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EMISSION OF HYDROGEN DURING COMBUSTION OF PLANT BIOMASS PELLETS ON THE GRATE OF A LOW POWER BOILER

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ABSTRACT

Analysis of the wheat, rye, triticale, buckwheat straw and meadow hay pellets combustion process was carried out for hydrogen emissions. Tests were performed in grate upper combustion boiler. The air was supplied through a ventilator beneath the grate at the rate of 1.5 $m \cdot s^{-1}$. Differences in obtained hydrogen amounts in exhausted gas were observed: from 216 to 266 ppm, on average. This substance presence was usually characterized by negative correlation with exhaust gas temperature, while positive with the air excess. This aspect emissions hydrogen is very important for achieving the goals of sustainable agriculture that meet current and future human needs. It would be advisable to enhance tests using other forms of combusted bio-fuels, as well as to carry out the analyses of other components of exhausted gas generated during combustion.

INTRODUCTION

Malaga-Tobola et al. (2008) report that Polish agriculture, due to the land and labor resources, has considerable opportunities to compete on European market, while structural reality, especially excessive resources of labor in agriculture, contributes to its low efficiency.

Increasing the productivity can be achieved by directing the production towards organic assortment using post-production remains. Therefore, it becomes important to use the agricultural-origin biomass for energy purposes. These actions should refer not only to agricultural production, but also subsequent utilization of products. Baum (2003) and Krasowicz (2006) indicated the need to realize the agricultural policy while maintaining the rules of sustainable development strategy, which when realizing the pro-ecological tasks, takes into account the compromise between energy and ecological effectiveness.

When combusting the solid bio-fuels, management of the air supplied, that depends on the type of combusted fuel, but also on the furnace construction, is very important. Much information on that can be found in works by Fournel et al. (2015), Obernberger (2003), Obernberger et al. (2006) as well as Van Loo and Koppejan (2007). Those papers, along with publications by Olsson and Kjällstrand (2002) and Kraszkiewicz (2016) include information that the use of solid bio-fuels in low-power heating devices makes problems with uncontrolled emission of many gaseous harmful products of incomplete combustion such as carbon monoxide (CO), nitrogen oxides (NOx), sulfur dioxide (SO_2), volatile organic compounds (LZO) and tars. Works by Schultz et al. (2003), Saxen et al. (2008), Vollmer et al. (2012) and Pieterse et al. (2013) indicate the poorly recognized hydrogen (H_2) emission, the presence of which in the atmosphere enhances the lifetime of greenhouse gases.

During combustion, hydrogen arises in a series of chemical reactions that are also used to its industrial production under controlled manner. These reactions are described in details by Kordylewski (2006) and Saxen et al. (2008).

Kothari et al. (2008) point out that the characteristic feature of hydrogen that can be determined its oxidation, thus emission into the atmosphere, is self-ignition temperature of 585 °C, which is even higher than that for methane 540 °C. Vollmer et al. (2012) found that hydrogen presence launches other reactions, e.g. decomposition of NO to N_2O. However, the literature lacks information about this compound emission size or mechanisms of its arising in an aspect of solid bio-fuels combustion in low-power heating devices.

Therefore, the aim of the preset study was to perform the combustion of pellets made of selected types of biomass in low-temperature upper combustion water boiler, and to carry out the analysis of exhaust gas for the hydrogen presence, supplied air excess, and exhaust gas temperature.

MATERIAL AND METHODS

Tests involved pellets made of rye, wheat, triticale, buckwheat straw and meadow hay. Following methods were applied for determining their physicochemical properties:

- moisture – gravimetric method according to PN-EN 14774-1:2010;
- calorific value – according to PN-EN 14918:2010 after determination of calorific value;
- ash – according to PN-EN14775:2010;
- carbon, hydrogen – IR absorption according to CEN/TS 15104:2006;
- nitrogen – using automatic analyzer equipped with thermal conductivity detector according to CEN/TS 15104:2006;
- sulfur – automatic IR analyzer according to PN-G-04584:2001;
- length and diameter – direct measurement of 10 representative pellets.

Average values of physical and chemical properties of tested solid bio-fuels are presented in Table 1.

Table 1. Physical and chemical properties of the treated pellets in working condition.

Fuel parameters - average values	Unit	Pellets				
		made of rye straw	made of wheat straw	made of triticale straw	made of buckwheat straw	made of meadow hay
Length	mm	28.7	32.3	31.3	36.6	31.7
Diameter	mm	8.5	8.3	8.4	8.1	8.5
Moisture	wt. %	10.82	11.42	10.6	11.3	9.6
Net calorific value	$MJ \cdot kg^{-1}$	16.23	16.32	16.1	15.45	16.14
Ash content	wt. %	3.4	2.31	3.78	6.28	6.21
C	wt. %	46.72	47.7	46.5	44.4	46.04
H	wt. %	5.6	5.5	5.74	5.56	5.64
N	wt. %	1.15	0.77	0.7	0.88	1.37
S	wt. %	0.12	0.06	0.09	0.13	0.61

Source: own study

The combustion tests of the study material were carried out in the testing position, the integral part of which consisted of boiler of upper combustion with fixed grate with nominal thermal power of 10 kW, fed periodically. The fuel feeding and ash removal was manual. Boiler was equipped in air supply ventilator and circulating pump of working liquid. The device was controlled by means of microprocessor regulator.

Tests consisted of combusting the 1 kg sample of pellets supplying air beneath the grates at the rate of 1.5 $m \cdot s^{-1}$. Exhaust gas was samples from the chimney at the distance of 1 m from boiler's flue. The measuring probe was connected to exhaust gas dryer PGD-100, from which gas was directed to analyzer. Portable exhaust gas analyzer Photon was used. This device works based on the IR sensors (NDIR). During combustion, measurement of H_2, O_2 contents in exhaust gas was performed using type K thermocouple. Measurement results were written to database every 4 seconds from the moment of combustion of the fuel portion after its supplying on stabilized embers layer, till the end of combustion process.

Achieved results of H_2 concentration in exhaust gas were also referred to the stream of dry exhaust gas volume of 10% oxygen content and normal conditions ($mg \cdot m^{-3}$) at 0 °C and 1013 mbar according to guidelines in PN-EN 303-5:2012. Accumulated data was subject to statistical analysis in STATISTICA 13.1 software. The Shapiro-Wilk test verified the conformity of results with normal distribution, while Brown-Forsyth was used to evaluate the variance uniformity. When the lack of variance uniformity was found, Kruskal-Wallis test was applied. In order to describe the dependence between particular variables, Spearman rank correlation test was used. In all analyses, the significance level was assumed at $p < 0.05$.

RESULTS

Concentration of hydrogen H_2 in exhaust gas, air excess, and temperature of exhaust gas characterizing the combustion process of tested pellets is presented in Tables 2-4.

Table 2. Concentration of hydrogen H_2 measured in the exhaust gas during combustion of the pellets in question.

Fuel type	Concentration H_2, ppm				
	sample size	min	max	mean	standard deviation
pellets made of rye straw	389	0	1871	216	364
pellets made of wheat straw	231	0	1572	103	329
pellets made of triticale straw	195	0	3035	237	559
pellets made of buckwheat straw	535	0	930	253	217
pellets made of meadow hay	208	0	1610	266	538

Source: own study

Table 3. Excess air during the combustion process of the pellets in question.

Fuel type	Excess air				
	sample size	min	max	mean	standard deviation
pellets made of rye straw	389	1.66	32	6	6
pellets made of wheat straw	231	1.40	81	12	15
pellets made of triticale straw	194	1.13	87	5	9
pellets made of buckwheat straw	535	4.07	299	28	45
pellets made of meadow hay	208	2.25	70	8	12

Source: own study

Concentrations of H_2 measured in exhaust gas originated during combustion of test pellets were similar and average values ranged within 216-266 ppm. Only for pellets made of wheat straw, the value was 103 ppm. Higher differentiation was revealed by maximum values that most often ranged within 1571-1871 ppm. However, for pellets made of buckwheat and triticale straw, the levels were completely different: maximum hydrogen concentrations in exhaust gas were 930 and 3035 ppm, respectively.

Table 4. The temperature of the exhaust gas during combustion of the pellets in question.

Fuel type	The temperature of the exhaust gas, ºC				
	sample size	min	max	mean	standard deviation
pellets made of rye straw	389	0	536	331	138
pellets made of wheat straw	231	0	598	294	154
pellets made of triticale straw	195	0	753	302	208
pellets made of buckwheat straw	535	0	232	96	52
pellets made of meadow hay	208	0	397	247	105

Source: own study

Parameter characterizing the combustion process was the air demand expressed as its excess. Combustion with the largest air excess (28 on average) was recorded for buckwheat straw pellets. Other types of pellets were combusted more intensively at larger air consumption (5-12 on average). Meanwhile, in this group with the largest air excess, wheat straw pellets were combusted. At the moment of the highest air demand, when combustion was the most intensive and advanced, the minimum values of air excess are very interesting: they amounted to 1.13-1.66 for pellets made of wheat, rye and triticale straw, while for buckwheat straw and meadow hay, these values were much higher – 4.07 and 2.25, respectively (Table 3).

Temperature of exhaust gas during combusting the analyzed pellets revealed similar differentiation as previously discussed parameters. Buckwheat straw pellets combustion was characteristic, because maximum temperature of exhaust gas was only 231 ºC (at the mean value of 96 ºC), which was from 30% to 60% of this parameter reached for other bio-fuels (Table 4).

Values of emission calculated for the normal conditions at 10% oxygen content are presented in Table 5. Hydrogen emission indicators referenced to the normal conditions revealed lower differentiation between applied pellets tested. Average values, in general, ranged within 0.10-0.13 $mg \cdot m^{-3}$. Only for pellets made of wheat straw, the value was lower at the level of 0.05 $mg \cdot m^{-3}$ (Table 5).

Table 5. Emission factors H_2 converted to reference state at 10% O_2 in exhaust gas.

Fuel type	Emission factors H_2 at 10% O_2 in exhaust gas, $mg \cdot m^{-3}$				
	sample size	min	max	mean	standard deviation
pellets made of rye straw	389	0	0.89	0.10	0.17
pellets made of wheat straw	231	0	0.75	0.05	0.16
pellets made of triticale straw	195	0	1.44	0.11	0.27
pellets made of buckwheat straw made of meadow hay	535	0	0.44	0.12	0.10
pellets made of meadow hay	208	0	0.76	0.13	0.26

Source: own study

Table 6 illustrates Spearman rank correlations between analyzed values.

Table 6. Spearman's correlation coefficients.

Variables	Pellets				
	made of rye straw	made of wheat straw	made of triticale straw	made of buckwheat straw	made of meadow hay
H_2 (ppm) vs Tgas (°C)	-0.835	-0.284	-0.519	0.798	-0.631
H_2 (ppm) vs Excess air (-)	0.848	0.166	0.528	-0.706	0.599
Tgas (°C) vs Excess air (-)	-0.981	-0.910	-0.950	-0.912	-0.940

Source: own study

In general, Spearman rank correlation coefficients indicated that negative dependencies were present between hydrogen content in exhaust gas and exhaust gas temperature. Only during combusting the buckwheat straw, the dependence was strongly positive, whereas between hydrogen concentration vs. air excess, these relations were positive, while for buckwheat straw pellets - negative (Table 6). Inter-relations occurring in test conditions indicate incomplete combustion of buckwheat straw pellets and intensive process of their gasification.

The combustion tests of selected bio-fuels differed due to use of pellets with different physical and chemical properties. Comparative analysis of achieved results of hydrogen content in exhaust gas recorded in particular combustion tests is difficult. The literature references, among others in Fournel et al. (2015), Obernberger (2003), Obernberger et al. (2006) as well as Van Loo and Koppejan (2007) did not take into account the hydrogen emission during the biomass fuels combustion. The own tests revealed that referring to tested pellets, there were remarkable divergences in the combustion process, hence hydrogen concentrations in exhaust gases. Pellets made of buckwheat straw differed from other ones, because they were not combusted in a satisfactory way due to their chemical properties.

CONCLUSIONS

Performed tests allowed for making following remarks and drawing conclusions:

1. Combustion of cereal straw and meadow hay pellets generated hydrogen presence in exhaust gas at the level from 216 to 266 ppm, while maximum concentration of this compound during combustion pellets made of buckwheat straw amounted to 930 ppm, and triticale straw – 3035 ppm.
2. Hydrogen emission indicators recalculated onto reference of 10% O_2 in exhaust gas were uniform and average values of the parameter, in general, range from 0.10 to 0.13 $mg \cdot m^{-3}$. Only combustion of wheat straw pellets resulted in the parameter value at the level of 0.05 $mg \cdot m^{-3}$.
3. Hydrogen emission to the atmosphere during combustion of tested fuels, in general, was characterized by negative correlation with exhaust gas temperature, while positive with the air excess. Only for pellets made of buckwheat straw, these dependencies were different.
4. Work on knowing and reducing hydrogen emissions, when burning biofuels of agricultural origin, into the atmosphere is part of the problem of improving air quality, which promotes quality of life in the community. This aspect is very important for achieving the goals of sustainable agriculture that meet current and future human needs.

5. Due to significant differentiation of concentrations and influence of hydrogen content in atmosphere on the natural environment and other chemicals, it would be reasonable to enhance studies with other forms of combusted bio-fuels, as well as to carry out the analyses of other components of exhaust gas generated during their combustion.

REFERENCES

Baum, R. (2003). Kryteria oceny zrównoważonego rozwoju w gospodarstwach rolnych. *Roczniki Akademii Rolniczej w Poznaniu, CCCLVIII, Ekon., 2,* 3-10.

Fournel, S., Marcos, B., Godbout, S., & Heitz, M. (2015). Predicting gaseous emissions from small-scale combustion of agricultural biomass fuels. *Bioresource Technology, 179*, 165-172.

Kordylewski, W. (2008). *Spalanie i paliwa. Wrocław: Oficyna Wydawnicza Politechniki Wrocławskiej.*

Kothari, R., Buddhi, D., Sawhney, R.L. (2008). Comparison of environmental and economic aspects of various hydrogen production methods. *Renewable and Sustainable Energy Reviews. Volume 12, (Issue 2),* 553-563.

Krasowicz, S. (2006). Sposoby realizacji idei zrównoważonego rozwoju w gospodarstwie rolniczym. *Zeszyty Naukowe Akademii Rolniczej we Wrocławiu, Nr 540*, 255-261.

Kraszkiewicz, A. (2016). The combustion of wood biomass in low power coal-fired boilers. *Combust. Sci. and Technol. Vol. 188, (Issue 3)*, 389-396.

Malaga-Tobola, U., Tabor, S., & Kocira, S. (2015). Productivity of resources and investments at selected ecological farms. *Farm Machinery and Processes Management in Sustainable Agriculture, Book Series: Agriculture and Agricultural Science Procedia, volume 7*, 158-164.

Obernberger, I., Brunner, T., & Bärnthaler, G. (2006). Chemical properties of solid biofuels – significance and impact. *Biomass and Bioenergy, 30*, 973-982.

Olsson, M., & Kjällstrand, J. (2002). Emissions from burning of softwood pellets. *In: Proceedings of the First World Conference on Pellets.* Stockholm, Sweden. pp. 111-114.

Pieterse, G., Krol, M. C., Batenburg, A. M., Brenninkmeijer, C. A. M., Popa, M. E., O'Doherty, S., Grant, A., Steele, L. P., Krummel, P. B., Langenfelds, R. L., Wang, H. J., Vermeulen, A. T., Schmidt, M., Yver, C., Jordan, A., Engel, A., Fisher, R. E., Lowry, D., Nisbet, E. G., Reimann, S., Vollmer, M. K., Steinbacher, M., Hammer, S., Forster, G., Sturges, W. T., Röckmann, T. (2013). Reassessing the variability in atmospheric H_2 using the two-way nested TM5 model. *J. Geophys. Res. Atmos., 118*, 3764-3780.

Saxena, R.C., Diptendu, S., Satinder, K., & Goyal H.B. (2008). Thermo-chemical routes for hydrogen rich gas from biomass: A review. *Renewable and Sustainable Energy Reviews, Volume 12, (Issue 7),* 1909-1927.

Schultz, M. G., Diehl, T., Brasseur, G. P., & Zittel W. (2003). Air pollution and climate-forcing impacts of a global hydrogen economy, *Science, 302(5645)*, 624-627.

Van Loo, S., & Koppejan, J. (2007). Handbook of biomass combustion and co-firing. *IEA Bioenergy Task 32*, 266-272.

Vollmer, M. K., Walter, S., Mohn, J., Steinbacher, M., Bond, S. W., Röckmann, T., & Reimann, S. (2012). Molecular hydrogen (H_2) combustion emissions and their isotope (D/H) signatures from domestic heaters, diesel vehicle engines, waste incinerator plants, and biomass burning, *Atmos. Chem. Phys., 12*, 6275-6289.