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Heat energy accumulation construction for bioethanol burner

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Abstract

Commonly sold bioethanol fireplaces can represent significant heat source, however due to their intermittent operation the heat energy output is strongly uneven. The aim of this study was to determine the possibilities of heat energy accumulation by individually built ethanol fireplace intended for commonly sold ethanol burner installation. For the measurements of heat energy output, long term tests of the individually built ethanol fireplace with 1, 2 and 3 consecutive combustion periods in a unique calorific room were performed. Accumulation ethanol fireplace has proven high ratio between accumulated heat energy after the ethanol burner last burn-out reaching from 21.4 to 48.4% according to the number of consecutive fuel doses. By usage of the described ethanol fireplace the time of heat energy releasing was increased from approximately 1.15, 2.35 and 3.55 h in case of ethanol burner usage in a non-accumulation fireplace for 1, 2 and 3 fuel doses to 6.5, 11 and 15 h in case of accumulation ethanol fireplace usage. This was also strongly connected with average heat output ranging between 2.54 to 2.47 kW in the case of ethanol burner usage in a non-accumulation ethanol fireplace and 0.38 to 0.59 kW in the case of accumulation ethanol fireplace usage.

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Keywords: Local heating; Bioethanol burner; Heat accumulation

1. Introduction

Energy security and heat energy comfort are more and more often inflected phrases in connection with the unstable geopolitics situation in Europe [1]. Concerns about unpredictable power outages connected with unpredictable energy pricing cause a significant increase in interest in local heating combustion units, such as wood log stoves, as was described by Canepa [2] and Mortimer [3]. Wood log stoves usually serves as the secondary or tertiary heat source in case of the failure of the main ones. However, the mentioned units have several disadvantages, including the presence of a suitable exhaust system, high purchase costs (the installation often involves many

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Nomenclature

EB	Ethanol burner
EF	Ethanol fireplace
FG	Flue gas
HE	Heat energy
HHV	Higher heating value
k	Heat of vaporization considering the volumetric work done by the water formed from the hydrogen during combustion at 25 °C, 2.37 MJ kg^{-1}
k_1	Specific heat of water evaporation at constant pressure at 25 ° C, 2.44 MJ kg^{-1}
LHV	Lower heating value, MJ kg^{-1}; kWh kg^{-1}
ω_H	Mass fraction of hydrogen in the fuel, kg kg^{-1}
ω_N	Mass fraction of the nitrogen in the fuel, kg kg^{-1}
ω_O	Mass fraction of the oxygen in the fuel, kg kg^{-1}
ω_w	Mass fraction of the water in the fuel, kg kg^{-1}

technological and security features surrounding the device, especially in the case of the stoves with flue gas/water heat exchanger) and high value of heat output. The last mention one must not necessarily be a disadvantage, but in case of low heat energy demand houses, using an oversized stove, especially during the spring or autumn season, could cause fast overheating of the surrounding area which can significantly decrease the residents' comfort. An EF, today considered preferably as the design element according to Neubrech [4], appears to be in some cases a suitable alternative to standard wood stoves.

The main part of the ethanol fireplace (further only as EF) is the ethanol burner (further only as EB), where the combustion process of ethanol takes place. EB is stainless steel container usually partly filled with ceramic wool with an opening equipped with a regulation flap as was described by Ryšavý et al. [5]. Mostly sold EB are a simple type without the possibility of adding the fuel during the combustion process (allowing only intermittent operation), without any combustion air control system, combustion air staging and any other combustion process improvements [4]. Possibilities of the EB utilization as the heating element for households were described by Hajamalala [6]. The maximum heat output of standardly sold EB depends on its opening area and could reach more than 4 kW as was described by Ryšavý et al. [5] together with their other heat output parameters.

Heat energy (further only as HE) is released from ethanol burning, which is an intricate process composed of many complicated chemical reactions described by Millán-Merino et al. [7]. Denatured ethanol is the only allowed fuel for this kind of combustion equipment, whereas fuels on the market significantly differ in the mass concentration of the water and consequently in LHV as was described by Martinka et al. [8], Nozza et al. [9] and Ryšavý et al. [5]. A huge advantage of ethanol usage is the possibility of its production from many kinds of feedstocks, which could be local, such as molasses [10], corn stems [11], palm empty fruit bunch [12], rice straw [13], waste food [14], brewers' spent grain [15] and sugar or starch crops [16].

The products of the ideal combustion process of ethanol are CO_2 and H_2O, which are together with nitrogen and oxygen (from excessive combustion air) main parts of the flue gas (further only as FG). The real flue gas also contains pollutants formed during the real combustion process such as CO, which can be significantly decreased by oxidation catalyst usage, as was described by Ryšavý et al. [17]. The FG is the main carrier of the released heat energy [18]. In commonly sold EF, the FG flows from the EB to the ambient air without any additional utilization in the EF.

Standard EF are only designed as the design element which should increase the enjoyment of the open fire and its other potentials are unused. When considering the intermittent operation of the EB, high HE output peaks and the possibility of the EF usage as the secondary or tertiary HE source (as the backup in case of primary source failure), designing the EF as the HE accumulator for equalizing of the uneven course of the released HE including the HE peaks and fast decline of the HE releasing during the burnout phase, seems to be very beneficial. Additionally, during the ethanol combustion in a non-accumulation EF in the house without any forced air ventilation with energy recovery major part of HE is lost after the necessary air ventilation (after every combustion period) usually carried out by an open window [9]. Accumulation EF can increase the share of usable HE and minimalize the HE losses in that case.

This study is aimed at the determination of the HE accumulation ability of individually built accumulation EF for standard EB.

The novelty of the study and its main contribution consists in the description of the possibility of partial equalizing the HE output of the EF which is completely new approach (never described before) to the EF which can make it a more valuable element in the entire energy system of the house by increasing its efficiency (decrease of the HE loss through the ventilation) and increasing of the thermal comfort of the house residents (slow releasing of the heat energy to avoiding the overheating).

2. Materials and methods

2.1. Fuel

As the fuel, standardly sold bio-ethanol (marking for ethanol produced by fermentation of organic material; hereafter only as ethanol). According to producers' information, fuel was without any water content only enriched by denaturants. The higher heating value (further only as HHV) of the fuel was measured in a calorimeter (LECO AC600). Each sample was measured at least five times and the average of individual results was taken into the consideration. The value of the LHV was calculated according to the formula Eq. (1) referred to in DIN 51900-1 [19]:

$$LHV = HHV - (k \cdot 8.94 \cdot \omega_H + 0.8 \cdot (\omega_N + \omega_O) + k_1 \cdot \omega_W) \tag{1}$$

k	heat of vaporization considering the volumetric work done by the water formed from the hydrogen during combustion at 25 °C, 2.37 MJ kg^{-1}
k_1	specific heat of water evaporation at constant pressure at 25 °C, 2.44 MJ kg^{-1}
ω_H	mass fraction of hydrogen in the fuel, kg kg^{-1}
ω_N	mass fraction of the nitrogen in the fuel, kg kg^{-1}
ω_O	mass fraction of the oxygen in the fuel, kg kg^{-1}
ω_w	mass fraction of the water in the fuel, kg kg^{-1}

The density of the fuel was taken over from its safety data sheet. Basic information about the used fuels is listed in Table 1.

Table 1. Basic information about the fuel and fuel mixtures.

Fuel	*HHV* [MJ kg^{-1}]	*LHV* [MJ kg^{-1}]	Density [kg dm^{-3}]
Ethanol	29.38	26.57	0.789

2.2. Accumulation EF

Accumulation EF was made from 15 fireclay plates (600 × 300 × 30 mm). Fireclay as the accumulation material was chosen for its low price, high thermal resistance, high density (1850 kg m3) and high thermal conductivity (0.8–1.0 W m^{-1} K^{-1}) [20].

As the heating element, EB with 3.5 kW of heat output (according to manufacturers' data) was chosen. The EB opening area was 11 200 mm^2. The maximal fuel dose was 500 ml, which was always used during the described tests. Overall dimensions of the EB were 450 × 150 × 50 mm. Chosen EB was equipped with the regulation flap, which was not used during the tests.

From the EF construction point of view, the bottom fireclay plate served as the support for the EB. There were 12 circular holes 53 mm in diameter (6 at the front part of the EB and 6 behind it). Another 16 holes of 8 mm in diameter were drilled on the sides of the EB (8 on the left side and 8 on the right side).

Two plates (one cut in half into two pieces) formed the side and back of the combustion chamber. The front part of the combustion chamber was equipped with heat resistance glass (to direct the flue gas flow through the upper part of the EF). Above the combustion chamber, the heat exchanger part consisting of the 12 plates was located. There were 8 holes in the heat exchanger plates of 63 mm in diameter. Holes dimensions in the support plate and in the heat exchanger plates enable free air and flue gas flow. Drilled plates work as the regenerative heat exchanger, while during the combustion process of the ethanol in EB, hot flue gas flowed through the holes and transferred part of the heat energy from them to the plates. After the burnout, ambient air flowed through the whole construction of the EF by the natural drought, while the accumulated heat energy was transferred to this air. Part of the heat energy was also transferred from the external surface of the accumulation plates (in case of free-standing installation without insulation).

Above the heat exchanger part, there is a chamber for the guidance of the flue gas and the airflow to the surroundings. This chamber is made from calcium silicate plates.

The weight of the combustion chamber plates (support, two sides and back) was 27.46 kg, the weight of the heat exchanger part was 103.27 kg.

The whole EF was supported by steel construction, which enables easy opening and closing of the heat resistant glass. A layout model of the accumulation EF in an exploded state is presented in Fig. 1 (left side), while the real photo of the accumulation EF is presented in Fig. 1 (right side).

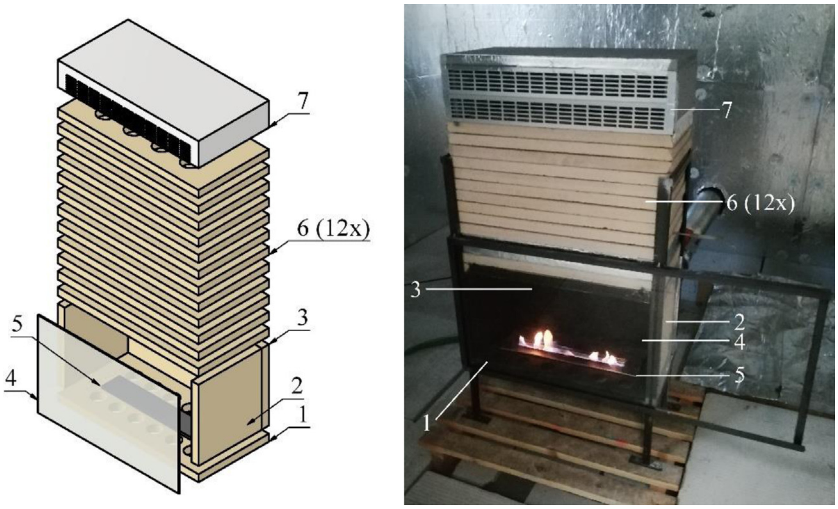

Fig. 1. Model of the accumulation EF in an exploded state — left side; real photo of the accumulation EF — right side (1 — support part; 2 — side part of the combustion chamber; 3 — back part of the combustion chamber; 4 — heat resistance glass; 5 — EB; 6 — chat exchanger parts; 7 — rectifier part).

2.3. Calorific room

The calorific room is equipment that enables the measurement of actual HE output of HE sources (wood stove, accumulation wood stove, wood cooker, individually built accumulation wood stove etc.) to their surroundings. Dimensions of the used calorific room located in the Energy Research Centre are 3 × 3 m with a width of 2 m. Calorific room is well insulated from the other parts of the laboratory by 10 cm wide glass wool plates equipped with reflective foil on the inner surface for the minimalizing of the HE accumulation. The floor is covered by 4 cm wide calcium silicate plates.

The measurement principle consists of constant forced airflow through the calorific room (maintained by PID regulator, the frequency converter and adjustable damper IRIS 250), while the temperature of the air at the calorific room inlet and the temperature of the air at the calorific room outlet is measured. Forced airflow is caused by two air fans. The fans are adjusted for maintaining the 0 Pa relative pressure in the calorific room related to the outer part of the laboratory. Before the tests, calibration curves for the actual arrangement of the calorific room were prepared by HE output measurement of the electric heaters with known electricity consumption. Based on the temperature difference and the calibration curve, the instantaneous heat output of the heater can be calculated. The used calorific room was designed for HE output range from 0 to 20 kW.

2.4. Process of the testing and data evaluation

The testing process consists of two main simultaneous procedures. The first of them was for a determination of the actual heat output of the EB based on the standard EN 16 647 [21]. This method was based on the periodical measurement of a decrease in the overall weight of the EB (including residual fuel). For these purposes, EB was placed on the scale (XS balance BL 30K1) and heat resistance plates to avoid scale damage and to avoid direct contact of the EB with the supporting plate. Before the test scale was reset to zero and consequently the fuel was filled into the EB and ignited. During the combustion process weight differences were recorded (every minute). From obtained values and known lower heating value (further only as LHV) of the fuel, actual HE output curves were constructed.

The second procedure was aimed at the actual HE output of the whole EF. For these purposes, the calorific chamber was used. Airflow to and from the calorific chamber was fixed several hours before the tests. Consequently, the stabilization phase of the closed calorific room took place with the aim of equalization of inlet and outlet temperatures. After the successful stabilization, ethanol was filled into the EB (described above) and ignited. Immediately after the ignition, the door was closed and the measuring phase started.

In the case of multiple fuel doses, emphasis was placed on the fast opening of the calorific chamber, fuel adding and door closing to avoid influencing the results.

Detailed information about the measuring equipment, the measured range of each measuring equipment, the principle of its measurement and the accuracy are presented in Table 2.

Table 2. Detailed information about the measuring equipment, measured range of each equipment, the principle of the measurement and the accuracy of the devices.

Device and measured component	Range	Principle	Accuracy
Cressto SPD 211 R5UB D			
Pressure difference	−100 to +100 Pa	Piezoelectric effect	±1.5% of the ultimate value of the measurement range
PT100			
Temperature	−75 to 250 °C	Resistance temperature detection	±0.3 °C
Scale, XS balance BL 30K1			
Weight	0 to 30 kg	Strain gage	±0.1 g

3. Results and discussion

Three combustion tests in the calorific room were performed in total. The most important results are presented in Table 3. Combustion phases of the EB took a similar time (1:09–1:12) and courses of the HE were also similar (with comparable times of ignition, heating and burnout phases). Phases of the combustion period of a one-chambered EB were described by Ryšavý et al. [5], while newly obtained results are completely in accordance with previously presented ones including the time and value of the maximal heat output and average heat output. Maximal heat output was reached during the first fuel dose, but this value (3.85 kW) was only slightly above the values reached during the second (3.68 kW) and the third (3.50 kW) dose when looking at the individual doses separately. From the average heat output of separate doses point of view, results were almost identical with 2.54 kW, 2.45 kW and 2.43 kW for the first, second and third dose respectively (the value of the first fuel dose is slightly higher especially because of faster burnout by 3 min in comparison to the other ones. In general, all three doses presented very similar results each other and also almost identical results in compassion to them obtained during the one and two-doses tests.

It was not confirmed, that starting of the subsequent combustion period (second and third) with the temperature of the EB above room temperature cause acceleration of the ethanol evaporation and consequently shortening the combustion period, increasing the maximum HE output, increasing the average HE output and shortening the heating phase.

Compared to the EB, the maximum heat output of the EF was increasing (1.94 kW, 2.25 kW and 2.45 kW) with the increasing amount of fuel doses. This was due to residual HE, which was not released before the ignition of the next fuel dose, which caused the warming up of the whole accumulation EF to the higher temperature during the next combustion period. The increased initial temperature of the EF before the consequent combustion period also meant

Table 3. The most important results from combustion tests.

Parameter	Unit	1 fuel dose		2 fuel doses		3 fuel doses	
		EB	EF	EB	EF	EB	EF
Total time of energy releasing[a]	hh:mm	1:09	6:30	2:21	11:00	3:33	18:00
Maximal HE output	kW	3.85	1.94	3.85	2.25	3.85	2.45
Average HE output	kW	2.54	0.38	2.49	0.51	2.47	0.59
Chemical energy input	kWh	2.95		5.90		8.85	
Accumulated HE after last burnout	kWh	>0.04	1.43	>0.04	1.81	>0.04	1.90
The ratio of accumulated HE after the last burnout	%	1.4	48.4	0.7	30.6	0.5	21.4

[a]In the case of EB total time of energy released means the total time of the combustion process.

worse conditions for heat transfer between flue gas and fireclay plates, as evident from the decreasing differences of the maximum heat outputs achieved with the increasing number of doses. The same trend was observed by Kubesa et al. [22] during the individually built wood accumulation stove.

The value of the average HE output of the EF mentioned in Table 3 is referred to the whole HE releasing time (ending by the decrease of HE releasing below 10 W), which lasted 6.5, 11 and 15 h respectively according to the number of fuel doses. The values are significantly affected by the HE releasing time, especially the cooling down time after burnout of the fuel. Reached values, ranging from 0.38 to 0.59 kW could be perfectly suitable for passive houses to avoid the overheating of the EF surroundings.

Accumulated HE after the burnout of the EB was important parameter. HE accumulated in EB was always lower than 0.04 kWh, which was determined from the average temperature of the EB after the test, its materials and thermo-technical parameters of the materials. In the case of EB installation of standardly sold non-accumulation EF, the value could increase approximately up to 0.1 kWh. HE accumulated in the accumulation EF was many times higher, 1.43 kWh, 1.81 kWh and 1.90 kWh for one fuel dose, two fuel doses and three fuel doses (calculated as the sum of the minute values of HE output before and after the EB burnout). This parameter is crucial in the case of EF usage in a house without forced air changing including the HE recuperation, because a huge part of the released HE during the combustion process will be lost during the necessary ventilation by the window. In that case, the ratio between HE accumulated in the EF after the last burnout and chemical energy input (mentioned in Table 3) can be considered as efficiency. In the case of EF usage in a house with forced air changing with the HE recuperation, the efficiency is close to 100%. Efficiency in that way is a very important parameter, which is significantly related to CO_2 emissions (increasing efficiency means decreasing CO_2 emissions).

Time courses of the released HE (EB HE output measured during the three doses test and EF HE outputs from all three tests) are presented in Fig. 2. The HE time course of the EF is always divided into two phases, warming-up and cooling. The warming-up phase (the rising part of the EF heat releasing course) took place always during the ignition and heating phase of the EB, while during the burn-out phase of the EB the cooling (descending part of the EF heat releasing course) of the EF started. A similar trend was also described by Kubesa et al. [22] and Garba et al. [23].

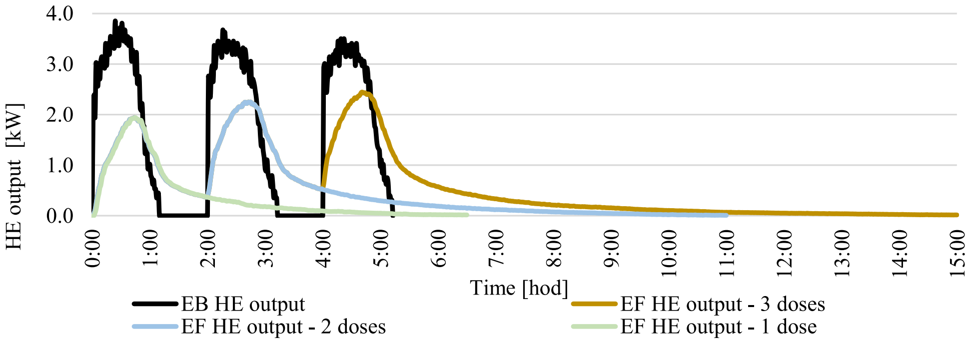

Fig. 2. Time course of the released heat energy by EB and EF to the surroundings.

4. Conclusions

The main parameters of individually built accumulation EF were described. The ratio between accumulated heat energy after the EB last burn-out ranging from 21.4 to 48.4% according to the number of consecutive fuel doses. Average HE output with non-accumulation EF ranging between 2.54 to 2.47 kW, while in case of accumulation EF usage it ranging between 0.38 to 0.59 kW.

Presented accumulation EF was built as a low-cost and easy construction, without any complicated control systems or insulation which could easily improve some of the presented parameters as well as the increase of the fireclay plates number, increase in the heat exchange surface between the flue gas and accumulation material or changing accumulation material into one with better thermo-technical parameters. Even though the high HE accumulation ability of the presented EF has been proven, which could lead to increasing the comfort of using the surrounding spaces (preventing overheating) and in the case of houses without forced airflow with HE recuperation, significantly higher overall efficiency could be obtained.

Next step of the research could be improvement of the EF design, choosing of the better material or implementation of control system for reaching better thermo-technical properties of the EF.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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