doi: 10.17221/36/2014-RAE

Flue gases thermal emission concentration during waste biomass combustion in small combustion device with manual fuel supply

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Abstract

Bradna J., Malaťák J. (2016): **Flue gases thermal emission concentration during waste biomass combustion in small combustion device with manual fuel supply**. Res. Agr. Eng., 62: 1–7.

The aim of the experiments is determination of emission concentrations in the observed substances produced in exhaust gas during combustion of various mixtures of waste biomass compacted samples. The samples were pressed into the form of briquettes with a diameter of 65 mm. During the actual measurements the following parameters were monitored: emissions of carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x) and flue gas temperature depending on the excess air coefficient. Measurements of emission parameters were carried out in storage heater fireplace with nominal heat output of 8 kW. During the measurements high concentrations of carbon monoxide in excess of the value of 5,000 mg/m^3 were determined, especially in the samples of waste from corn cleaning and wheat straw. The results show an excess air factor optimum adjustment on value 3, where the combustion device achieves optimum parameters of CO and NO_x emissions. The results of emission measurements confirmed that the excess air is a very important operating variable which affects both monitored emissions concentrations and the combustion temperature in the fireplace.

Keywords: wheat straw; wood chips; molasses; beet chips; sludge; carbon and nitrogen oxides; flue gas temperature

Waste which cannot be recycled, reused or otherwise used (e.g. for energy purposes) should be safely burnt (in the case when waste combustion efficiency cannot meet the criteria for efficient energy recovery), and landfilling should be the last resort (European Parliament and Council Directive 2008/98/EC). Both these methods require close monitoring due to their effect to potential environmental damage. Therefore, the EU adopted a directive establishing strict rules for landfilling. The so-called Landfill Directive, among others, prohibits the landfilling of certain types of waste, such as whole used tires, and sets targets for reducing the amount of landfilled biodegradable waste, which follows the intention to reduce pollution of groundwater and surface water and soil and the release of landfill gas (methane) (Council Directive 1999/31/EC). Other directive (Air Protection Act; No. 201/2012 Coll.; Ministry of Environment of the Czech Republic.) prescribes strict emission limits for waste incineration; the European Union also wants to reduce emissions of dioxins and acid gases (NO_x, SO_2, HCl), which may be harmful to human health (European Parliament and Council Directive 2000/76/EC).

Supported by the Internal Grant Agency of the Faculty of Engineering of the Czech University of Life Sciences Prague, Grant No. 2013:31170/1312/3116.

doi: 10.17221/36/2014-RAE

The energy use of waste biomass as a renewable source of energy has many positive aspects and helps solve problems not only ecological but also in agro-forestry (McBurney 1995). The biomass-based fuels contain almost no sulfur and sulfur dioxide emissions (Hájek et al. 2013). Other pollutants in emissions from waste biomass are favourable in comparison with emissions from fossil fuels (Malaťák, Passian 2011). Ash from biomass-based fuels can be largely used as a fertilizer with a favourable content of calcium, magnesium, potassium and phosphorus (Olsson, Kjallstrand 2004).

This paper addresses urgent issues of energy use of fuels based on waste biomass in small combustion devices with manual fuel supply in the form of briquettes. For example, the authors Johansson et al. (2003); Olsson et al. (2003); Gürdíl et al. (2009) point to a very good emission properties of biomass combustion in modern combustion devices. If we have to decide on biomass waste, whether it is suitable for burning in a certain type of combustion device, it is necessary to know those of its properties that characterize it enough. One of these properties is the heat-emission characteristics.

MATERIAL AND METHODS

As part of the research project waste biomass was experimentally combusted in the form of pellets with a diameter 65 mm in storage heater fireplace with open system and nominal heat output 8 kW. The basic task was to identify the individual thermal emission concentrations of CO, CO_2, NO_x and flue gas temperature depending on the excess air coefficient.

To determine the mass flow rates, emission factors and characteristics of solid particles during thermal processing of biomass briquettes multipurpose flue gas analyser Madur GA-60 (Madur Polska Sp. z o.o., Zgierz, Poland) was used. Standard equipment of this analyser are converters to analyse components of flue gas: oxygen (O_2), carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2) and hydrogen chloride (HCl). GA-60 analyser allows measuring both ambient temperature (T_{ok}) and flue gas temperature (T_{sp}). Fuel and combustion devices are assessed through these measurements, as regards their thermal parameters and emission ratios.

The samples of solid waste materials for briquettes production are obtained from the Central Bohemia Region of the Czech Republic during 2014. First waste biomass from agricultural sector is selected, such as wheat straw, reed canary grass, poplar wood chips from forestry and waste from the cleaning grain from grain to flour processing, dried and stabilized sludge from the wastewater treatment plant in Prague, beet chips and molasses from sugar refinery. These waste materials are mixed in a ratio shown in Table 1 and pressed into briquettes shape with a diameter of 65 mm by briquetting equipment of the company Briklis Ltd. (Malšice, Czech Republic)

Operational tests were conducted according to the CSN EN 13229:2002. The chimney draft values depending on the nominal heat output fluctuated within a prescribed range of 12 ± 2 Pa (values of static pressure in the flue gas measuring section), because the heating system was tested with a lockable fireplace. During the tests average concentrations of carbon monoxide and other gaseous emissions were converted to 13% oxygen (O_r).

Combustion device with manual fuel supply is designed to burn any wood or wood briquettes. Its main component is the fireplace insert from sheet steel or cast iron stove thickness of 5–8 mm. From the sides and above it is panelled by feolite bricks that allow accumulating heat and giving it some time after burning. The accumulation bricks are covered with an insulating layer specifically made and shaped by isolation of calcium silicate. The doors are fitted

Table 1. Samples of briquettes with diameter of 65 mm

No. of sample	Sample types of briquettes and the ratio of raw materials
1	wheat straw
2	reed canary grass and poplar wood chips in ratio1:1 and 10% of brown coal
3	waste from cleaning of grain
4	wheat straw and 15% of beet chips
5	wood chips and 10% of dried stabilized sludge
6	wheat straw and 10% of molasses

doi: 10.17221/36/2014-RAE

with ceramic glass resistant up to 750°C. Flue gases are discharged through the flue pipe with a diameter of 150 mm and then vented into the chimney.

All measured values were statistically evaluated with statistical regression analysis with the regression equation expression and the value of reliability, and are converted to standard conditions (at temperature $T = 0°C$ and pressure $p = 101.325$ kPa) and to reference oxygen content in the flue gas $O_r = 13\%$.

RESULTS AND DISCUSSION

The resulting thermal-emission concentrations in ppm from the flue gas analyser are converted to standard conditions and to mg/m^3 and then converted to 13% reference oxygen content in the flue gas. Firstly, carbon monoxide and carbon dioxide are plotted in dependence on the size of excess air coefficient. In the calculation of excess air coefficient carbon dioxide emission concentrations are used according to equation (Malaťák, Passian 2011):

$$n = 1 + \left(\frac{CO_{2\max}}{CO_2} - 1 \right) \times \frac{V^s_{sp,\min}}{L_{\min}} \qquad (1)$$

where:

$CO_{2\max}$ – theoretical volume concentration of carbon dioxide in dry flue gas (%), $n = 1$

CO_2 – measured value of carbon dioxide concentration in dry flue gas (%)

$V^s_{sp,\min}$ – theoretical volume of dry flue gas (m^3_N/kg), $n = 1$

$L_{\min}$ – theoretical amount of air for complete combustion (m^3_N/kg), $n = 1$

The resulting emission concentrations of carbon monoxide and carbon dioxide according to the excess air coefficient are shown in Fig. 1.

Graphical illustration of carbon monoxide and carbon dioxide according to the excess air coefficient is significant due to its progress. Dependence of carbon dioxide, the product of complete combustion, on the excess air coefficient is similar in all cases. With increasing amount of air the concentration of carbon dioxide decreases from maximum to minimum when the flame cooling and dilution of flue gas are done by combustion air.

Given that hydrocarbons and other incompletely combusted products behave like carbon monoxide, this emission component represents a significant indicator of the combustion process quality (Johansson et al. 2003). Carbon monoxide, a product of incomplete combustion, first in a very low excess air coefficient, decreases to the optimum values. For each considered waste biomass sample optimal values are shifted depending on the excess air coefficient. After crossing these optimal values of the excess air coefficient carbon monoxide is gradually increasing up to its maximum concentration. This process can be monitored in samples of wheat straw briquettes and wood chips with 10% dry stabilized sludge. Other samples have the opposite course except for briquettes from waste after cleaning grain, in which occurs a gradual increase of carbon monoxide from the beginning of measurement.

The question arises why other courses of carbon monoxide emission concentration during combustion of selected samples occur. It can be seen in more factors such as calorific value, proportion of volatile matter in the sample and amount of combustion air supplied to the combustion chamber. Also in the combustion chamber these samples occur to varying degrees of volatile combustible substances mixing with combustion air and degree of burning. The part of combustibles burn not enough and are entrained with the flue gas.

From these characteristics expressed during combustion it is possible to optimise combustion device with the greatest combustion efficiency. From the Fig. 1 it is seen that each sample has an individual setting. This optimum boundary of combustion air intake to combustion chamber is around three times of the excess air coefficient.

Equally important emission components are nitrogen oxides emission concentration and flue gas temperature. The resulting values of nitrogen oxides and carbon dioxide emission concentrations depending on the excess air coefficient are shown in Fig. 2.

The course of flue gas temperature in dependence on the excess air coefficient is identical in all cases. With increasing amount of air the flue gas temperature decreases from maximum to minimum, where flame cooling and dilution of flue gas by combustion air happens.

The concentration of nitrogen oxides at low excess air coefficient values depends primarily on the temperature of combustion (flue gas temperature). In the course of its increase, the excess air coefficient occurs first to cool the combustion temperature (flue gas temperature). With increasing amount of atmospheric nitrogen in the combustion air (excess air coefficient) the concentration of nitrogen oxides increases. This course can be ob-

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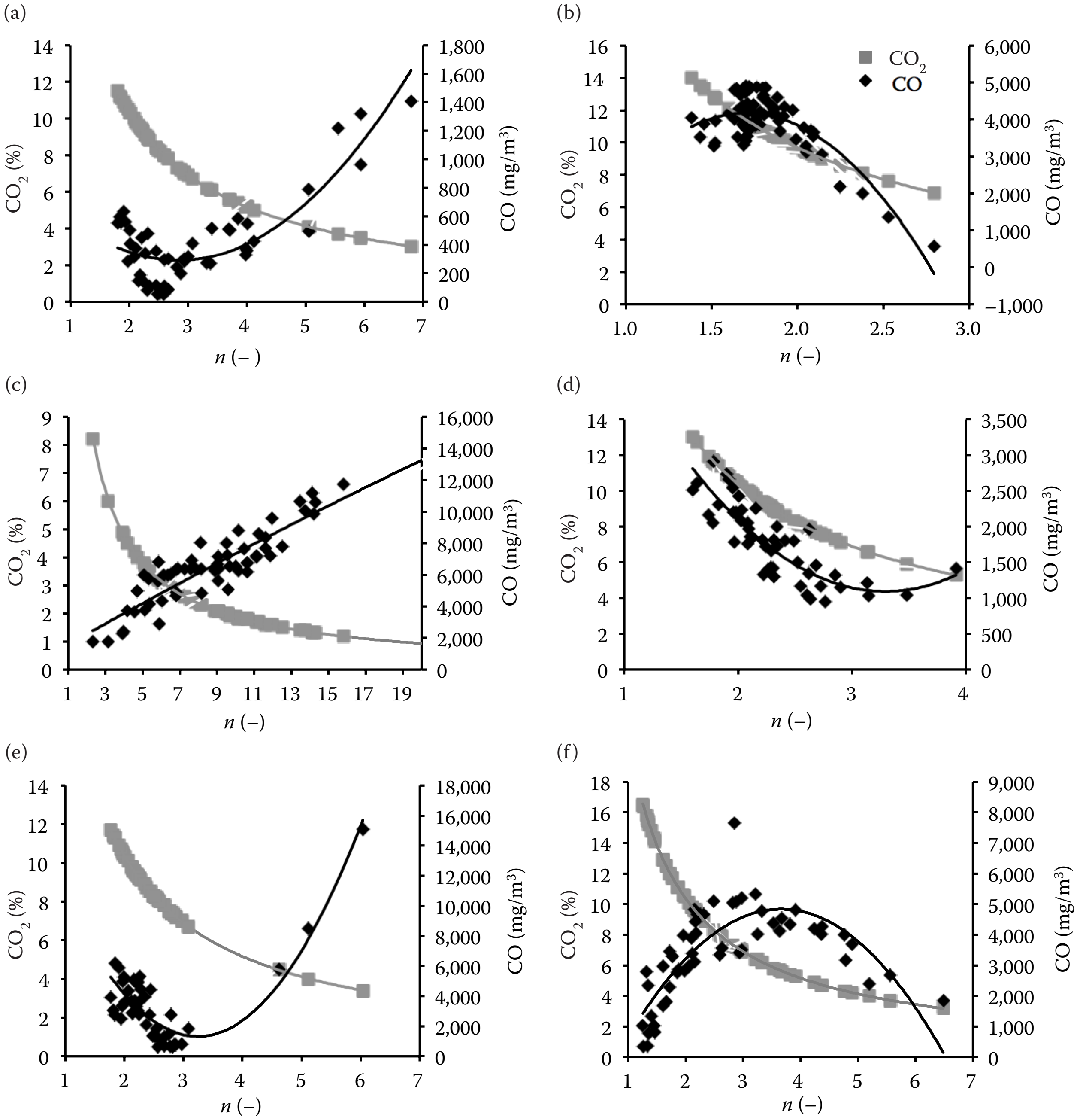

Fig. 1. The resulting emission concentrations of carbon monoxide (CO) and carbon dioxide (CO_2) according to the excess air coefficient for sample (a) No. 1, (b) No. 2, (c) No. 3, (d) No. 4, (e) No. 5, and (f) No. 6

served in nearly all samples of waste biomass. For a single sample of wheat straw the opposite course occurs. The flue gas temperature at low excess air coefficient exceeds the high value of 700°C and in the course of increasing excess air coefficient the flue gas temperature drops only to around 400°C.

From the resulting NO_x emission concentrations and flue gas temperature depending on the excess air coefficient combustion device can be optimised with the lowest possible nitrogen oxides emission concentrations and heat loss. The Fig. 2 shows that for each sample of waste biomass the settings are individual. This optimum boundary of combustion air intake to combustion chamber varies also about three times of the excess air coefficient.

The cause of high nitrogen oxides emissions may be elemental composition of waste biomass whose samples typically have a greater amount of nitrogen in the fuel itself. These fuels can lead to increased emissions of nitrogen oxides in flue gases (Liu et al.

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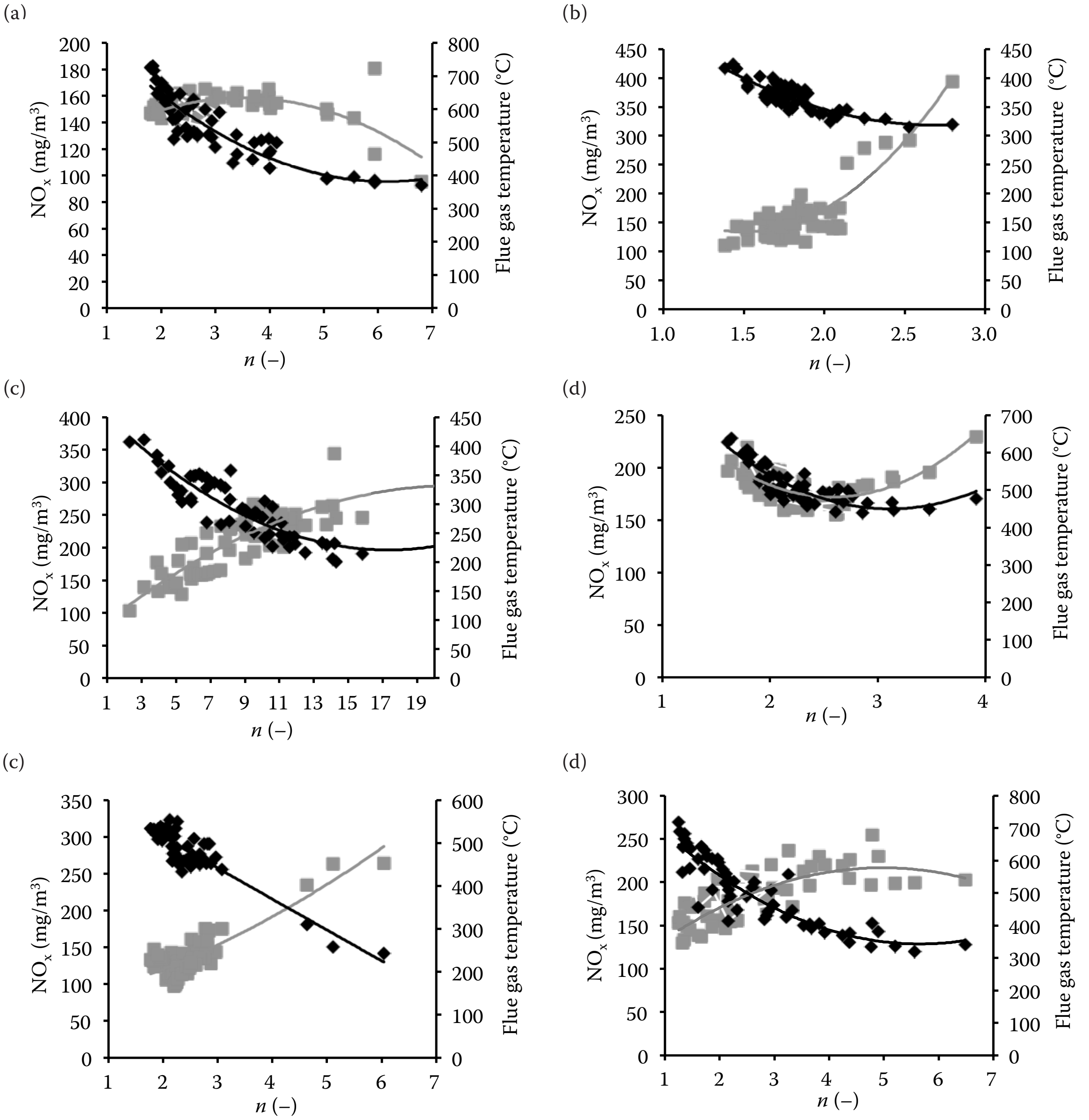

Fig. 2. Resulting NO_x emission concentrations and flue gas temperature depending on the excess air coefficient *n* for sample (a) No. 1, (b) No. 2, (c) No. 3, (d) No. 4, (e) No. 5, and (f) No. 6

2013). Another factor that brings about the higher nitrogen oxides formation is high flue gas temperature, which is caused by overheating of the combustion chamber and by the high excess air coefficient (Hájek et al 2013). Increased temperature in the combustion chamber increases the combustion temperature, which gives rise to high-nitrogen oxides (Fiedler, Persson 2009). A large amount of combustion air in the combustion chamber improves the oxidation reaction of flue gas (Houshfar et al. 2011). To avoid excessive emissions of nitrogen oxides, simply adjust the fuel mass flow into the combustion chamber and thus the amount of combustion air into the combustion space. Another solution requires more intervention into the combustion chamber, such as relocation of refractory retorts or heat exchangers.

Flue gas temperature difference in the individual samples of waste biomass can be justified by the amount of air supplied to the combustion device, by

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Table 2. Regression statistical analysis values for carbon monoxide (CO) and carbon dioxide (CO_2) according to the excess air coefficient *n*

No. of sample	Regression equation CO	Reliability	Regression equation CO_2	Range *n*
1	$CO = 85.36n^2 - 484.86n + 978.23$	0.726	$CO_2 = 20.829n^{-1.0045}$	1.8–6.8
2	$CO = -3629.3n^2 + 12355n - 6351$	0.672	$CO_2 = 19.5n^{-1.0107}$	1.4–2.8
3	$CO = -2.7247n^2 + 672.18n + 903.69$	0.827	$CO_2 = 19.444n^{-1.0151}$	2.0–16.0
4	$CO = 600.13n^2 - 3950n + 7595.3$	0.731	$CO_2 = 20.859n^{-1.007}$	1.7–3.9
5	$CO = 1844.7n^2 - 11959n + 20702$	0.784	$CO_2 = 20.871n^{-1.0073}$	1.8–6.1
6	$CO = -589.41n^2 + 4317.7n - 3071.7$	0.638	$CO_2 = 20.839n^{-1.0062}$	1.0–7.0

Table 3. The resulting regression statistical analysis values for flue gas temperature (T_{sp}) and NO_x according to the excess air coefficient *n*

No. of sample	Regression equation T_{sp}	Reliability	Regression equation NO_x	Reliability
1	$T_{sp} = 15.243n^2 - 187.42n + 958.2$	0.814	$NO_x = -4.1492n^2 + 29.149n + 107.36$	0.409
2	$T_{sp} = 56.26n^2 - 303.82n + 728.7$	0.728	$NO_x = 158.66x^2 - 477.13x + 492.43$	0.797
3	$T_{sp} = 0.8652n^2 - 29.964n + 480.38$	0.802	$NO_x = -0.5109n^2 + 21.695n + 64.779$	0.721
4	$T_{sp} = 72.506n^2 - 450.75n + 1151$	0.761	$NO_x = 33.906n^2 - 174.92n + 397.68$	0.566
5	$T_{sp} = 0.1806n^2 - 73.558n + 660.79$	0.829	$NO_x = 2.7301n^2 + 19.289n + 71.049$	0.759
6	$T_{sp} = 15.828n^2 - 178.89n + 848.57$	0.816	$NO_x = -5.2277n^2 + 51.949n + 87.669$	0.630

the calorific value of samples and also by the weight percentage of the sample volatile components. Thus provided high levels of flue gas temperatures may increase heat loss through increasing flue gas heat.

Foreign research works confirm the measuring conclusions that elevated temperature and high combustion air content (5–21%) has a significant effect on the increased production of nitrogen oxides from fuel nitrogen (Eskilsson 2004; Fiedler, Persson 2009). Decreasing amount of combustion air results in reducing nitrogen oxide emissions, but also increase emissions of carbon monoxide in the flue gas. New carbon monoxide chemical sensors in cooperation with the lambda probe provide an effective control for optimal performance of combustion device with respect to emissions and thermal efficiency (Vierle et al. 1999).

In the Eskilsson (2012) research work there is a compromise between the unburnt carbon oxides and nitrogen oxides. Decreasing amount of air in the combustion chamber reduces the amount of nitrogen oxides in flue gas, but on the other hand increases emissions of unburnt carbon oxides. Finding an optimal adjustment of the excess air coefficient for different types of fuels from biomass solves the problem of nitrogen oxides and carbon monoxide emissions.

Waste biomass also has a high level of carbon monoxide due to high humidity of the fuel and due to wrong construction of the combustion chamber. Generally, it should be brought secondary air for perfect burning, time delay of combustible gaseous particles should be at least 0.5 and the temperature of combustion should reach around 1,000°C (Vierle et al. 1999).

The resulting values of the regression statistical analysis are presented for carbon monoxide and carbon dioxide depending on the excess air coefficient in Table 2 with the expression values of reliability. Table 3 shows resulting regression equations for flue gas temperature and NO_x in dependence on the excess air coefficient with expression values of reliability.

CONCLUSION

The quality requirements for heating are rising considerably, even from the perspective of its impact on the environment. For local solid fuel appliances, which are mainly used in homes, the flue gas cleaning system cannot be used as in larger devices and therefore it is necessary to use standardized high quality level solid fuel. By using the closed and controllable combustion chamber in fireplace in-

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sert bad combustion conditions in open fireplaces are removed. In tiled stove inserts primarily the combustion chambers with an upper afterburning are asserted, especially where there are suitable storage heaters. For these reasons the storage heater with a rated nominal heat output of 8 kW was selected as the experimental combustion device.

As regards the carbon monoxide emissions, combustion equipment should work as evidenced by other research works in the nominal parameters. Any uncontrolled change of combustion material flow and combustion air leads to high carbon monoxide emissions (Fiedler, Persson 2009).

Every type of combustion device has its own characteristic behaviour of carbon monoxide. The greatest emissions occur mainly during the ignition and stopping of combustion device. When setting combustion plant to reduce emissions during ignition and stopping, an increased emission occurs again during combustion. When stopping combustion process, fuel in the combustion chamber still smoulders and produces high emissions (Friberg, Blasiak 2002).

The greatest emission concentration of carbon monoxide and nitrogen oxides is achieved at high excess air coefficient. The high amount of combustion air cools the combustion chamber and results in high emissions of carbon monoxide in the flue gas (Johansson et al. 2003).

From the carbon dioxide (CO_2) content combustion quality (effectiveness) can be deduced. If the highest possible concentration of CO_2 is achieved at low excess air (complete combustion), the loss caused by flue gas (at the same flue gas temperature) is minimal. For each liquid and solid fuel maximally attainable percentage of CO_2 (i.e. CO_{2max}) exists in the flue gas, which is determined by combustible fuel elemental composition. This value is, however, unattainable in actual devices.

It is generally known that for complete combustion the excess air must be greater than 1. Otherwise sufficient oxygen quantity would not be available. If, on the other hand, the excess air is too large (greater than 2 to 3) flame is cooled for this excessive air supply and combustion becomes also imperfect due to low temperature (Malaťák, Passian 2011).

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Received for publication December 19, 2014
Accepted after correction April 15, 2015

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