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The use of maize stalks for energy purposes and emissions measurement during their combustion

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Abstract. Biomass is an ideal renewable energy with advantages of abundance resources and neutral in greenhouse gas circulation. Majority of this energy could have been used directly in agriculture itself. The rest of the biomass for other parts of industry or even communal parts could be made available as a refined and densified biomass available for direct combustion in form of bales. The objective of the work was a monitoring of possibilities of maize cortical use for energy purposes during combustion. Emissions measurement from the combustion of maize phytomass was performed by measuring device TESTO 350 M/XL. During the combustion of packages with the moisture of 18% and 38% was monitored and the effect of moisture on the content of gas emissions of CO, CO_2, NO, NO_2 as well as the percentage of residual O_2 in the flue gas after combustion. All values of monitored emission limits were in current normative limits defined in Collection of Laws no. 356/2010. All emissions limits are in accordance to monitored standards for CO, CO_2, NO, NO_2, but on the other hand it should be noted that the more favourable results are based on combustion of cortical with moisture of 18% than at 38%. The issue of maize cortical harvesting considering machinery, technological and economical viewpoint within the Slovak republic but also worldwide is poorly understood and therefore these issues should be the subject of further research.

Key words: maize cortical, renewable energy, emission limits, maize cortical harvesting, maize cortical combustion.

INTRODUCTION

Biomass is an ideal renewable energy with advantages of abundance resources and neutral in greenhouse gas circulation (Krištof et al., 2011; Fei et al., 2014).

Maize is one of the agricultural crops, which have wide use from the view of phytomass production and is considered the third millennium crop. Why? Because the human and animal nutrition is impossible without utilization of maize. Alcohol, oil and biogas, also plastics, thermal insulation and other materials can be produced from maize, even electric energy by means of biogas cogeneration. Maize is primarily an economically profitable crop.

Considering combustion, characteristics of biomass are important; main indicators of quality are values of water content in biofuel, chemical composition of combustible fuel, content of volatile matter, biofuel heat value (Findura et al., 2006; Maga & Piszczalka, 2006; Jobbágy et al., 2011). Maize stalks have a heat value of 14.4 MJ kg^{-1} at moisture level of 10%, at the volumetric weight of 100 k gm^{-3} in packages. However, Straw, Miscanthus, maize, and horse manure were reviewed in terms of fuel characteristics by Carvalho et al. (2008) with conclusion that all the fuels showed problems with ash lumping and slag formation. Different boiler technologies showed different operational performances. Maize and horse manure are problematic fuels regarding NOx and particulate emissions. Miscanthus was the best fuel tested. It was also empathised that due to the big variation of fuel properties and therefore combustion behaviour of agricultural biomass, further R&D is required to adapt the existing boilers for these fuels.

Theoretically, in agricultural industry at Slovakia is possible to produce about 46,500 TJ (46.5 PJ) of energy from biomass without it even affect negatively on animal production (feeding, litter) or replacement of organic matter into soils. Majority of this energy could have been used directly in agriculture itself. The rest of the biomass for other parts of industry or even communal parts could be made available as a refined and densified biomass available for direct combustion in form of bales (selected types of fytomass) or wooden chips. From the maize biomass itself, with average annual production for energy purpose about 667,880 tons, is possible to be counted with production of equivalent amount of energy about 2,610 GWh or 9,400 TJ, respectively. This amount of relatively clean energy is therefore not insignificant while biomass is considered as carbon free fuel. Zhang et al., 2011 studied particle size distribution and polycyclic aromatic hydrocarbons (PAHs) emissions from the burning of rice, wheat, and corn straws, three major agricultural crop residues in China. He concluded that the total PAHs emissions from the burning of three agricultural crop residues in China were estimated to be 1.09 Gg for the year 2004 which is a great amount of emissions without energy production despite of the potential if studied biomass.

At the same time it needs to be noted that treatment of biomass is required for its use improvement. Moreover, biomass material pressing at very high pressure is aworking process, which we refer to as compaction in the final phase (Pepich, 2006).

Traditional multi-operational maize straw harvesting is performed in the following steps, which are defined by primary method of grain maize harvesting, it means what type of machine was used to harvest maize crop (Jandačka & Mikulík, 2008).

Grain harvest is performed by conventional combine harvesters with adapter for grain maize harvesting with crushing maize stalks under combine-harvester. After that, maize straw crushing is performed. This is followed by maize straw and stubble grinding by means of hammer and knife mulching machine (Birrell, 2006; Collection of Laws, 2010).

The objective of the study was a monitoring of possibilities of maize cortical harvesting by combine harvesters and its subsequent use for energy purposes during combustion. We monitored the combustion of packages with the moisture of 18% and 38% and the effect of moisture on the content of gas emissions of CO, CO_2, NO, NO_2 as well as the percentage of residual O_2 in the flue gas after combustion.

MATERIALS AND METHODS

Maize cortical was cultivated on farm in Rastislavice on the area of 34.62 hectare. Biological grain and maize stalks yield were evaluated from the selected area as well. The methodology of sampling and evaluation was performed according to recommendation by Jobbágy et al. (2011). Samples were manually harvested from area

10 m^2 from 5 different places of the field before complete harvest by harvester. Despite of the biological yields of maize, only around 60% of maize residues were collected due to complicated post-harvest treatment. For grain harvesting was used altered combine harvester JD assembled with corn adapter Olimac.

The pressing of maize cortical was performed by pressing machine KUHN LSD 1270 for large-volume; square packages. Packages have been removed from the territory and stored.

We chose incineration of Menert-Therm in Šaľa, Slovakia which provides heating of several residential buildings, for packages from maize cortical combustion. The combustion unit is characterised by following parameters: Combustion unit CHP JUTSEN (Datatherm, ltd., Slovakia); Nominal power output of boiler (1.5 MW); Nominal power output of steam (13 t h^{-1}); Nominal working pressure (38 bar); Nominal working temperature (400 °C); Power output of generator (2,775 kVA) with Turbine produced by SIEMENS. The combustion unit is designed for combustions of various biomass materials with relative moisture content up to 30% (straw, wood chips, densified pellets and briquettes, and maize straw as well as it was observed in the study). The combustion units works on the principal of continuous feeding of material into combustion chamber while the dimension of the combusted material is among the most important parameters. The combustion chamber is filled by gravimetric principle where chopped piece of whole package is delivered to the combustion process in time intervals controlled by control units which observe and adapt the speed of feeding at the basis of evaluation of combustion processes.

Compressed packages of maize cortical with dimensions of 2,200 x 1,200 x 900 mm, with a weight of 400 kg, with a moisture content of 18% and 38% (Fig. 1) were used as combustion material.

Figure 1. Package of maize cortical inserted into the dosing device of incinerator.

Emissions measurement from the combustion of phytomass was performed by measuring device TESTO 350 M/XL, which is used by the Department of machines and production systems. Modular system TESTO 350 M/XL is composed of three main parts (Fig. 2). This device is calibrated for accurate emissions measurement, while the evaluations of the measured values are based on emission limits defined by the Clean Air Act no. 137/10 and by the Decree Ministry of Environment of the Slovak Republic no. 356/2010.

Figure 2. Modular system TESTO 350 M/XL for the analysis of flue gases: A – control unit; B – analyzer box; C – sampling probe.

From a variety of values, which could be measured by TESTO 350 M/XL, for analysis, we chose O_2, CO, CO_2, NO, NO_2 gases, as well as control values: flue gas temperature, qA, lambda and efficiency.

Ultimate analyses for the carbon (C) and nitrogen (N) content in dry mass, as well as proximate analyses for the moisture, ash, volatile matter, and fixed C content as received (Liao et al., 2004). When studying the effect of different moisture contents on emissions, we rehydrated the crop residues by adding ultrapure water to obtain fuels with different moisture levels (~10%, 18% and 38%), and then sealed the wet fuel in plastic bags for 1–2 days before combustion (Chen et al., 2010). The moisture content was tested before each burn.

RESULTS AND DISCUSSION

Considering opportunities of PD Rastislavice, Slovakia and incineration of Menert-Therm in Šaľa, Slovakia we proceeded with maize cortical utilization as a source of energy for heating of residential buildings.

Monitored values of biological yield of maize phytomass

Based on measured and graphically evaluated values we can conclude that the phytomass yield is very variable. Biological yield of grains on monitored parcel ranged from 8.36 to 12.05 t ha^{-1} and yield of maize material was in the range of 11.34 to 15.8 t ha^{-1}.

Comparison of measured characteristics parameters of combustion and emissions at different moisture level

Results of experimental measurements are shown in Fig. 6. (CO emissions) and Table 1 (all parameters). Some values are presented in internationally recognized units of ppm (parts per million). Results of the average values of experimentally monitored emissions are more favourable for combustion of maize cortical at moisture of 18% than at 38% moisture.

Utilization of the maize straw as a source of energy was also studied by Carvalho et al. (2013). In their study, maize straw was also considered as satisfactory due to its energy potential, however, their emphasis that boiler controls should be improved to better adapt the combustion conditions to the different properties of the agricultural fuels. Additionally, there is a need for a frequent cleaning of the heat exchangers in boilers operated with agricultural fuels to avoid efficiency drops after short term operation.

However, biomass burning emissions, including carbon dioxide (CO_2), carbon monoxide (CO), elemental carbon (EC), organic carbon (OC), particulate matter (PM) and others (Andreae & Merlet, 2001; Jenkins et al., 1992), still have significant impacts on the local and regional environment (Huang et al., 2012a; 2012b; 2014). Emission factors (EFs), defined as the mass of a pollutant emitted per unit of fuel consumed, are used to compile emission inventories, as inputs to dispersion models, and to evaluate the effectiveness of pollutant control strategies. EFs strongly depend on the type of crop, and burning conditions, such as fuel load and moisture content (Reid et al., 2005; McMeeking et al., 2009; Chen et al., 2010) as it was indicated in our study (see Table 1).

Table 1 Descriptive statistic of measured parameters of emissions

Moisture, %	PARAMETERS	O_2, %	CO, ppm	CO_2, %	NO, ppm	NO_2, ppm
18	MEAN	**15.63***	**479.01***	**5.86***	**42.69***	**1.27***
	Median	20.33	493.55	3.57	7.75	0.99
	s.d.	6.24	225.10	3.04	47.84	0.72
	Kurtosis	-1.74	0.00	-1.55	-1.51	2.73
	Skewness	-0.55	-0.25	0.64	0.62	1.91
	Minimum	6.43	40.75	3.06	3.15	0.56
	Maximum	20.69	970.20	10.69	131.15	3.29
	Count	28	28	28	28	28
38	MEAN	**11.13**	**384.96**	**7.24**	**88.63**	**14.83**
	Median	13.33	409.85	5.62	88.05	10.24
	s.d.	3.54	183.91	2.60	14.75	9.96
	Kurtosis	-1.76	-1.27	-1.76	-1.03	-1.17
	Skewness	-0.47	-0.05	0.47	0.39	0.27
	Minimum	5.71	110.19	4.70	68.00	0.48
	Maximum	14.60	702.15	11.21	115.00	32.37
	Count	33	33	33	33	33

*denotes statistical significant difference; *Duncan´s test*; $n = 28$; $\alpha = 0.05$ (for CO $p = 0.07$; for CO_2 $p = 0.06$; for other means $p < 0.05$).

Measurement of percentage values of residual oxygen in the flue gases

Measured and evaluated results are shown graphically in Fig. 3.

Previous studies have obtained many EFs for open burning of crop residue worldwide as summarized in Supplemental (e.g. Nguyen et al., 1994; Yokelson et al., 1996; Turn et al., 1997; Andreae & Merlet, 2001; Hays et al., 2005; Dhammapala et al., 2006; Kim Oanh et al., 2011), but few of these studies have considered the effect of moisture content on EFs (Kim Oanh et al., 2011). A more recent study by Hayashi et al. (2014) determined EFs for open burning of rice straw, wheat straw and barley straw in Japan using a portable combustion hood, and evaluated the effects of fuel moisture content on the EFs. Hayashi et al. (2014) found that increased moisture content enhanced the emissions of CO, CH_4 and particulate organic matter.

As it was indicated by Ni et al. (2015), fuel moisture decreased the CO_2 EF but increased the EFs of incomplete combustion products (e.g. CO, $PM_{2.5}$ and OC). This may be caused by the enhanced smouldering burn of wet fuels. The increased OC emissions due to an increase in moisture (from Level I to II, and from Level II to III) accounted for ~50% of the increase in $PM_{2.5}$ emissions. Hence, the increased emission of $PM_{2.5}$ could partly be attributed to the increased OC emission. Even though the EFs of EC did not decrease with increased moisture content, the EC fraction in total carbon (TC) displayed a decreasing trend with increasing moisture content: 0.05, 0.04 and 0.03, respectively. This corresponds to EC being generated from a flaming phase that is intensified when the fuel is dry (Lobert & Warnatz, 1993).

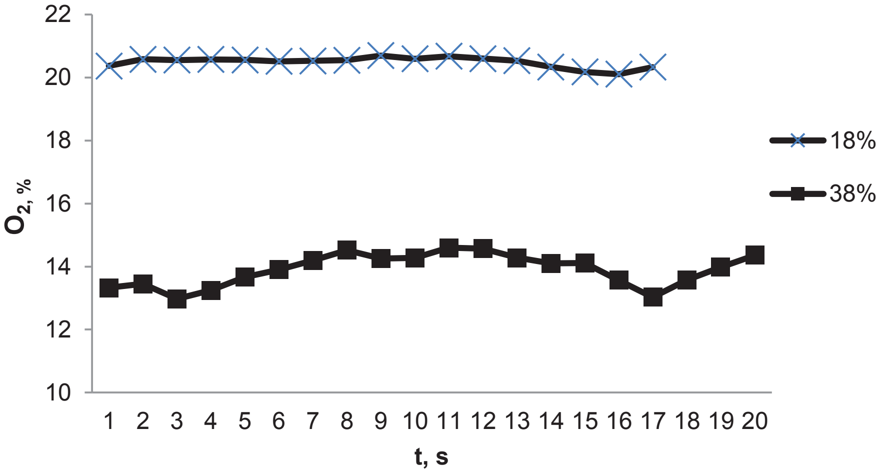

Figure 3. Comparison of percentage state of residual oxygen.

Based on measured values, we can allege that time-scale percentage state of oxygen in the flue gas has an average value of 15.12% with a maximum value of 21% and a minimum value of 5.37%. As presented in graphical form, at the start of combustion (inserting the tapered part of the package to the boiler) oxygen conditions are very different but after stabilization of combustion oxygen conditions are stable in the range from 10 to 15%.

As it shown in Fig. 3, in case of maize straw bale with lower moisture content (18%) resulted in increased mean value of oxygen at level 20% while in case of bale with greater moisture (38%) resulted in decreased mean value of 13.89% of oxygen in gas emissions. More importantly, the lowest value of oxygen was recorded at the beginning of bale combustion (12.97%) while later on values starts to increase by roughly linear trend up to 8th second of measurement to value 14.52% and then decrease slowly again down to value 13.02% in 17th second of measurement while then starts to increase roughly by linear trend.

He et al. (2009) studied reaction heat of agro-stalks smouldering, wheat straw, corn stalk, cotton stalk, millet straw, sorghum stalk and sweet potato rattan powder were smouldered and pyrolyzed in a simultaneous thermal analyzer (STA). This study showed that the oxidative polymer degradation heat of the agro-stalks is more than 6.92 MJ kg^{-1} consumed matters, higher than that of cellulose paper. And char oxidation heat is around 23 MJ kg^{-1} consumed matters, similar to that of cellulose paper, but higher than that of cigarette.

Measurement of CO_2 content in the flue gases

Process of CO_2 content in the timeframe is shown in Fig. 4. Based on measurement results, we detected very different values of CO_2 emissions when inserting the package into the boiler and subsequent stabilization of values in the range of 0.6 to 11.4 ppm.

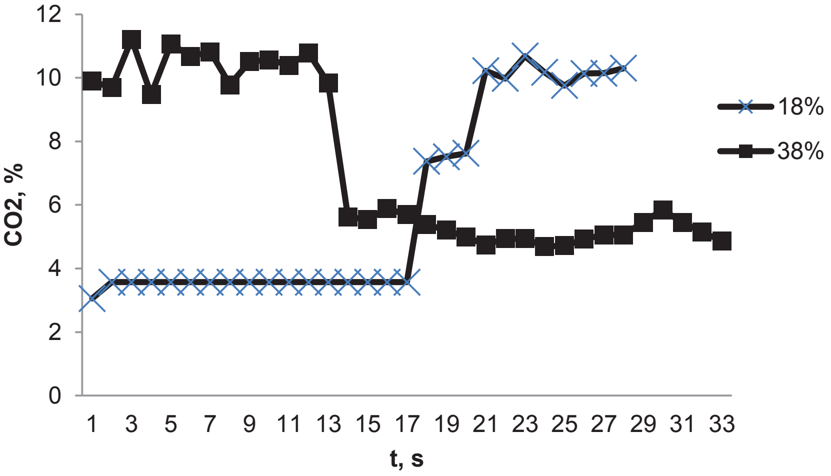

Figure 4. Comparison of state of CO_2 emissions.

The results again shown reasonable different values of CO_2 emissions during combustion of bales made of maize straw with overall moisture 18% and 38%. As is is possible to see at the Fig. 8, the beginning of combustion in case of bale with 18% moisture was characterized by values of 3.05% and 3.57% until the 17th second when the increase was recorded up to value 10.68% in 23th second when it starts decreasing in slow rate. Despite of that, mean value of CO_2 emissions 5.85% was recorded. In contrast, bale with greater moisture (38%) caused greater amount of CO_2 emissions at the beginning of combustion process and values ranged from 9.47% to 11.21% until 13th second when it reach dramatically value 5.53%. Rest of the combustion was characterized by relatively stable measured value of CO_2 emissions until 30th second when it increased to 5.84% and then decrease roughly by linear trend while mean value of emissions were observed at level of 7.23%.

Big jumps in values at 17th second of burning process were observed in the measurement of all types of emissions. These jumps are probably caused by opening and closing the combustion chamber which take place each time when fuelling the combustion chamber. Opening and closing caused an additional supply of oxygen to the chamber and thus incomplete combustion of materials. In such cases, it tends to increase the emission flow (Shen et al., 2013). Despite this fact, were not recorded exceeding emission limits.

Measurement of NO content in the flue gases

Process of measured values of NO emissions is shown in Fig. 5. State of NO emission from the combustion of cortical is very variable at the start of combustion, but after stabilization of combustion, values are within acceptable numbers around 43.56 ppm. The production of NO emissions during combustion of maize straw bale with 18%

of moisture at the beginning of measurement indicated as a relatively stable where the values ranged from 3.15 ppm to 8.3 ppm. Later on (about 18 seconds) production rapidly raised even at the level of 118.35 ppm while continuous trend was characterized by a great variability and values ranged from 78 ppm up to 131.15 ppm. In contrast, emission production in case of greater bale moisture (38%) varies a lot (from 68.45 ppm to 115 ppm) until 16 seconds of combustion time. The values fluctuated until it reached 109 ppm where it starts decrease linearly until 29 seconds of combustion to value of 106 ppm and the again linearly decrease to the minimum of measured emissions.

According to Qian et al. 2011, temperature and excess air ratio are the major operating parameters for NO emission. For biomass with high nitrogen content, NO emission decreases with excess air, and increases with bed temperature.Compared with char-N, volatile-N is the more dominant reactant source for NO emission. Therefore, according to our study, moisture content of biomass may be considered also as one of the affecting parameter even only at the beginning of combustion process as it is shown at Fig. 5.

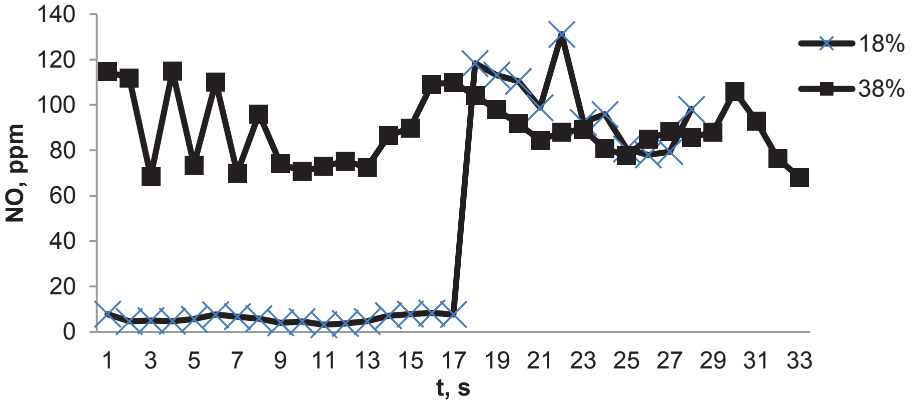

Figure 5. Comparison of state of NO emissions.

Measurement of NO_2 content in the flue gases

The results of measurements of NO_2 emissions by modular system TESTO 350 M/XL are shown in Fig. 6. State of NO_2 emissions from the combustion throughout the time horizon is circulating around the value of 0.99 ppm, but combustion of dumpy cortical after the chamber closing caused an increase of value to 43.8 ppm.

Brunner et al. (2013) focused on relevant combustion characteristics of biomass fuels in grate combustion systems. In this study it was comprised a wide variation of different fuels, including conventional wood fuels (beech, spruce, and softwood pellets), bark, wood from short rotation coppice (SRC) (poplar and willow), waste wood, torrefied softwood, agricultural biomass (straw, Miscanthus, maize cobs, and grass pellets), and peat and sewage sludge. Study showed that that the thermal decomposition behavior and the combustion behavior of different biomass fuels vary considerably. It was concluded that the conversion rate from N in the fuel to N in NOx precursors varies between 20 and 95% depending upon the fuel and generally decreases with an increasing N content of the fuel. Moreover, as it was stated, the release of ash-forming vapors also considerably depends upon the fuel used. In general, more than 91% of Cl, more than

71% of S, 1–51% of K, and 1–50% of Na are released to the gas phase. Study also reveal that the potential for aerosol emissions can be estimated, which varies between 18 mg Nm^3 (softwood pellets) and 320 mg N m^3 (straw) (dry flue gas at 13% O_2). Moreover, these results also provide first indications regarding the deposit formation risks associated with a certain biomass fuel.

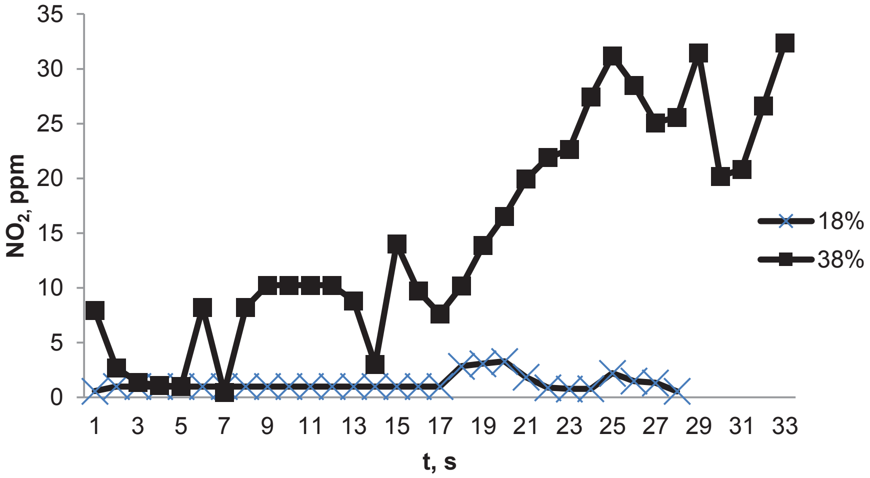

Figure 6. Comparison of state of NO_2 emissions.

Shen et al. (2013) conducted a study to investigate the influences of fuel mass load, air supply and burning rate on the emissions and size distributions of carbonaceous particulate matter (PM) from indoor corn straw burning in a cooking stove. Among other conclusions it was also suggested that special attention should be paid to the use of CO as a surrogate for other incomplete combustion pollutants due to the observation that emission factor of organic matter, particulate matter and elemental carbon were found to be positively correlated with each other but they were not significantly correlated with the emission factor of co-emitted CO (Fig. 7).

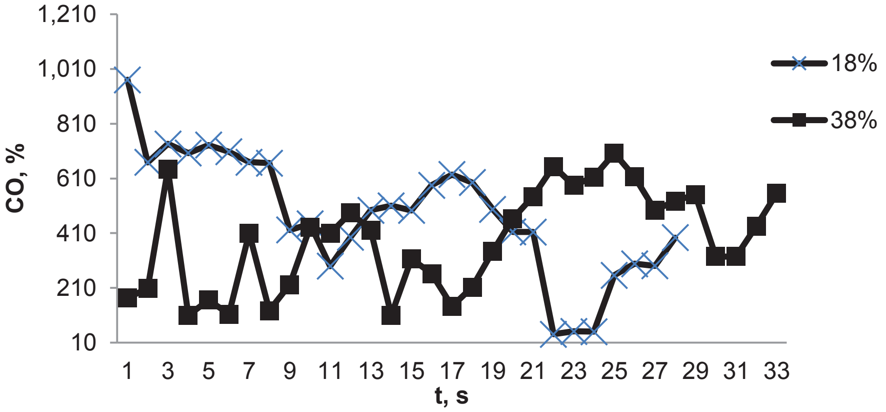

Figure 7. Comparison of state of CO emissions.

The use of corn straw as a source of energy is important also in conjunctions with conclusions made by Ni et al. (2015) while it was concluded that open burning of crop residue is an important source of carbonaceous pollutants, and has a large impact on the regional environment and global climate change. In addition, the effect of fuel moisture was investigated through the controlled burning of wheat straw. Increasing the moisture content decreased the CO_2 emission factor, and increased the emissions factors of CO and organic carbon.

Moreover, the gasification of straw stalk in CO_2 environment was studied by isothermal thermogravimetric analysis. The characteristics of rice straw and maize stalk gasification at different temperatures were examined under CO_2 atmosphere. The relationship between reaction time and carbon conversion of two biomass chars was analyzed by the random pore model (RPM), and compared with the simulation of the shrinking core reaction model (SCRM). The results show that the random pore model is better to predict the experimental data at different temperatures. This means that the characteristics of pore structure for the influence of biomass chars gasification is well reflected by parameter ψ used in RPM. It indicates that the RPM can be applied to the comprehensive simulation of biomass chars gasification in CO_2 environment (Fei et al., 2014).

CONCLUSIONS

Based on measured experimental results and their assessment it can be concluded that the use of maize cortical for energy purposes during combustion is real and, considering climate gas emissions, measured values are within emissions limits defined in Collection of Laws no. 356/2010, page 2,955, article 1.9. Stationary equipment for combustion of fuel with a total nominal power of 0.3 MW to 50 MW. All emissions limits are in accordance to monitored standards for CO, CO_2, NO, NO_2, but on the other hand it should be noted that the more favourable results are based on combustion of cortical with moisture of 18% than at 38%. This observation is even more interesting while the combustion unit was designed to utilize only few biomaterials and as limited value was set the moisture of this material to 30%. The issue of maize cortical harvesting considering machinery, technological and economical viewpoint within the Slovak republic is poorly understood, therefore, these issues will be the subject of further research at the Department of machines and production systems.

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