are presented in Table 3. They are expressed in $g \cdot kg^{-1}$ and $g \cdot GJ^{-1}$ to facilitate their confrontation with literature data.

Table 3. Emission factors of CO, NO_X and SO_2 emission determined by the index method and the direct measurement method [own research]

Emission factors	Method	Pellets									
		Wood		Rape straw		Virginia mallow		Miscanthus		Sunflower husks	
		$g \cdot kg^{-1}$	$g \cdot GJ^{-1}$	$g \cdot kg^{-1}$	$g \cdot GJ^{-1}$	$g \cdot kg^{-1}$	$g \cdot GJ^{-1}$	$g \cdot kg^{-1}$	$g \cdot GJ^{-1}$	$g \cdot kg^{-1}$	$g \cdot GJ^{-1}$
E_{CO}	Index	57.00	470.75	48.84	2180.9	54.32	1297.4	56.39	3306.8	53.10	5304.8
	DM	6.57	3473.6	30.48	2976.3	18.09	3310.3	46.12	3436.5	73.98	3236.1
E_{NOx}	Index	1.52	92.43	0.28	17.2	0.18	11.18	0.17	10.53	0.60	36.54
	DM	2.54	154.32	1.03	62.68	1.79	108.79	1.28	77.84	0.92	56.21
E_{SO2}	Index	0.02	1.22	0.62	37.78	0.14	8.531	0.112	6.82	0.34	20.72
	DM	0	1.122	0.002	0.061	0.001	0.061	0.001	0.061	0.001	0.061

DM – Direct measurements

CO emission factors determined using the index method were similar to each other, which results from small differences in the content of initial coal in particular types of biomass (Table 1). On the other hand, the factors determined on the basis of direct measurements showed considerable variation, from 6.57 $g \cdot kg^{-1}$ for wood pellets to 73.98 $g \cdot kg^{-1}$ for sunflower husk pellets. Such large discrepancies result from the combustion conditions. During the combustion of sunflower husk pellets, problems with stabilizing boiler operation were noted, especially during the final test phase. This was related to the caking of slag, which prevented ash from being poured into the ash pan and at the same time hindered the access of air to the retor, thus preventing CO afterburning to CO_2 (Szyszlak-Barglowicz et al., 2017). It should be noted that there are significant differences between the factors determined by the index method and the direct measurement method. The factors obtained by the index method were over 700% higher for wood pellets, 200% for Virginia mallow pellets, and the smallest difference, 22%, was found for Miscanthus pellets, whereas due to the reported combustion problems for the sunflower husk pellets, for them the CO emission factor determined using the index method was lower by nearly 40% than the one determined by the direct measurements method.

As the obtained test results have proved, biomass combustion in low power boilers encounters a number of problems, which are related to different chemical composition of biomass and its variable properties that cause agglomeration of slag and deposit formation on the boiler, resulting in a change of combustion organization (Vamvuka & Kakaras, 2011; Zajac et al., 2017). In view of the above, the determination of CO emission factors based on the index method was charged with a large error. For typical fuels such as wood pellets, these factors were significantly higher compared to the ones obtained on the basis of direct measurements.

It is well known that the CO emission from low-power boilers depends on the type of boiler, burner design, thermal load and excess air coefficient (Lasek et al., 2018). Verma et al. (2011) described the principle of T-3: combustion temperature, turbulence and time. These authors have found that CO emissions may result from low combustion temperature, insufficient oxygen, poor fuel mixing with combustion air and/or too short exhaust gases residence time in the combustion zone. Garcia-Maraver et al. (2015) also noticed that the CO emission depends on the residence time of the gas in the combustion chamber as well as on the temperature and turbulence.

The determined NO_X emission factors for the studied biomass fuels were very diverse. The highest values of gas emission factors determined by both the discussed methods were found for wood pellets: 1.52 $g \cdot kg^{-1}$ by the index method and 2.54 $g \cdot kg^{-1}$ by empirical method. At the same time, NO_X emissions were the highest during combustion tests of this fuel (Table 3). The lowest values of the NO_X emission factor were found, depending on the method of their determination, as: 0.92 $g \cdot kg^{-1}$ and 1.03 $g \cdot kg^{-1}$ for sunflower and rape straw pellets using the empirical method and 0.17 $g \cdot kg^{-1}$ and 0.18 $g \cdot kg^{-1}$ for pellets from Miscanthus and Virginia mallow using the index method. At the same time, the lowest NO_X emissions (Table 2) were found during the combustion tests on sunflower husk pellets and rape straw pellets.

When comparing the NO_X emission factors determined by the direct measurement method and the index method, it was found that the factors determined by the direct measurement method were higher in comparison to the ones determined using the index method. Differences ranged from 35-40% for wood pellets and sunflower husk to 86-90% for pellets from Miscanthus and Virginia mallow, i.e. for the biofuels characterized by lower nitrogen content (Table 1). However, it should not be forgotten that the final level of nitrogen oxide emissions is determined not only by the nitrogen content of the fuel but also by the combustion conditions.

The determination of SO_2 emission factors is a special case. The amount of SO_2 emitted depends on the reflux of sulfur in the fuel. The higher it is, the higher the SO_2 charge introduced into the environment (Ściążko & Zieliński, 2003). Biomass generally contains small amounts of flammable sulfur, which results in SO_2 emission factors even by an order lower in comparison with CO and NO_X emission factors. Higher sulfur content can be found in some of the agribiomas (rape and cereal straw), which corresponds to higher SO_2 emissions during its combustion. This is also confirmed by the results of the tests carried out.

The SO_2 emission factors determined on the basis of direct measurements differed significantly from the ones determined using the index method. In combustion tests SO_2 emissions were very low (Table 2), and empirically determined emission factors for this gas were close to zero (from 0 for wood pellets to 0.002 $g \cdot kg^{-1}$ for rape straw pellets). The SO_2 emission factors determined using the index method were from several dozen to several hundred times higher than the ones determined by the empirical method. It follows that the sulfur contained in the fuel remained mainly in the furnace waste. Using the index method, the lowest SO_2 factors were determined for wood pellets and the highest for sunflower seed pellets (Table 3). The SO_2 factors, both the ones determined by the index method and those determined empirically, correspond with the sulfur content in the burned pellets.

In the literature, one can find works that were aimed at determining emission factors during biomass combustion in low-power installations, but the results presented there are divergent. There are a few reports regarding emissions during biomass combustion in an automatic boiler, but they usually concern research using wood pellets as test fuel.

The emission factors of NOx and CO determined in the studies by means of direct measurements for the studied biofuels were higher than the ranges of these gases emission factors for wood pellets presented in the works (Boman et al., 2011; Johansson et al., 2004; Paulrud et al., 2010 Win and Others, 2012), with the exception of the CO emission factor for wood pellets, which was comparable.

Carvalho et al., (2013) set emission factors for pellets from various types of agricultural biomass and wood pellets. The factors were also significantly lower when burning wood pellets. The highest values of CO emission factors were found for hay pellets (280 $g \cdot GJ^{-1}$), wheat bran (224 $g \cdot GJ^{-1}$) and straw (223 $g \cdot GJ^{-1}$), They were from eleven to fourteen times higher in comparison to emission factors for wood pellets. CO emission factors for corn straw pellets as well as for waste from vineyard and sorghum clearings were relatively low (two to five times higher than CO emissions for wood pellets). NOx and SO_2 emissions were also higher when the boiler was fed with pellets from biomass of agricultural origin.

Zając et al. (2017) found high CO emissions when burning pellets from agrobiomass in a boiler designed for burning wood-based pellets, due to incomplete combustion and poor process organization. The higher CO concentration resulted from the lowering of temperature in combustion chamber due to difficulties in feeding fuel. In the case of wood pellets combustion, this phenomenon was not observed, and the CO emission was lower.

Juszczak (2012) points out that for pellets from various types of agricultural biomass, burners adapted to wood pellets are often used in boilers. Too high temperature in the furnace, however, causes the ash to soften and clump, creating problems in the operation of the burner, increasing the emission of CO and HC and reducing the thermal efficiency of the boiler. To reduce the phenomenon of ash softening, you need to lower the temperature in the furnace. This results in poorer performance and lower thermal efficiency of the boiler, with a slightly lower, but still high, emission of CO and sometimes also HC.

Hrdlička et al. (2016) draw attention to the fact that during the empirical determination of emission factors, the boiler's working conditions, power load and excess air ratio are significant. The emission factors for various biomass fuels presented by these authors were the lowest at 100% nominal boiler load. The lowest emission factors were also found for wood pellets (CO 1.6 $g \cdot kg^{-1}$; NOx 1.2 $g \cdot kg^{-1}$; SO_2 0.01, $g \cdot kg^{-1}$). For pellets from other types of biomass slightly higher factors were noted (for rape straw: CO 27.3 $g \cdot kg^{-1}$; NOx 3.9 $g \cdot kg^{-1}$; SO_2 0.1 $g \cdot kg^{-1}$, for cereal straw CO 3.2 $g \cdot kg^{-1}$; NOx 3.8 $g \cdot kg^{-1}$; SO_2 0.8 $g \cdot kg^{-1}$). At lower boiler load, these factors were higher for all the biofuels tested, and in many cases the differences were very large.

4. Conclusion

The main disadvantage of devices for biomass combustion, especially of low power devices, is the high level of emission variability (Evtyugina et al., 2014). Emissions from biomass combustion depend on such factors as: combustion conditions, properties and quality of biomass, boiler and burner design.

A comprehensive and detailed inventory of biomass combustion, representing the current state, is important to provide the necessary information to manage emissions at the local, regional and global levels. The conducted research allowed to conclude that the values factors and factors determined on the basis of direct measurements differed significantly, which was related to the various combustion conditions of the examined biomass fuels. In particular, it was found that:

1. The CO emission factors determined using the index method for the fuels tested were higher from several dozen to several hundred percent from the factors determined on the basis of direct measurements, with the exception of the factor for sunflower seed pellets, which was lower by several dozen percent from the empirically determined one, due to the problems at the boiler's work. For the basic fuel, which is wood pellets, in the case of the boiler used in the tests, the CO emission factors determined using the index method were significantly higher than the ones obtained on the basis of direct measurements.
2. NOx emission factors determined by the direct measurement method were higher by several dozen percent compared to the factors determined using the index method. The largest differences were found for biofuels characterized by lower nitrogen content (pellets from Miscanthus and Virginia mallow).
3. The SO_2 emission factors determined empirically differed significantly from the factors determined using the index method. Since the SO_2 emission during combustion tests was very low, the emission factors determined on the basis of direct measurements were close to zero. SO_2 emission factors determined using the index method were from several dozen to several hundred times higher.
4. The CO, NOx, SO_2 emission factors determined using the index method were burdened with a large error. In the case of CO and NOx emission factors, this resulted from the course of the combustion process, which for neither of the biofuels ran smoothly and accurately at all times, and this fact inevitably affected the obtained boiler power. During the conducted combustion tests, when the boiler reached the rated power and the maximum load, the CO emission factors determined using the index method were much higher than those determined empirically. On the other hand, the NOx emission factors determined using the index method were significantly lower than those determined empirically. It follows, that setting emission factors for biomass fuels using the index method can be highly erroneous and does not provide reliable information about the actual emissions from low-capacity boilers installed in individual households.

As the combustion process is very sensitive to the conditions in which it occurs, and even a small change in them can cause major changes in emission factors, it cannot be assumed that the emission factors obtained in the conducted tests can be an undisputable source of information about emissions from this type of installations. Further emission tests are needed, taking into account different types of equipment, a wide range of their models and technologies as well as various biomass fuels. The results of the present studies will allow the development of more accurate drift rates for biomass fuels and also more precise estimation of emission factors. It would be difficult to base emission calculations solely on emission measurements, especially due to the costs of research, which should involve a huge number of facilities and devices in the country. The use of available emission factors and calculation methods is advisable, as an empirical determination of individual factors to be used for all the devices/installations would be practically unfeasible.

References

Boman, C., Pettersson, E., Westerholm, R., Boström, D., Nordin, A. (2011). Stove performance and emission characteristics in residential wood log and pellet combustion, part 1: pellet stoves. *Energy & Fuels*, *25*(1), 307-314.

Borycka, B. (2008). *Towaroznawcze studium nad żywnościową i energetyczną użytecznością bogatobłonnikowych odpadów przemysłu owocowo-warzywnego*. Wyd. Polit. Radomskiej, Radom.

Borycka, B. (2009). Walory ekologiczne spalania biomasy z odpadów owocowo-warzywnych. *Energetyka*, *12*, 847-851.

Carvalho, L., Wopienka, E., Pointner, C., Lundgren, J., Verma, V. K., Haslinger, W., Schmidl, C. (2013). Performance of a pellet boiler fired with agricultural fuels. *Applied Energy*, *104*, 286-296.

Chen, Y., Bond, T. C. (2010). Light absorption by organic carbon from wood combustion. *Atmospheric Chemistry and Physics*, *10*(4), 1773-1787.

Dołżyńska, M., Obidziński, S. (2017). Wpływ dodatku zużytego oleju spożywczego na efekty spalania osadów ściekowych. *Przemysł Chemiczny*, *96*(9), 1848-1851.

Evtyugina, M., Alves, C., Calvo, A., Nunes, T., Tarelho, L., Duarte, M., Prozil, S.O., Evtuguin, D.V., Pio, C. (2014). VOC emissions from residential combustion of Southern and mid-European woods. *Atmospheric environment*, *83*, 90-98.

Garcia-Maraver, A., Rodriguez, M. L., Serrano-Bernardo, F., Diaz, L. F., Zamorano, M. (2015). Factors affecting the quality of pellets made from residual biomass of olive trees. *Fuel Processing Technology*, *129*, 1-7.

Gonçalves, C., Alves, C., Pio, C. (2012). Inventory of fine particulate organic compound emissions from residential wood combustion in Portugal. *Atmospheric Environment*, *50*, 297-306.

Grudziński, Z., Stala-Szlugaj, K. (2016). Koszty środowiskowe a użytkowanie węgla kamiennego w obiektach o mocy do 50 MW. *Rocznik Ochrona Środowiska*, *18*(1), 579-596.

Hrdlička, J., Skopec, P., Dlouhý, T., Hrdlička, F. (2016). Emission factors of gaseous pollutants from small scale combustion of biofuels. *Fuel*, *165*, 68-74.

IPCC/OECD. (1995). Greenhouse Gas Inventory Relerence Manual. IPCC Guidelines for National Greenhouse Gas Inventorries. Vol. 1.2 and 3. Bracknell, UK.

Janka, R. (2014). Zanieczyszczenia pyłowe i gazowe. *Podstawy obliczania i sterowania poziomem emisji. WNT, Warszawa*.

Johansson, L. S., Leckner, B., Gustavsson, L., Cooper, D., Tullin, C., Potter, A. (2004). Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets. *Atmospheric Environment*, *38*(25), 4183-4195.

Juszczak, M. (2012). Pollutant concentrations from a 15 kW heating boiler supplied with sunflower husk pellets. *Environment Protection Engineering*, *38*(1), 35-43.

Kowalczyk-Juśko, A. (2010). Redukcja emisji zanieczyszczeń dzięki zastąpieniu węgla biomasą spartiny preriowej. *Problemy Inżynierii Rolniczej*, *18*(*4)*, 69-77.

Lasek, J. A., Matuszek, K., Hrycko, P., Piechaczek, M. (2018). Adaptation of hard coal with high sinterability for solid fuel boilers in residential heating systems. *Fuel*, *215*, 239-248.

Lewtas, J. (2007). Air pollution combustion emissions: Characterization of causative agents and mechanisms associated with cancer, reproductive, and cardiovascular effects. *Mutation Research/Reviews in Mutation Research*, *636*(1), 95-133.

Lighty, J. S., Veranth, J. M., Sarofim, A. F. (2000). Combustion Aerosols: Factors Governing Their Size and Composition and Implications to Human Health. *Journal of the Air & Waste Management Association*, *50*(9), 1565-1618.

Maj, G. (2015). Diversification and Environmental Impact Assessment of Plant Biomass Energy Use. *Polish Journal of Environmental Studies*, *24*(5), 2055-2061.

Maj, G. (2017). Analysis of energy properties and emissions factors of selected plant biomass and peat. W *IX International Scientific Symposium Farm machinery and processes management in sustainable agriculture : Symposium Proceedings* (ss. 222-227). (Red.) E. Lorencowicz, J. Uziak, B. Huyghebaert, Lublin.

Niemczewska, J. (2017). Określanie wielkości emisji zanieczyszczeń do powietrza towarzyszących eksploatacji złóż ropy naftowej i gazu ziemnego metodą wskaźnikową. *Nafta-Gaz*, *73*(4), 287-292.

Pastorello, C., Caserini, S., Galante, S., Dilara, P., Galletti, F. (2011). Importance of activity data for improving the residential wood combustion emission inventory at regional level. *Atmospheric Environment*, *45*(17), 2869-2876.

Paulrud, S., Kindbom, K., Gustafsson, T. (2010). Emission factors and emissions from residential biomass combustion in Sweden; 34. *Swedish Meteorological and Hydrological Institute: Norrköping*.

PN-EN 14778: 2011. Biopaliwa stałe - Pobieranie próbek.

PN-EN ISO 18122: 2016. Biopaliwa stałe -Oznaczanie zawartości popiołu.

PN-EN ISO 18123: 2016. Biopaliwa stałe - Oznaczanie zawartości części lotnych.

PN-EN ISO 18134-3: 2015. Biopaliwa stałe - Oznaczanie zawartości wilgoci - Metoda suszarkowa - Część 3: Wilgoć w próbce do analizy ogólnej.

PN-ISO 1928: 2002. Paliwa stałe - Oznaczanie ciepła spalania metodą spalania w bombie kalorymetrycznej i obliczanie wartości opałowej.

Radović, U. (1997). *Zanieczyszczenie atmosfery: źródła oraz metodyka szacowania wielkości emisji zanieczyszczeń*. CIE. ZE, Warszawa.

Stolarski, M. J., Krzyżaniak, M., Warmiński, K., Tworkowski, J., Szczukowski, S. (2015). Willow Biomass Energy Generation Efficiency and Greenhouse Gas Reduction Potential. *Polish Journal of Environmental Studies*, *24*(6), 2627-2640.

Szyszlak-Barglowicz, J., Zajac, G., Słowik, T. (2017). Badanie emisji wybranych zanieczyszczeń gazowych podczas spalania peletów z agro biomasy w kotle małej mocy. *Rocznik Ochrona Środowiska*, *19*, 715-730.

Ściążko, M., Zieliński, H. (2003). *Termochemiczne przetwórstwo węgla i biomasy*. Zabrze- Kraków: ICPW.

Vamvuka, D., Kakaras, E. (2011). Ash properties and environmental impact of various biomass and coal fuels and their blends. *Fuel Processing Technology*, *92*(3), 570-581.

Verma, V. K., Bram, S., Gauthier, G., De Ruyck, J. (2011). Performance of a domestic pellet boiler as a function of operational loads: Part-2. *Biomass and Bioenergy*, *35*(1), 272-279.

Warych, J. (1999). *Procesy oczyszczania gazów: problemy projektowo-obliczeniowe*. Oficyna Wydawnicza Politechniki Warszawskiej.

Win, K. M., Persson, T., Bales, C. (2012). Particles and gaseous emissions from realistic operation of residential wood pellet heating systems. *Atmospheric Environment*, *59*, 320-327.

Zajac, G., Szyszlak-Barglowicz, J., Dudziak, A., Kuranc, A., Wasilewski, J. (2017). Ash composition and deposition tendencies of selected biomass types. W *IX International Scientific Symposium Farm machinery and processes management in sustainable agriculture : Symposium Proceedings* (ss. 438-443). (Red.) Edmund Lorencowicz, Jacek Uziak, Bruno Huyghebaert, Lublin.

Zajac, G., Szyszlak-Barglowicz, J., Slowik, T., Wasilewski, J., Kuranc, A. (2017). Emission characteristics of biomass combustion in a domestic heating boiler fed with wood and Virginia Mallow pellets. *FEB-Fresenius Environmental Bulletin*, *26*(7), 4663-4670.

Zielinska, B., Samburova, V. (2011). Residential and Non-Residential Biomass Combustion: Impacts on Air Quality. W J. O. Nriagu (Red.), *Encyclopedia of Environmental Health* (ss. 819-827). Burlington: Elsevier.

Zwoździak, J., Walawska, B. (2008). Źródła oraz metodyka szacowania wielkości emisji zanieczyszczeń. *Chemik*, *61*(3), 146-149.

Abstract

The assessment of environmental benefits resulting from biomass burning is a complex issue. The most reliable is when there is the possibility of empirical emission assessment using various fuels in energy installations. If no specific emission data is available, it should be estimated using appropriate indicators.

There is still considerable uncertainty in the assessment of the impact of pollutant emissions accompanying the combustion of biomass on air quality on a local scale. This is caused not only by the lack of data on the amount of biomass burned but also by the lack of emission factors that would characterize real combustion. In this context, it is extremely important to expand knowledge about environmental aspects resulting from the use of energy biomass.

The aim of the work was to compare and assess emission factors of toxic exhaust components obtained on the basis of direct measurements and indicators estimated using the index method, calculated on the basis of appropriate fixed-point indicators available in the literature. The work uses a commercially available automatic pellet boiler with a capacity of 10 kW. Combustion tests were carried out for five different materials, including wood pellets, energy plant pellets and agricultural waste. The emission factors were determined for CO, NO_x and SO_2 with reference to the unit of mass of fuel and calorific value of fuel.

The CO, NO_X, SO_2 emission indices determined using the index method were burdened with a large error. In the case of CO and NO_x emission indicators, this resulted from the course of the combustion process, which for the biofuels tested did not always run equally smoothly and without problems, which affected the obtained boiler power. During the conducted combustion tests, when the boiler reached its rated power and maximum load, the CO emission indices determined using the index method were much higher than those determined empirically. On the other hand, the NO_X emission factors determined using the index method were lower than those determined empirically. It follows that setting emission indicators using biomass fuels may be subject to a very large error and not to inform about the actual emissions from low-capacity boilers installed in individual households.

Because the combustion process is very sensitive to the conditions in which it occurs, and their slight change may cause major changes in emission factors, it can not be considered that the emission factors obtained in the conducted research can be an undisputable source of information about emissions from this type of installations. Further emission tests are required, taking into account different types of equipment, a wide range of their models and technologies as well as various biomass fuels. The results of this research will allow the development of more accurate drift rates for biomass fuels and for more precise estimation of emission factors.

Keywords:
pellets, biomass combustion, small scale boilers, emission factor

Porównanie i ocena wskaźników emisji toksycznych składników spalin podczas spalania paliw biomasowych

Streszczenie

Ocena korzyści środowiskowych, wynikających ze spalania biomasy, jest zagadnieniem złożonym. Najbardziej wiarygodna jest wówczas, gdy istnieje możliwość empirycznej oceny emisji z wykorzystaniem różnych paliw w instalacjach energetycznych. Jeżeli brak jest konkretnych danych o emisji, należy ją oszacować, wykorzystując odpowiednie wskaźniki.

Wciąż istnieje znaczna niepewność oceny wpływu emisji zanieczyszczeń towarzyszących spalaniu biomasy na jakość powietrza w skali lokalnej. Spowodowane jest to nie tylko brakiem danych dotyczących ilości spalanej biomasy ale również brakiem współczynników emisji, które charakteryzowałyby spalanie rzeczywiste. W tym kontekście niezwykle istotne jest poszerzanie wiedzy dotyczącej aspektów środowiskowych wynikających z wykorzystania energetycznego biomasy.

Celem pracy było porównanie i ocena wskaźników emisji toksycznych składników spalin, uzyskanych na podstawie pomiarów bezpośrednich oraz wskaźników oszacowanych za pomocą metody wskaźnikowej, obliczonych na podstawie odpowiednich, dostępnych w literaturze wskaźników unosu. W pracy wykorzystano dostępny komercyjnie, automatyczny kocioł na pelety o mocy 10 kW. Testy spalania przeprowadzono dla pięciu różnych materiałów, w tym peletów drzewnych, peletu z roślin energetycznych i odpadów rolniczych. Wskaźniki emisji wyznaczono dla CO, NOx i SO_2 w odniesieniu do jednostki masy paliwa i wartości opałowej paliwa.

Wskaźniki emisji CO, NOx, SO_2 wyznaczone metodą wskaźnikową były obciążone dużym błędem. W przypadku wskaźników emisji CO i NOx wynikało to z przebiegu procesu spalania, który dla badanych biopaliw nie zawsze przebiegał jednakowo sprawnie i bezproblemowo, co wpływało na uzyskiwaną moc kotła. Podczas prowadzonych testów spalania, kiedy kocioł osiągał moc znamionową i maksymalne obciążenie, wskaźniki emisji CO wyznaczone metodą wskaźnikową były o wiele wyższe od wyznaczonych empirycznie. Natomiast wskaźniki emisji NO_X wyznaczone metodą wskaźnikową były niższe niż wyznaczone empirycznie. Wynika stąd, że wyznaczanie wskaźników emisji metodą wskaźnikową dla paliw biomasowych może być obarczone bardzo dużym błędem i nie informować o rzeczywistej emisji z kotłów małej mocy zainstalowanych w indywidualnych gospodarstwach domowych.

Ponieważ proces spalania jest bardzo wrażliwy na warunki w jakich zachodzi, a niewielka ich zmiana może spowodować duże zmiany wskaźników emisji, nie można uznać, że wskaźniki emisji uzyskane w przeprowadzonych badaniach mogą stanowić bezdyskusyjne źródło informacji o emisjach z instalacji tego typu. Niezbędne są dalsze badania emisji z uwzględnieniem różnych typów urządzeń, szerokiej gamy ich modeli i technologii oraz różnych paliw biomasowych. Wyniki tych badań pozwolą na opracowanie dokładniejszych wskaźników unosu dla paliw biomasowych oraz na precyzyjniejsze szacowanie wskaźników emisji.

Słowa kluczowe:
pelety, spalanie biomasy, kotły małej mocy, wskaźniki emisji