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THE EFFECT OF MOISTURE CONTENT OF FIREWOOD ON THE ENERGY EFFICIENCY OF FIREPLACE INSERT AND EMISSION PRODUCTION IN THE COMBUSTION PROCESS

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ABSTRACT

The effect of beech wood burnt in a furnace of fireplace insert on the energy efficiency, energy performance and emission production is analysed in the paper. Burning the fire beech firewood with the moisture content of W = 12.49% resulted in the highest energy performance, the highest energy efficiency and the lowest emission production at the same time. An increase in moisture content of burnt beech wood caused a decrease in wood heat value and an increase in concentration of CO, organic gaseous hydrocarbons (OGC) and solid polluting substances (TZL) in a form of soot in the combustion process. Mentioned facts resulted in a decrease in the energy performance of fireplace insert and the energy efficiency as well. Energy performance of a fireplace insert during the combustion process of wet beech wood with the moisture content of W = 46.95 % and heat capacity of Q_n = 8.8 MJ·kg^{-1} decreased seven-times and energy performance decreased to η = 23.1 %. Emission concentration in flue gases released into the atmosphere reached the value of $CO_{13\%}$ = 6.751 mg·m^{-3}, $OGC_{13\%}$ = 88.7 mg·m^{-3} and $TZL_{13\%}$ = 60.9 mg·m$^{-3.}$

Keywords: wood, moisture content, combustion process, fireplace insert, emission**.**

INTRODUCTION

Wood of deciduous trees with its energetic properties in seasoned state in accordance with the standard *STN EN 14961 Solid biofuels* is a biofuel with the heat value of Qn = 18.1 MJ·kg^{-1}, with high percentage of volatile flammable substance V = 85 % and a low ash content of A = 0.3 %. Heat value of coniferous trees due to higher percentage of carbon and lower ash content is Qn = 18.9 MJ·kg^{-1}. Lower ash content which is according to the authors JANDAČKA *et al*. (2007), DZURENDA *et al*. (2013), NOSEK *et al*. (2016), DZURENDA – PŇAKOVIČ (2016a, b) 15 or up to 30 times lower than ash content of coal can be considered to be a positive feature of firewood energetic properties in comparison to fossil fuels. Affinity to water and water vapour is a negative feature of firewood. Relative moisture content of freshly felled tree in the dormant season ranged from W = 35–65 % depending upon the wood species. Firewood in a branch form stacked under cover or against a sheltering wall dries naturally to air-dried state, i.e. the moisture content of W = 18–25 % TREBULA – KLEMENT (2005), NOSEK – HOLUBČÍK (2016).

According to the authors DEMIRBAS (2005), ČARNOGURSKÁ *et al.* (2012), MARTINÍK *et al.* (2014), CHABADOVA *et al*. (2014), DZURENDA (2015), DZURENDA – BANSKI (2015, 2017), HRONCOVÁ *et al.* (2016), KRPEC *et al.* (2016), RIMÁR *et al.* (2016), *et al*. (2016),

JANDAČKA *et al.* (2016), HORÁK *et al.* (2017), HOLUBČIK *et al.* (2018) efficiency of producing heat from biofuels – firewood depends upon the construction of heat generator as well as upon the energetic properties of firewood and energetic and environmental benefits delivered by a boiler. Energetic properties of firewood depend especially upon its moisture content. Basic energetic properties: gross calorific value Q_s, heat value $Q_{n,}$ but also the burning process in the furnace: flame temperature, the amount of flue gases created, dew-point temperature of flue gases, emission production are affected by the wood moisture content in a negative way.

The effect of the moisture content of beech wood on energy performance, energy efficiency and emission production in the combustion process of beech wood in fireplace insert is analysed in the paper.

MATERIAL AND METHODS

Beech wood with following moisture contents was used in the research into the impact of moisture content of firewood burnt in fireplace insert (Fig.1):

- sample 1 – dried beech wood with relative moisture content of W = 7.58 % stored in a heated interior space,
- sample 2 – dried beech wood with relative moisture content of W = 12.14 % stored in a well unheated interior space,
- sample 3 – air dried beech wood with relative moisture content of W = 20.93 % stored in an outdoor roofed shelter,
- sample 4 – beech wood with relative moisture content of W = 46.95 % stored in outdoor racks for approximately 2 weeks after harvesting.

Beech wood heat value was determined using the equation:

$$Q_n = 18840 - 24350 \cdot W$$

The length of fuel burning in a furnace depends on fuel properties as well as on burning conditions. In order to compare results within the experiments, the length of wood combustion process was determined by the time of 50 minutes after firewood was being fed into the furnace of the fireplace insert. The weight of firewood in all experiments was the same m = 2500 ± 50 g. Two logs of beech wood of approximately same size were placed in the same part of the furnace.

Measurements to determine the effect of moisture content of fuel were carried out in the same heat source – fireplace insert with the energy performance of 10 kW (Fig. 1) in accordance with the standard *STN EN 13 229 "Solid Fuel Combustion Appliances Determined to Heat a Residential Property. Requirements and Testing Methods*".

Each fuel was tested three times and presented results are arithmetic means of all measurements. The combustion process of each sample was carried out under the same conditions – same settings to supply and redistribute combustion air, chimney air flow rate (12 ± 2 Pa), approximately same temperature (21 ± 2 °C), relative air humidity (40 ± 2 %) and temperature of flue gases in chimney at the beginning of each experiment t = 180 ± 2°C.

Energy efficiency and energy performance of fireplace insert was determined by an indirect method of calculation in accordance with the standard STN EN 13 229. Measurements of gaseous emissions, especially carbon monoxide (CO), nitrogen oxides (NO_X), organic gaseous hydrocarbons (OGC), carbon dioxide (CO_2) and oxygen (O_2) were carried out using the emission analyser with nondispersive infrared sensor NDIR. Values of emissions were calculated in terms of reference conditions (t = 0 °C, p = 101325 Pa and content of oxygen in flue gases O_2 = 13 %). Production of solid polluting substances was

determined using gravimetric method in accordance with the standard *STN ISO 9096* when conditions of isokinetic sampling of flue gases are met. Temperature in the chimney and in surroundings was determined using the thermo element type K (NiCr-Ni). Ventilator with frequency converter was used to ensure constant chimney air flow rate in order to deliver flue gases.

Fig. 1 Fireplace insert as a source of heat used in experiments.

RESULTS AND DISCUSION

Dependence of the heat value of beech wood burnt in fireplace insert on the moisture content is shown in Fig. 2.

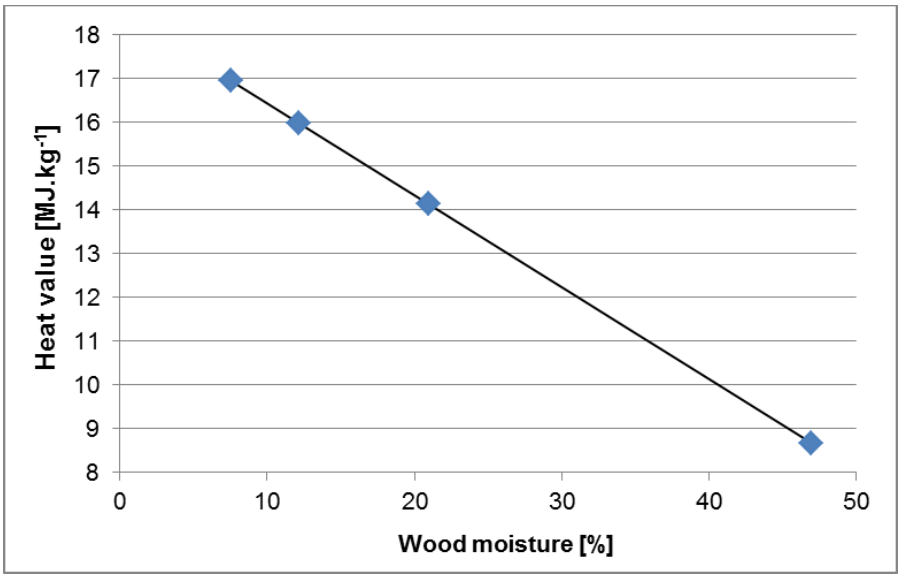


Fig. 2 Dependence of beech wood heat value on the moisture content.

Measured values of individual thermal and environmental parameters describing the combustion process of dried (W=7.58%, W=12.14%), air dried (W=20.93%), and wet beech wood in the furnace of fireplace insert during the combustion cycle are mention in Tab.

Tab. 1 Average experiment results (P – energy performance, Ŋ – energy efficiency, t_{kom} –temperature of flue gases in chimney, O_2 – oxygen content in flue gases, CO_2 – carbon dioxide content in flue gases, $CO_{13\%}$ - concentration of carbon monoxide in flue gases, $NO_{X,13\%}$ - concentration of nitrogen oxide in flue gases, $OGC_{13\%}$ - concentration of organic gaseous hydrocarbon in flue gases, $TZL_{13\%}$ - concentration of solid polluting substances in flue gases.

Fuel	Batch	P [kW]	Ŋ [%]	t_{kom} [°C]	O_2 [%]	CO_2 [%]	$CO_{13\%}$ [mg·m^{-3}]	$NO_{x,13\%}$ [mg·m^{-3}]	$OGC_{13\%}$ [mg·m^{-3}]	$TZL_{13\%}$ [mg·m^{-3}]
Sample 1 (W=7.58 %)	1	10.7	77	249.9	12.5	8.9	1,628	77.2	14.1	12.6
	2	10.6	76	244.9	13	8.3	1,637	103.3	14.4	15.4
	3	10.8	77.1	242.4	12.6	8.7	1,671	77.8	14.6	10.1
	Average	**10.7**	**76.7**	**245.8**	**12.7**	**8.6**	**1,645**	**86.1**	**14.5**	**12.7**
Sample 2 (W=12.14 %)	1	10.6	81.4	232.5	11.7	9.7	1,068	71.9	9.3	10.6
	2	10.5	80.9	230.2	12.4	9	1,164	93	10.3	13.3
	3	10.6	81.3	227.6	12	9.5	1,189	68.3	11.1	15.3
	Average	**10.6**	**81.2**	**230.1**	**12**	**9.4**	**1,140**	**77.7**	**10.2**	**13.1**
Sample 3 (W=20.93%)	1	6.4	56.7	216.8	15.4	5.4	2,128	81.6	28	26.1
	2	6.4	56.5	215.6	15.1	5.8	2,374	65.7	31.2	35.7
	3	6.3	55.8	221.4	15.5	5.3	2,919	66.7	38.1	29.3
	Average	**6.4**	**56.3**	**217.9**	**15.4**	**5.5**	**2,474**	**71.3**	**32.5**	**30.4**
Sample 4 (W=46.95 %)	1	1.5	23.5	172.5	17.5	3.5	6,419	26.7	84.3	51.7
	2	1.4	20.8	169.4	17.6	3.4	7,846	19.3	103.3	81.3
	3	1.6	24.7	172.2	17.5	3.5	5,988	15.9	79.1	49.7
	Average	**1.5**	**23**	**171.4**	**17.5**	**3.5**	**6,751**	**20.6**	**88.7**	**60.9**

Time flow data for energy performance of fireplace insert during the combustion cycle of the beech wood sample are shown in Fig. 3. Dependence of average energy performance of fireplace on the moisture content of beech wood are mentioned in Fig. 4.

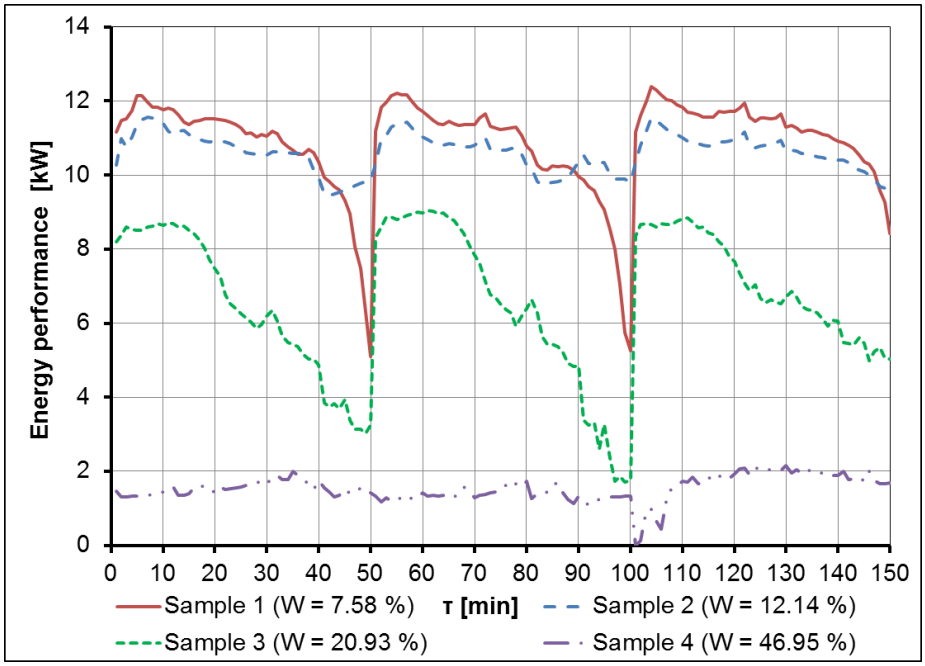


Fig. 3 The effect of wood moisture content on energy performance.

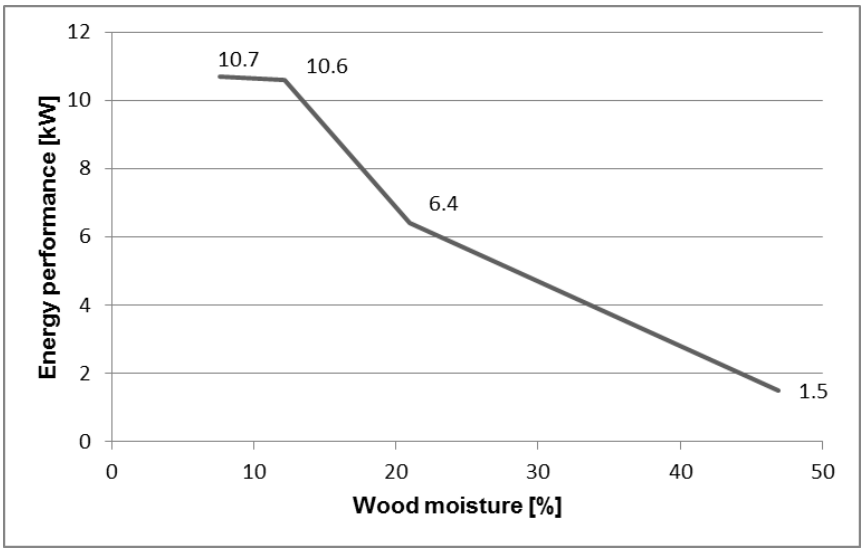


Fig. 4 The effect of wood moisture content on the energy performance of the fireplace insert.

The highest energy performance of fireplace insert P = 10.65 kW was observed in the combustion process of dried beech wood with the moisture content of W = 7.58–12.14 % and the average heat value of wood Q_n = 16.7 MJ·kg^{-1}. The combustion of air dried beech wood with the moisture content of W = 20.93 % was associated with a decrease in energy performance of fireplace insert to P = 6.4 kW, i.e. there was a decrease in energy performance by ΔP = 41.3 %. The energy performance of fireplace insert in the combustion process of wet wood with the moisture content of W = 46.95 % and the heat value of Q_n = 8,8 MJ·kg^{-1} was 7 times lower than the energy performance of fireplace insert in the combustion process of dried wood. The energy performance of fireplace insert during measurements was only 15% of a nominal energy performance. Following the findings the fact that combustion of wet beech wood is inefficient in terms of fuel consumption as well as in terms of energy performance of fireplace insert can be stated.

Fig. 5 shows the effect of moisture content of beech wood burnt in furnace of fireplace insert on energy efficiency of fireplace insert.

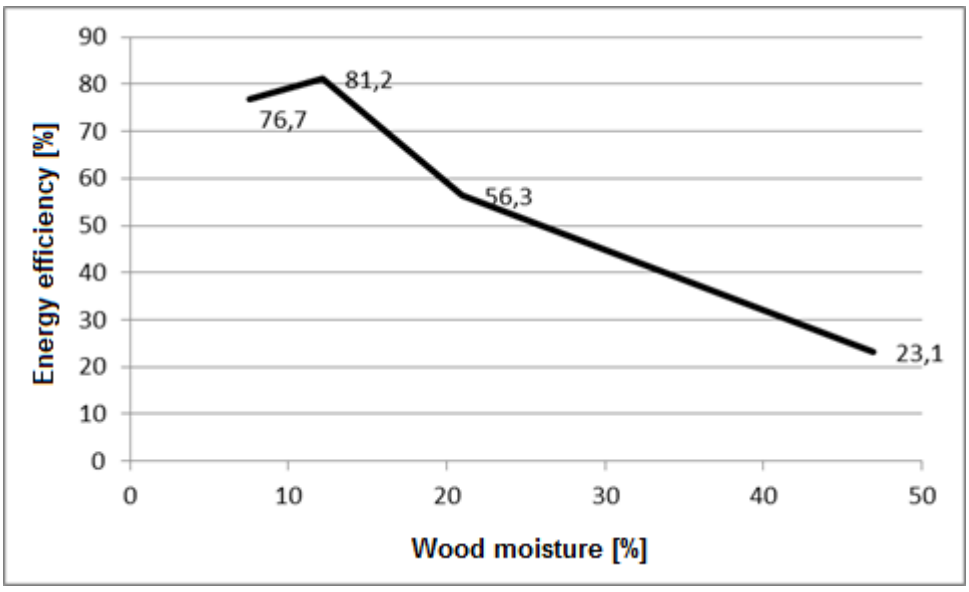


Fig. 5 The effect of wood moisture content on the energy efficiency of the fireplace insert.

The highest energy efficiency of fireplace insert was obtained in the combustion process of beech wood with the moisture content of W = 12.14 %.

The lowest energy efficiency of fireplace insert by η = 4.5 % was measured in the combustion process of beech wood with the moisture content of W = 7.58 %. Combustion of drier beech wood was intense with the highest energy performance in the first 40 minutes shown in the graph in Fig. 2. After mentioned time, during flaming and smouldering phase of beech wood, a significant decrease in the furnace temperature and in the energy performance of fireplace insert was observed. At the same time, the increase in concentration of carbon monoxide CO and organic hydrocarbons OGC was determined. Increased concentration of carbon monoxide CO and organic gaseous hydrocarbons OGC in flue gases causes worse emission balance of fireplace insert and heat loss (volatile flammable substance leak) resulting in a decrease in energy performance of fireplace insert.

The lowest energy performance of fireplace insert was observed in the combustion process of wet beech wood with the moisture content of W = 46.95 %. It results from the worse combustion conditions of wet beech wood and an increase in the concentration of carbon monoxide in flue gases to $CO_{13\%}$ = 6,751 mg·m^{-3}, in organic gaseous hydrocarbons to $OGC_{13\%}$ = 88.7 mg.m^{-3}and in soot to $TZL_{13\%}$ = 60 mg·m^{-3}. Moreover, the energy loss in a stack caused by the increase in combustion air excess delivered to furnace of fireplace insert by 2.4 times in comparison to the combustion process of the dried beech wood can be considered a reason. Mentioned statement was confirmed by visual observation of the combustion process of wet beech wood in the furnace of fireplace insert. Fireplace insert front glass turned black due to black smoke created in the combustion process.

The moisture content affects the combustion process of beech wood in furnace of fireplace insert in negative way. Not only the combustion process gets worse but also the energetic properties of fireplace insert fall and emission production increases. It can be confirmed by Fig. 6 showing the effect of moisture content of beech wood on the production of carbon monoxide CO in the combustion process. In addition, production of individual emissions calculating in terms of standard conditions and the content of oxygen in flue gases O_2 = 13 % are summarised in Fig. 7.

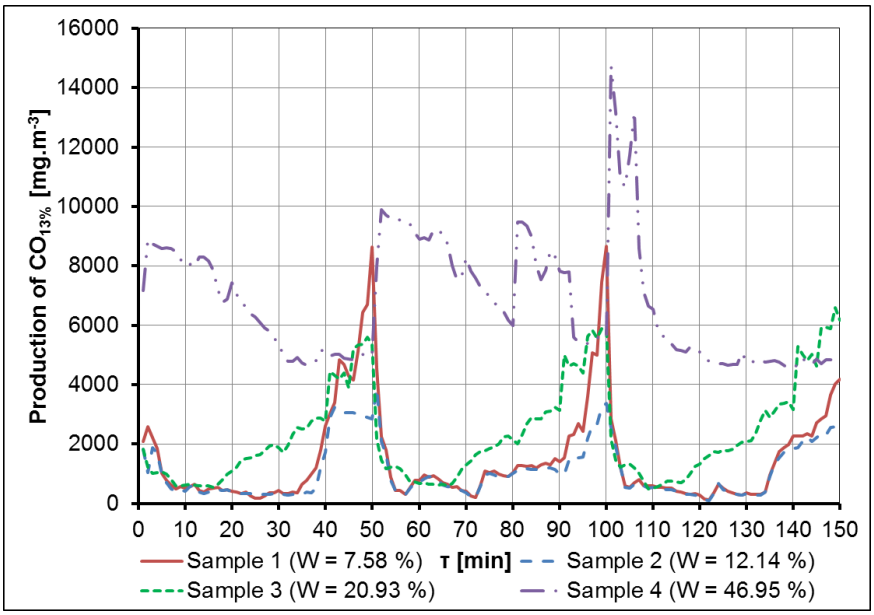
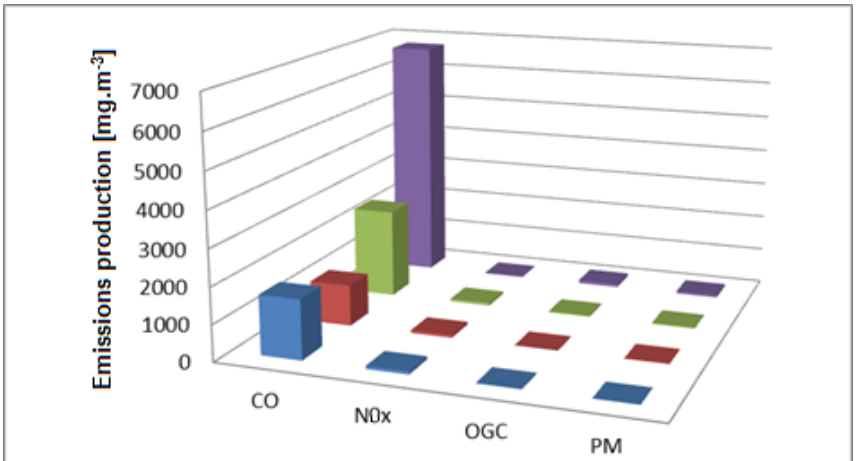


Fig. 6 The effect of wood moisture content on the production of carbon monoxide.



	CO	N0x	OGC	PM
W=7,58%	1645	86,1	14,5	12,7
W=12,14%	1140	77,7	10,2	13,1
W=20,93%	2474	71,3	32,5	30,4
W=46,95%	6751	20,6	88,7	60,9

Fig. 7 The effect of wood moisture content on the emission production: CO, NOx, OGC, PM and oxygen content in flue gases O_2= 13 %

Measured values of emissions of beech wood combustion with the moisture content of W = 12.14 % in the furnace of fireplace insert gathered within the experiments were the lowest and they did not exceed the values mentioned in the standard *STN EN 13 229 "Solid Fuel Combustion Appliances Determined to Heat a Residential Property. Requirements and Testing Methods*".

Dried beech wood with the moisture content of W = 12 % is a source of higher production of gaseous emissions: of carbon monoxide CO, organic hydrocarbons OGC due to unsteady combustion.

The combustion process of beech wood with the moisture content of W = 12 up to 15% in the fireplace insert is accompanied not only by a significant increase in production of gaseous emissions: carbon monoxide CO and organic hydrocarbons OGC, but also in production of solid polluting substances TZL in a form of soot. The increase in emission production resulting from the combustion of beech wood with the moisture content of W = 46.95 % in comparison to beech wood with the moisture content of W = 12.14 % was observed. The emission of carbon monoxide $CO_{13\%}$ increased 5.9 times, of organic gaseous hydrocarbons OCG $CO_{13\%}$ increased 8.7 times and of solid polluting substances TZL $CO_{13\%}$ increased 4.6 times.

The increase in moisture content resulted in the decrease in production of nitrogen oxides NOx. The findings are consistent with the knowledge mentioned by the authors DZURENDA *et al*. (2017).

Higher oxygen concentration in the furnace of fireplace insert in the combustion process of air dried wood and wet wood seems to be a negative factor causing a decrease in the temperature in furnace as well as an increase in the concentration of volatile flammable substance. Moreover, when the wet wood is burnt, the soot is formed in the furnace of fireplace insert. According to the authors: NOSEK *et al*. 2016, KRPEC *et al*. 2016, HORAK *et al*. 2017 mentioned negative situation caused by higher moisture content of wood can be eliminated by the control of delivered combustion air, for example by λ – sensor.

CONCLUSIONS

1. Experiment results confirmed the fact that the moisture content affects combustion process significantly and thereby affecting the energetic and emission parameters of a heat source – fireplace insert. An increase in the moisture content of fuel results in a decrease in the heat value and also in the energy performance of a heat source.
2. An increase in moisture content of fuel results in the higher emission production during the combustion process, especially carbon monoxide CO, organic gaseous hydrocarbons OCG and solid polluting substances TZL in a form of soot.
3. Following the analysis we can say that the combustion of too dried wood is intense and the combustion chamber is overheated. Therefore, fuel burns faster and higher amount of carbon monoxide, organic gaseous hydrocarbons is produced when the fire is fed in the same way.
4. Following the results of the experiments, the wood with relative moisture content of about 12% seems to be the right firewood used in fireplace insert.

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