Efficiency and gases emissions with incineration of composite and one-component biofuel briquettes in room heater

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Abstract: In accordance with the technical standard ČSN EN 13229 "Inset appliances for heating including open fires fired by solid fuels – Requirements and test methods" was performed the basic assessment of thermal efficiency and emission parameters of prototype of combustion accumulation stove SK-2 with upper after-burning and nominal heat output of 8 kW. Verified gradually were the bio-briquettes of diameter 65 mm from mixture of wheat straw and 20% m/m of brown coal, wheat straw and 5% m/m of brown coal, wheat straw, mixture of wheat straw and 10% m/m of water and molasses solution, Ecobiopal created with the fermented blend of 33% m/m of digested clean water plant sludge and 67% m/m of wood chopped material, blend of wheat straw and 15% m/m of sugar beet pulp, mixture of timothy hay and 25% m/m of brown coal, timothy grass hay, meadow hay, mixture of meadow hay and 25% m/m of brown coal. The lowest CO emissions, when the limit value of 3000 mg/m^3_N at 13% of O_2 has not been exceeded, determined for more strict 1st class and the highest efficiency at nominal heat performance, i.e. higher or equal to 70% (Class I) have been reached by the briquettes produced from mixture of wheat straw and 15% m/m of sugar beet pulp, timothy hay and mixture of meadow hay with addition of 25% m/m of brown coal. Further were measured NO_x and HCl emissions. NO_x values were significantly lower than limit values determined for similar combustion of solid biofuel. Higher differences of HCl emissions correlate with various Cl content in fuels. Only the wheat straw briquettes with share of 25% m/m of brown coal have exceeded the limit value by 16%. Other fuels have shown considerably lower values. The results have proved better heat-technical and emission parameters of blended briquettes and are significant also for solid biofuels and solid recovered fuels standardization as well as for increasing efficiency method detection and ecological parameters optimization including HCl emissions.

Keywords: biofuel briquette; composite briquette; combustion; efficiency; combustion gases; emission

Ecological consequence in term of protection against emissions should be assessed within the energy conversion through the fuels combustion according to partial aspects: atmosphere cleanness and residual matter maintenance, heat utilization (achievement of as high as possible efficiency) and equipment safety (Strehler 1998; Brenndörfer 2003; Rössert 2003). With regard to the combustion course the following substance groups are involved in the combustion products (Nussbaumer 1999; Jevič *et al.* 2000; Šedivá *et al.* 2005):

- emissions of C, H, O and N incomplete combustion: carbon monoxide CO, hydrocarbons (C_xH_y), tar, soot and non-combusted hydrocarbon particles (combustible part of dust emissions) and hydrogen (H_2);
- incomplete oxidized nitrogen compounds: HCN, NH_3 and N_2O;
- emissions and required products of C, H, O and N complete combustion: NO and NO_2, carbon dioxide CO_2, water vapor H_2O;
- emissions trace elements of solid biofuels impurities: dust particles in waste gas (incombustible part of dust emissions), sulphur and chlorine compounds in waste gas, SO_2, HCl, or PCDD/F, heavy metals in waste gas: Cu, Pb, Zn and Cd.

The work is aimed at basic evaluation of heat efficiency and emission parameters in accordance

Supported by the Ministry of Agriculture of the Czech Republic, Project No. QF 3153.

with valid Czech technical standard for combustion accumulation stove SK-2 prototype of nominal heat output of 8 kW. The manufacturer recommends for combustion any dry wood and biofuels briquettes of various size.

MATERIAL AND METHODS

The operational experiments were conducted in accordance with standard ČSN EN 13229 (2002). Because there was used the heating system with closing fireplace, the chimney draught values have been in the determined range of 12 ± 2 Pa depending on nominal heat output (values of steady pressure within combustion products measured section). While measuring the average CO and other gaseous emissions concentrations were converted to 13% of oxygen (O_2) content. By the mentioned standard the average CO values have to meet the limit values in combustion products for appropriate CO class as presented in Table 1.

Effective utilization of heat energy with appliance operating is evaluated according to efficiency at nominal heat output in compliance with manufacturer data and with combustion of testing fuels. The total measured efficiency has to be in accordance with the limit values for appropriate efficiency class as presented in Table 2. The accumulation bricks layout in the verified combustion stove SK-2 is shown in Figure 1.

Table 1. CO emissions classes for local appliances for solid fuels according to standard ČSN EN 13229 (2002)

Appliance CO class	Appliances with closed door limit values of CO emissions classes (at 13% of O_2) (%)
Class 1	≤ 0.3[1]
Class 2	> 0.3 ≤ 1.0[1]

[1]1 mg/m^3_N = 0.0001%

In upper part of the door is situated the air vent for secondary air supply. This vent assures better combustion and prevents the combustion products deposition on the glass. The combustion products are discharged from the fireplace through the steel stack flue into the smoke ducting of 150 mm diameter.

Table 2. Efficiency classes at nominal heat output for local appliances for solid fuels according to standard ČSN EN 13229 (2002)

Appliance efficiency class	Appliances with closed door limit values of efficiency class (%)
Class 1	≤70
Class 2	≤ 60 < 70
Class 3	≤ 50 < 60
Class 4	≤ 30 < 50

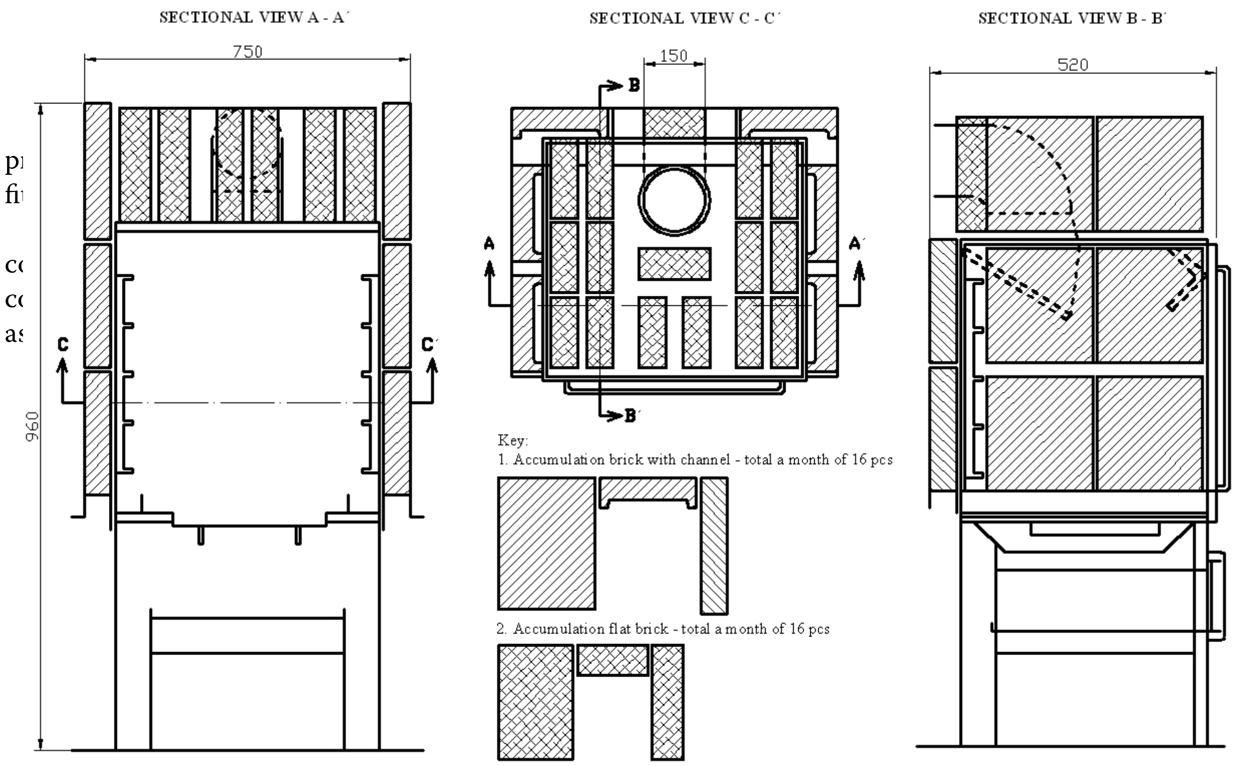


Figure 1. Optimized layout of accumulation bricks of verified combustion stove SK-2 RETAP

The accumulation stove installation for operational tests was also performed in accordance with the standard ČSN EN 13229 (2002). Required weight of fuel supply for particular tests was determined by the formula:

$$B_{fl} = \frac{360\ 000 \times P_n \times t_b}{H_u \times \eta} \qquad (1)$$

where:
B_{fl} – mass of supplied fuel (kg),
H_u – net calorific value (kJ/kg),
η – lowest thermal efficiency according to this standard or such value as determined by manufacturer (%),
P_n – nominal heat output (kW),
t_b – shortest interval of fuel supply or combustion time (h) determined by manufacturer.

At H_u = 16 500 kJ/kg, $\eta \geq 30\%$, P_n = 8 kW and t_b = 2 h the required fuel portion is about 12 kg. The operational properties test at nominal net calorific value consisted of:
– introduction into operation and time necessary to reach steady state
– test time (about 40–70 min).

For smoke gases analysis was utilized measuring apparatus of Research Institute of Agricultural Engineering in Prague with main part consisting of flue gas analyzer GA 60 with measuring principle based on electro-chemical converters utilization. Type of converters, measuring ranges and uncertainty of measuring are evident from Table 3.

Temperature measuring serves for calculation of thermal and physical parameters and converts temperature compensation. The controlling systems are based on two CMOS micro-processors. These collect all signals coming from measuring sensors (electro-chemical converters, temperature, pressure) and thus they control the keyboard, display, printer, gases main ways elements (pump, electromagnetic valve), interface for work with peripheries and EPROM memory systems. Basic principles of results calculating:

Table 3. Types of electro-chemical converters, measuring ranges and uncertainty of analyzer GA-60 measuring (verified before measuring with calibration gases)

Converter	Type	Measuring range	Measuring uncertainty
O_2	2FO	0–20.95% v/v	0.01% v/v
CO_2	IR sensor	0–20% v/v	
CO	3F/F	0–20 000 ppm	± 0.5% of measuring range
NO	3NF/F	0–5000 ppm	
NO_2	3NDH	0–800 ppm	
SO_2	3SF	0–2000 ppm	
HCl	3HL	0–200 ppm	

Heat losses and efficiency

Heat losses were determined from average values of combustion products and room temperatures, combustion products and combustible components composition in combustion solid residua.

Efficiency was determined from these losses according to formula:

$$\eta = 100 - (q_a + q_b + q_r) \qquad (2)$$

where:
η – efficiency (%),
q_a – relative loss through sensible heat of the combustion gases (Q_a) in relationship to fuel net calorific value (%),
q_b – relative loss through gaseous underfiring (Q_b) in relationship to testing fuel net calorific value (%),
q_r – relative loss through mechanical underfiring (Q_r) in relationship to testing fuel net calorific value (%).

Relative losses through sensible heat of the combustion gases

$$Q_a = (t_a - t_r)\left[\frac{C_{pmd}\,(C - C_r)}{0.536\,(CO + CO_2)} + C_{pm_{H_2O}} \times 1.92\ \frac{9H + W}{100}\right] \qquad (3)$$

where:
Q_a – losses through sensible heat of the combustion gases in relationship to testing fuel mass (kJ/kg),
t_a – combustion gases temperature (°C),
t_r – room temperature (°C),
C_{pmd} – dry combustion gases mean specific heat capacity under comparative conditions in dependence on combustion gases heat and composition (kJ/K.m^3),
C – carbon mass share in testing fuel (%),
C_r – carbon reduced mass share in solid combustion residua fallen down through the grate in dependence on amount of combusted testing fuel (%),
CO – volume concentration of CO in dry combustion gases (%),
CO_2 – volume concentration of CO_2 in dry combustion gases (%),
$C_{pm_{H_2O}}$ – water vapor mean specific heat capacity under comparative conditions in dependence on heat (kJ/K.m^3),
H – mass share of total hydrogen in testing fuel (%),
W – mass share of total moisture in testing fuel (%).

$$q_a = 100 \frac{Q_a}{H_u} \quad (4)$$

Relative losses through gaseous underfiring

$$Q_b = \frac{12\,644\ CO\ (C - C_r)}{0.536\ (CO_2 + CO) \times 100} \quad (5)$$

where:

Q_b – losses through gaseous underfiring in relationship to testing fuel mass (kJ/kg).

$$q_b = 100 \frac{Q_b}{H} \quad (6)$$

Relative losses through mechanical underfiring

$$Q_r = 335 \frac{bR}{100} \quad (7)$$

where:

Q_r – losses through mechanical underfiring in relationship to testing fuel mass (kJ/kg),

b – mass share of combustible components in combustion solid residua in relation ship to their mass (%),

R – mass share of solid combustion residua fallen down through grate in relationship to combusted testing fuel mass (%).

$$q_r = 100 \frac{Q_r}{H_u} \quad (8)$$

Total heat output

Total heat output was computed from the mass flow of fuel combusted within 1 hour, testing fuel net calorific value and efficiency using the formula:

$$P = \frac{\eta \times B \times H_u}{100 \times 3600} \quad (9)$$

where:

P – total heat output (kW),

B – mass flow of testing fuel (kg/h).

Mass flow-rate of dry combustion gases

This quantity was determined as approximate value of CO_2 mass concentration in combustion gases and specific quantities of fuel according to the formula:

$$m = \frac{\dfrac{1.3\ B\ (C - C_r)}{0.536\ (CO_2 + CO)} + \dfrac{9H + W}{100}}{3.6} \quad (10)$$

where:

m – combustion gases mass flow-rate (g/s).

Table 4. Normative properties of tested briquettes

Composition of briquettes	Total moisture	Volatile mater	Non-volatile mater	Ash	Gross calorific value	Net calorific value	Particle density (kg/m^3)
	(% m/m as received)				(MJ/kg)		
Wheat straw	5.99	72.31	15.13	6.57	16.51	15.17	810
Wheat straw with 5% m/m of brown coal	6.68	70.65	15.79	6.88	16.70	15.35	900
Wheat straw with 20% m/m of brown coal	8.77	65.66	17.76	7.81	17.27	15.89	990
Wheat straw with 10% m/m of water and molasses solution	8.02	68.50	14.73	8.75	15.91	14.54	805
Wheat straw with 15% m/m of sugar beet pulp	6.34	72.15	15.09	6.42	16.62	15.03	820
Timothy grass hay	10.65	68.42	15.77	5.16	15.90	14.38	810
Timothy grass hay with 25% m/m brown coal	12.96	61.01	18.90	7.13	17.01	15.48	815
Meadow hay	11.02	67.91	15.82	5.25	16.13	14.40	920
Meadow hay with 25% m/m of brown coal	13.24	60.70	18.94	7.12	17.18	15.50	825
Dried fermented mixture of wood chips and digested sludge	8.04	63.29	16.55	12.12	16.91	15.64	970

Dry combustion gases mean specific heat capacity under comparative conditions

This quantity was computed according to formula:

$$C_{pmd} = 3.6\left(0.361 + 0.008\left(\frac{t_a}{1000}\right) + 0.034\left(\frac{t_a}{1000}\right)^2 + \left(0.085 + 0.19\left(\frac{t_a}{1000}\right) - 0.14\left(\frac{t_a}{1000}\right)^2\right)\left(\frac{CO_2}{100}\right) + \left(0.03\left(\frac{t_a}{1000}\right) - 0.2\left(\frac{t_a}{1000}\right)^2\right)\left(\frac{CO_2}{100}\right)\right) \quad (11)$$

Water vapor mean specific heat capacity

$$C_{pm_{H_2O}} = 3.6\left(0.414 + 0.038\left(\frac{t_a}{1000}\right) + 0.034\left(\frac{t_a}{1000}\right)^2\right) \quad (12)$$

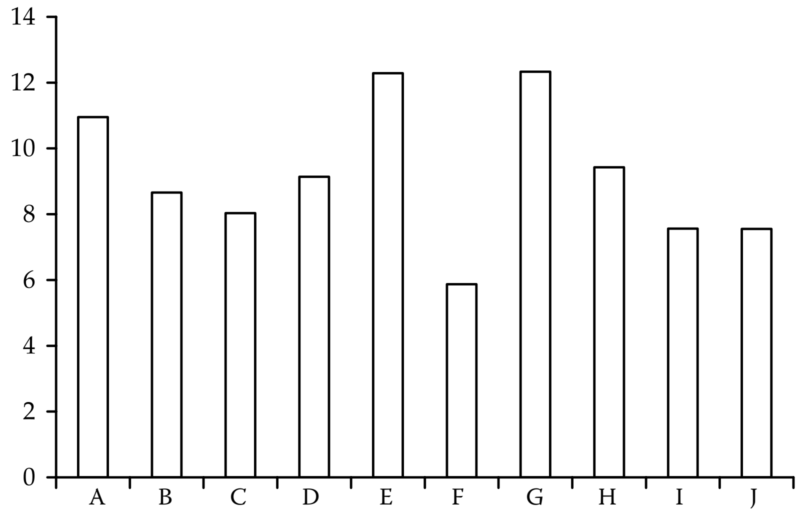
RESULTS

Tables 4 and 5 present chemical and physical briquette properties by the standard test method.

In Figure 2 is shown comparison of ranged CO_2 emissions average values, in Figure 4 NO_x and in

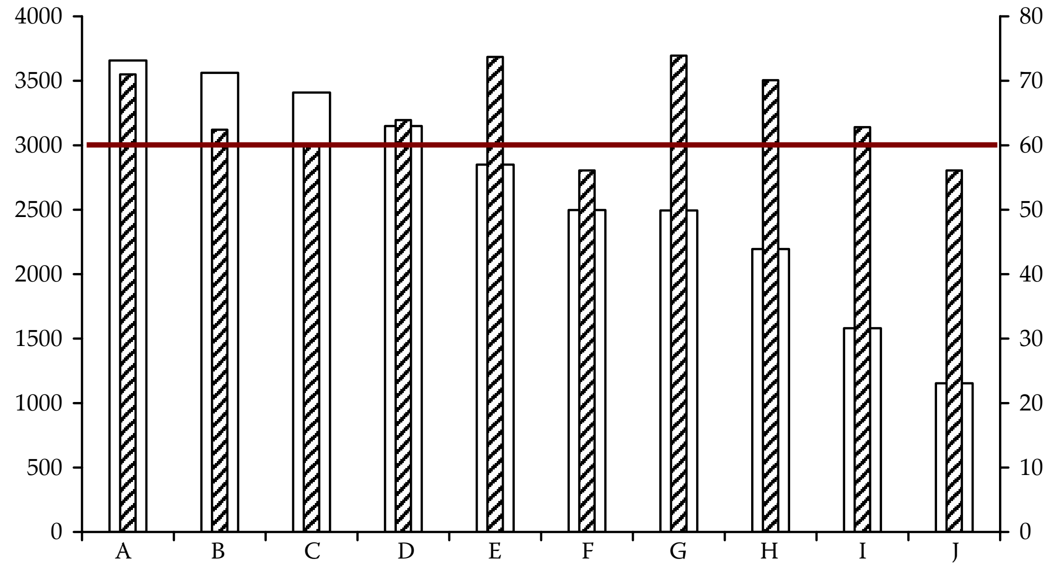
Table 5. Ultimate analysis of tested briquettes (in % m/m as received)

Composition of briquettes	C	H	N	S	O	Cl
Wheat straw	43.00	5.49	0.54	0.05	37.87	0.49
Wheat straw with 5% m/m of brown coal	43.70	5.46	0.55	0.08	36.15	0.49
Wheat straw with 20% m/m of brown coal	45.81	5.36	0.60	0.16	31.01	0.49
Wheat straw with 10% m/m of water and molasses solution	41.85	5.35	0.50	0.05	36.21	0.46
Wheat straw with 15% m/m of sugar beet pulp	42.61	5.41	0.53	0.05	37.22	0.48
Timothy grass hay	44.68	5.82	0.68	0.10	32.54	0.37
Timothy grass hay with 25% m/m brown coal	47.78	5.58	0.72	0.23	25.29	0.40
Meadow hay	44.20	5.77	0.66	0.10	32.01	0.35
Meadow hay with 25% m/m of brown coal	47.42	5.54	0.70	0.23	24.90	0.38
Dried fermented mixture of wood chips and digested sludge	42.47	4.90	1.18	0.28	31.01	0.12



A – Meadow hay (briquettes of diameter 65 mm); B – Dried fermented mixture of wood chips and digested sludge (briquettes of diameter 65 mm); C – Timothy grass hay with 25 % m/m of brown coal (briquettes of diameter 65 mm); D – Wheat straw with 10 % m/m of water and molasses solution (briquettes of diameter 65 mm); E – Meadow hay with 25 % m/m of brown coal (briquettes of diameter 65 mm); F – Wheat straw with 20 % m/m of brown coal (briquettes of diameter 65 mm); G – Timothy grass hay (briquettes of diameter 65 mm); H – Wheat straw with 15 % m/m of sugar beet pulp (briquettes of diameter 65 mm); I – Wheat straw with 5 % m/m of brown coal (briquettes of diameter 65 mm); J – Wheat straw (briquettes of diameter 65 mm)

Figure 2. Average values of CO_2 emissions in combustion gases of verified briquette fuels



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□ CO (O_2 = 13%) (mg/m^3); ▨ Technical -thermal effect combustion; CO = 3000 mg/m^3 limit value for Class 1

Figure 3. Comparison of average values of gaseous CO emissions at referential content of O_2 = 13% with average value of thermal efficiency of verified briquette fuels

Figure 6 HCl for verified briquette fuels. In Figure 3 are also presented the CO investigated emissions including combustion efficiency according to standard ČSN EN 13229 (2002).

Examples of CO_2 and CO emissions dependence on excess air factor λ at briquette timothy grass and blended briquettes of meadow hay with 25% m/m of brown coal are presented in Figures 6–9.

DISCUSSION

Investigation of CO_2 emissions is important due to the fact that they regard the greenhouse gas in question and represent very significant parameter of the conversion process perfection. Its value should range between 8.0–12.5% v/v. As evident from Figure 2, CO_2 value below the above mentioned limit value was for wheat straw with 20% m/m of brown coal, wheat straw with 5% m/m of brown coal and wheat straw. These fuels have displayed also the lowest value of heat efficiency (Class 2 and 3) despite the CO values were the least (Class 1 is best). For as high as possible CO_2 value within the toleration limit (variability is evident from Figures 6 and 8) the crucial is the best fuels utilization and thus high efficiency of heat conversion – see other verified briquettes.

Regarding the fact the hydrocarbons and other incompletely combusted products behave identically as carbon monoxide, the CO is often being utilized as indicator of after-burning quality. As evident from Figure 2, the operation suitable value (Class 2) was reached by briquettes produced from mixture of wheat straw with 10% m/m of water and molasses solution, Ecobiopal consists of fermented mixture of 33% m/m of digested sewage sludge with 67% m/m of wood chips, mixture of timothy grass hay with 25% m/m of brown coal and meadow hay. Other briquette fuels have met the strict Class 1 from point of view of very low CO content. CO courses in dependence on the excess air factor λ for timothy grass hay briquettes are presented in Figure 7 and from mixture of meadow hay with 25% m/m of brown coal (Figure 9). These values comply well with the thermal efficiency (Figure 3). Higher value than 60% (Class 2) was reached for briquettes from mixture of wheat straw with 5% m/m of brown coal, mixture of wheat straw with 10% m/m of molasses and water solution, Ecobiopal and mixture of timothy grass hay with 25% m/m of brown coal. Class 1 where the

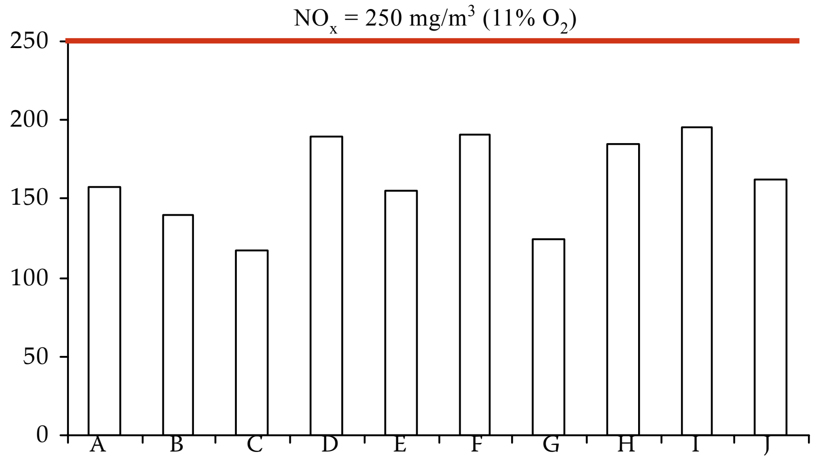

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Figure 4. Average values of NO_x gaseous emissions in combustion gases of verified briquette fuels at referential content of O_2 = 13%

thermal-technical efficiency is higher than 70% was reached for briquettes from mixture of wheat straw with 15% m/m of sugar beet pulp, timothy grass hay, meadow hay, mixture of meadow hay with 25% m/m of brown coal.

Very positively can be assessed the NO_x values for all investigated fuels (Figure 4). For the used combustion equipment the NO_x limit value is not specified with regard to low heat performance. But if the comparison of the NO_x limit value (250 mg/m$_N^3$ at 11% O_2) (Decree No 352/2002), is performed, and then this value has not been exceeded for any investigated fuels with sufficient reserve. Also HCl emissions (Figure 5) which are not limited for that type

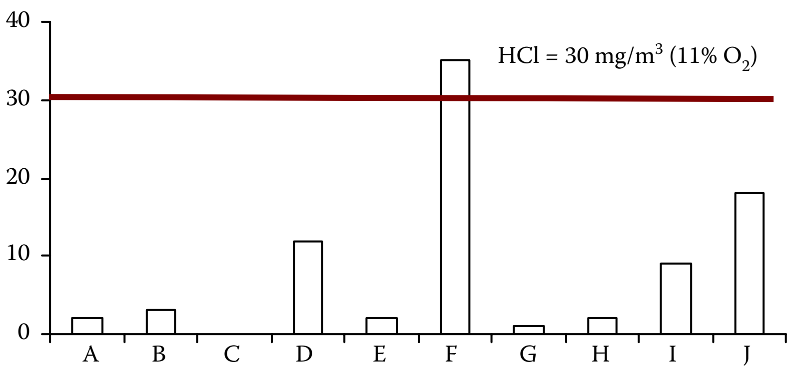

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Figure 5. Average values of HCl emissions in combustion gases of verified briquette fuels at referential content of O_2 = 13%

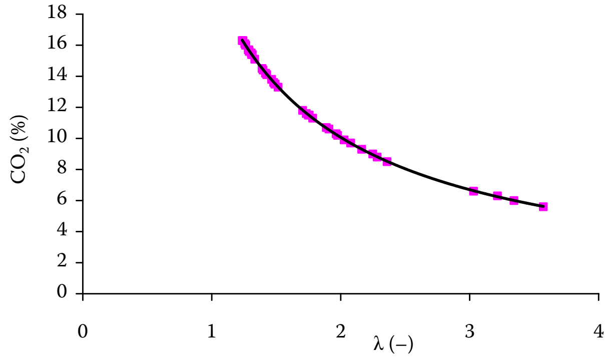

Figure 6. Dependence of CO_2 emissions on excess air factor λ at combustion of briquette timothy grass hay

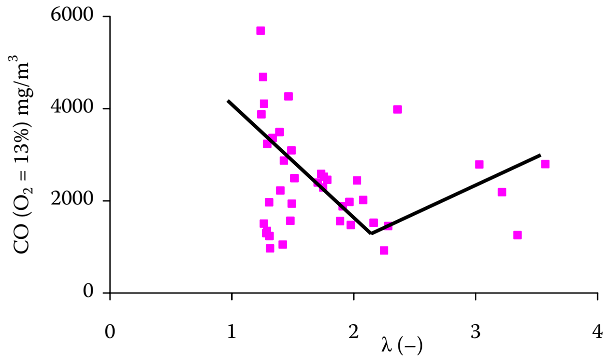

Figure 7. Dependence of CO emissions on excess air factor λ at combustion of briquette timothy grass hay

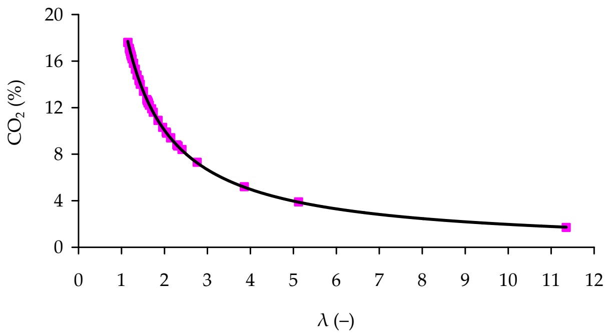

Figure 8. Dependence of CO_2 emissions on excess air factor λ at briquette combustion from mixture of meadow hay with 25% m/m of brown coal

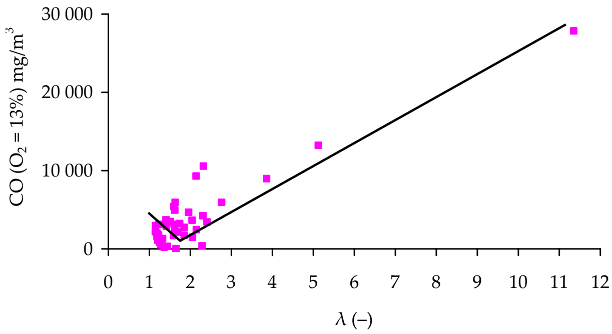

Figure 9. Dependence of CO emissions on excess air factor λ at briquette combustion from mixture of meadow hay with 25% m/m of brown coal

of combustion equipment, are significantly lower as compared with the maximum value (30 mg/m^3_N at 11% O_2) except the briquette mixture of wheat straw and 20% m/m of brown coal, for combustion equipment over 100 kW with straw and other culm crops biomass combustion.

The Cl content in fuel (see Table 5) pertains to larger attention. Various research works gradually prove reduction of PCDD/F in reaction of Cl and S presented in the fuel (Strehler 1998; Jevič *et al.* 2000).

CONCLUSION

Blending of generated gases with air during the combustion process is complicated for device with manual feeding of solid fuels, particularly for small-scale thermal efficiency plants in comparison with those with automated feeding of all fuels types including biofuels pellets. Thus correct construction of combustion space with easy regulated primary and secondary air intake is necessary. This allows to reach the optimum operational values. The excess air factor affects also amount of oxidants in combustion chamber and combustion temperature. From this view there is further space for improvement of the thermal-technical and emission parameters of this verified equipment. The operational investigation of selected single-component and blended briquette fuels utilization in the prototype of combustion heat storage stove has provided, along with other information acquisition for its improvement, determination of other types of suitable culm crop biomass for their processing to standardized briquette fuels.

The blended briquette fuels produced from wheat straw, meadow hay, timothy grass hay and also with additive (slogging inhibitors) of brown coal have proved very good and excellent emission parameters and thermal-technical properties. When other certification requirements are fulfilled these fuels also are suitable for similar local appliances for solid biofuels.

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Received for publication January 25, 2007
Accepted after corrections February 27, 2007

Abstrakt

Jevič P., Hutla P., Malaťák J., Šedivá Z. (2007): **Účinnost a plynné emise při spalování kompozitních a jednosložkových biopalivových briket ve vyhřívacích kamnech.** Res. Agr. Eng., **53**: 94–102.

V souladu s technickou normou ČSN EN 13229 „Vestavné spotřebiče k vytápění a krbové vložky na tuhá paliva – Požadavky a zkušební metody“ proběhlo základní zhodnocení tepelné účinnosti a emisních parametrů prototypu spalovacích akumulačních kamen SK-2 s horním odhořínáním a jmenovitým tepelným výkonem 8 kW. Ověřovány byly postupně biopalivové brikety Ø 65 mm ze směsi pšeničné slámy a 20 % m/m hnědého uhlí, pšeničné slámy a 5 % m/m hnědého uhlí, pšeničné slámy, směsi pšeničné slámy a 10 % m/m roztoku vody a melasy, „ekobiopalu“ tvořeného fermentovanou směsí 33 % m/m vyhnilého čistírenského kalu a 67 % m/m dřevní štěpky, směsi pšeničné slámy a 15 % m/m vyslazených řepných řízků, směsi bojínkového sena a 25 % m/m hnědého uhlí, bojínkového sena, lučního sena, směsi lučního sena a 25 % m/m hnědého uhlí. Nejnižší emise CO, kdy nebyla překročena mezní hodnota 3000 mg/m^3_N při 13 % O_2, stanovena pro přísnější 1. třídu a nejvyšší účinnost při jmenovitém tepleném výkonu, tj. vyšší nebo rovno 70 % (Třída 1), vykazovaly brikety ze směsi pšeničné slámy a 15 % m/m vyslazených řepných řízků, bojínkového sena a směsi lučního sena s přídavkem 25 % m/m hnědého uhlí. Dále byly měřeny emise NO_x a HCl. Hodnoty NO_x byly významně nižší než limitní hodnoty stanovené pro obdobné spalovací zařízení na tuhé biopalivo. Větší rozdíly emisí HCl korelují s různým obsahem Cl v palivech. Pouze u brikety z pšeničné slámy s podílem 25 % m/m hnědého uhlí emise HCl překročily limitní hodnotu o 16 %. U dalších paliv byly výrazně nižní. Výsledky ukazují na lepší tepelně-technické i emisní parametry směsných biobriket. Jsou významné pro standardizaci tuhých biopaliv, tuhých alternativních paliv a hledání způsobu zvyšování účinnosti a optimalizaci ekologických parametrů včetně emisí HCl.

Klíčová slova: biopalivové brikety; kompozitní brikety; spalování; účinnost; plynné složky ve spalinách; emise

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