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Effects of air excess control in a heat storage solid fuel-fired household furnace

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Abstract

Due to a significant increase in electricity prices during the last decade and insufficient production capacity of the electric power industry in Serbia, many households that are currently using electric heat storage furnaces for heating have been forced to find an alternative solution for heating. A possible solution is replacing electric heating appliances with similar solid fuel-fired ones. Existing solid fuel-fired furnaces are often unsatisfactory with respect to their efficiencies and flue gas emissions. A prototype of a new concept of heat storage, solid fuel-fired furnace has been developed to meet these growing needs, providing electricity saving together with considerable environmental benefits. In order to examine furnace performance, efficiency and environmental aspects, and to assess the influence of air excess control in the furnace on the efficiency and flue gas emissions, numerous experimental tests were conducted. The amount of combustion air, the flue gas flow rate and the fuel feeding regime have been adjusted in order to keep the flue gas oxygen content in a relatively narrow range, thus obtaining controlled combustion conditions and, correspondingly, lower carbon monoxide emission and higher furnace efficiency. In this way, the furnace was made able to respond to the changes in heating needs, fuel quality and other parameters, which is considered to be advantageous in comparison with similar solid-fuel fired furnaces.

Keywords: Household furnace; Heat storage; Control; Solid fuel; Air excess

1. Introduction

Many households in Serbia are heated with electric heat storage stoves, with 2–6 kW installed power each. Heating with existing heat storage stoves is fairly comfortable, but heat is transferred from the stove to the heated room primarily by radiation, which can cause the feeling of unpleasantness at times. A more acceptable and pleasant way of heating could be achieved if the contribution of convective heating of heat storage stoves was increased. In addition, due to the increase of electricity prices and limited electric power production capacities, electric heating is becoming very expensive for many households. These facts, as well as general trends in the society, give quite a few incentives to replace this type of heating with an alternative one. One of the possible solutions is replacing these electric appliances with solid fuel-fired heat storage furnaces. Under the assumption that ≈25% of households in Serbia is heated with electric heat storage stoves, and that one third of these are replaced with solid fuel-fired furnaces, it can be concluded that there is a need for replacing some 150 000 electric stoves with solid fuel – biomass and/or coal – fired furnaces. This is also a requirement imposed by the measures of the European Union for achieving energy savings in households. The reserves of coal, which is the principal source of primary energy for electricity production in Serbia, are being exhausted gradually. This points out to the importance of introducing larger amounts of biomass as

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Nomenclature

B	fuel consumption (kg/h)
C	carbon content in the fuel (mass%)
$\mathrm{CO_{ref}}$	concentration of CO at reference oxygen content in the flue gases (vol.%, mg/Nm^3)
$\mathrm{CO_{meas}}$	measured concentration of CO in the flue gases (vol.%)
$\mathrm{CO_{2meas}}$	measured concentration of CO_2 in the flue gases (vol.%)
c_{pm}	specific heat (under $p = \mathrm{const.}$) of the flue gases (kJ/kg K)
C_{r}	percentage of combustibles in the unburnt that falls through the grate (mass%)
$E_{\mathrm{CO}}(\tau)$	cumulative CO emission from the beginning of the test (g), until the moment of time τ
H	hydrogen content in the fuel (mass%)
$\dot{m}_{\mathrm{CO}}$	mass flow rate of carbon monoxide in the flue gases (mg/s)
$m_{\mathrm{CO}}(3\ \mathrm{s})$	mass of CO released in 3 s (mg)
$\mathrm{O_{2ref}}$	reference oxygen content in the flue gases (vol.%)
$\mathrm{O_{2meas}}$	measured oxygen content in the flue gases (vol.%)
P	furnace thermal power (W)
Q_{g}	heat losses in the flue gases (kJ/kg)
q_{g}	percentage of heat lost with the flue gases (%)
Q_{h}	heat losses due to incomplete combustion (kJ/kg)
q_{h}	percentage of heat lost due to incomplete combustion (%)
q_{r}	percentage of heat lost due to combustibles in the unburnt that falls through the grate (%)
t_0	temperature at the top of the middle flue (°C)
t_1	combustion chamber wall temperature (°C)
t_2	middle flue wall temperature (°C)
t_3	third flue wall temperature (°C)
t_4, t_5, t_6 and t_7	ceramic tiles temperatures (°C)
t_8	flue gas temperature at the catalyst section entrance (°C)
t_9	flue gas temperature at the catalyst section exit (°C)
t_{10}	furnace exit flue gas temperature (°C)
t_{amb}	surrounding air temperature (°C)
$\dot{V}_{\mathrm{fg}}$	dry flue gases flow rate (m^3/s)
W	moisture content in the fuel (mass%)
Greek symbols	
η	furnace efficiency (%)
τ	time (s)

fuel in the future, and biomass-fired furnaces can play a significant role.

Utilization of solid fuel-fired heat storage furnaces, compared to electric stoves, has certain advantages. The possibility of electricity saving that can arise from replacing electric stoves with solid fuel-fired ones is of immense importance, since it could decrease the load of the power production system in Serbia. This is in accordance with energy saving tendencies in space heating [1]. For instance, 4 000 000 kW h/day could be saved, and power production load lowered, especially during peak hours, by replacing 100 000 electric stoves, with 4 kW of electric power and working 10 h/day each. If all of these electric stoves are turned on at the same time (since the heat is accumulated usually during the low-tariff electricity period), their power would correspond to the power production of the 400 MW unit.

Electricity saving implies significant indirect pollutant emission reduction from power production facilities, the most important being reduction of greenhouse gases emissions, above all carbon dioxide (CO_2). Based on total emissions from Serbian power plants data [2], by saving 4 000 000 kW h of electricity per day, indirect CO_2 emission reduction of 3228 t/day is achieved. Indirect emission reductions for nitrogen oxides (NO_x), carbon monoxide (CO), and sulphur dioxide (SO_2) are also important – in the previous example, reductions would be 5.4 t NO_x/day; 2.56 t CO/day, and 46 t SO_2/day [2].

One of the most important tasks in the field of residential heating is to improve the efficiency of heating devices [3]. By proper organization of the combustion process, furnace efficiency of more than 75% can be achieved. Solid fuel-fired furnaces can utilize, apart from coal, various kinds of waste and biomass, which is a renewable energy source. The biomass potential of Serbia is enormous. It is estimated that the total amount of biomass from agricultural production is 7 000 000 t/year. With an average biomass heating value of 14 000 kJ/kg, if only 10% of the available annual amount was used for production of energy for heating, thermal power achieved in this way would be 310 MW. Using biomass, as a renewable energy source, is of wide social importance, both for the savings that may arise from it, as well as for environmental reasons, which include complying with Kyoto Protocol requirements.

For all the reasons stated above, a new solid fuel-fired heat storage furnace has been developed in the Laboratory for Thermal Engineering and Energy of the "Vinca" Institute in Belgrade. Furnace design enables good conditions for complete combustion – the heat losses due to chemical reasons (incomplete combustion) and the heat losses with the flue gases are kept low, as well as flue gases emissions, and the furnace efficiency has been found to be over 75% [4,5]. Furnace design contributes in diminishing the unpleasantries linked to this type of heating facilities [6], and also enables uniform space heating – a problem very commonly addressed nowadays [7–9] – by combining radiative and convective heat transfer. The furnace also offers the possibility of firing both low- and high-rank solid fuels (biomass, coal, etc.) with simultaneous firing of different solid fuels, when needed.

Development efforts have been focused on three concepts of the heat storage solid fuel-fired furnace – furnace with basic equipment, furnace with a heat exchanger, used for generating hot water, and furnace supplied with a catalyst and a simple system for air excess control, with the aim to find the influence of different flow and combustion conditions on furnace efficiency and emissions. Thorough tests of the furnace basic version [10] and the version with the heat exchanger in the third flue [11] were previously carried out. These tests proved that furnace design enabled excellent combustion conditions and almost complete transformation of toxic CO into CO_2. The tests were done with wood biomass used as fuel. The average exit flue gas temperature was 139.8 °C, and the average values of water inlet and outlet temperature were 48.5 °C and 57.6 °C, respectively. Since the fuel did not contain any sulfur, the danger of dewpoint corrosion was not present. However, this risk might occur in case the stove is coal-fired. The results obtained in the experiments with the heat exchanger have served as a basis for developing a heat transfer and flow model in the heat exchanger zone [12].

In order to enhance the furnace design further, tests were done with the aim to assess the influence of air excess control on furnace performance, its efficiency and environmental impact. The oxygen content in the flue gases was continuously monitored with the help of a data acquisition system, and combustion air flow rate was adjusted accordingly, so as to keep the oxygen content in a relatively narrow range (≈12%). These tests were done on the furnace version without the heat exchanger, both with the installed catalyst and without it, in accordance with the European Standard for solid fuel-fired furnaces (EN 12815) [13].

2. Household heat storage furnace design

The basis for the development of the household heat storage solid fuel-fired furnace designed and built in the Laboratory for Thermal Engineering and Energy of the “Vinca” Institute, was a registered patent [14]. A scheme of the furnace is given in Fig. 1.

Furnace walls consist of blocks, made of refractory material. From the outside, the walls are lined with removable ceramic tiles. On the furnace front side, there are three openings, two of which for fuel feeding and fire support, and the lowest one serving as air inlet and used for draft control, as well as for accessing the space under the grate which is used for collecting the ash.

Combustion of solid fuel (wood biomass, briquettes, low- or high-rank coals) takes place on a horizontal grate, and the flue gases flow through three flues, which are divided by vertical partitioning walls, made of refractory bricks. The essential design characteristics of the furnace are the convective heating ducts, made of steel sheets. These ducts are placed between the refractory furnace wall and the ceramic tiles. Their purpose is to increase convective heat exchange and decrease radiative heat exchange at the same time, thus contributing to the feeling of pleasantness in the heated room. The presence of convective ducts increases the total heat flow rate and the furnace efficiency as well. Thermal energy of the flue gases is transferred to the furnace refractory walls by radiation and heat convection, through the walls by heat conduction and then by radiation and convection to the surrounding air. A more detailed furnace description was given in [12].

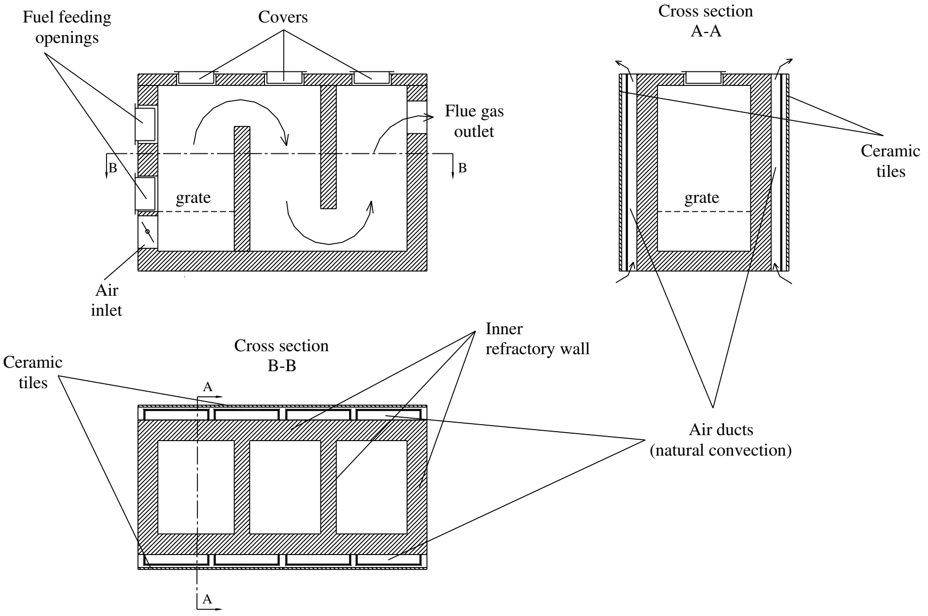

Fig. 1. Scheme of the heat storage solid fuel-fired furnace.

3. Experimental set-up and procedure

Experimental tests were done in order to examine the influence of air excess control on furnace efficiency and on its environmental impact, primarily the emission of CO. The experimental set-up, consisting of the examined furnace, the gas sampling line and the temperature measurement equipment, is shown in Figs. 2 and 3.

The examined heat storage solid fuel-fired furnace (position 1 in Fig. 2) consists of three flues (1a – the combustion chamber, 1b – the middle flue, 1c – the third flue). Pieces of solid fuel are burnt on a grate (2). In order to additionally decrease CO emission, the Pt/Al_2O_3 catalyst (3) has been used in one of the experimental regimes. With respect to the catalyst efficiency diagram (the temperature dependence of the catalyst's capability for removing certain flue gas components), pre-tests were performed to find the place for optimal catalyst installation.

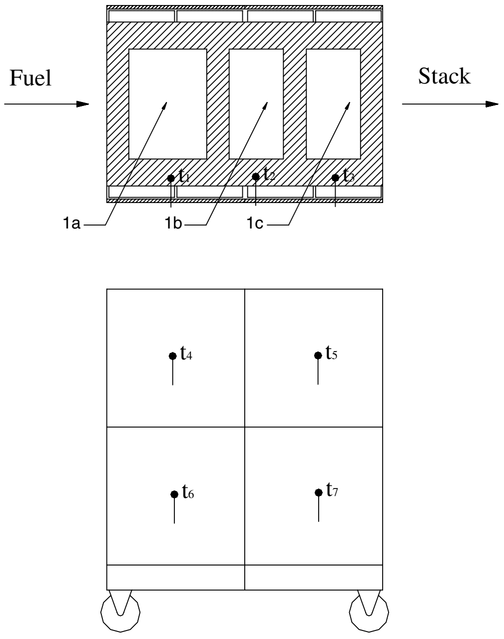

Fig. 3. Temperature measurement points.

The Pt/Al_2O_3 catalyst is used, in the form of 3 ± 0.3 mm spheres. The support used for the catalyst is commercial $(\gamma + \theta)$ Al_2O_3 from Rhone Poulenc in the form of spheres. The platinum catalyst has been prepared by impregnation of a dry support with aqueous solution of chloroplatinic acid [15]. After several hours of tests of the heat storage furnace, the catalyst particles were partially covered with soot, but its efficiency did not deteriorate with time. Apart from CO reduction, this catalyst can also help in lowering hydrocarbons and nitrogen oxides emissions. The pre-tests have shown that the temperature range of the catalyst optimal efficiency for CO conversion corresponds to the flue gas temperatures measured in the middle flue (1b), and therefore this flue has been chosen as the most appropriate place for catalyst positioning. The first flue (1a) could have not been selected in any case, since the combustion with intensive flame takes place here. The flue gases, passing through the catalyst section (3), leave the furnace through

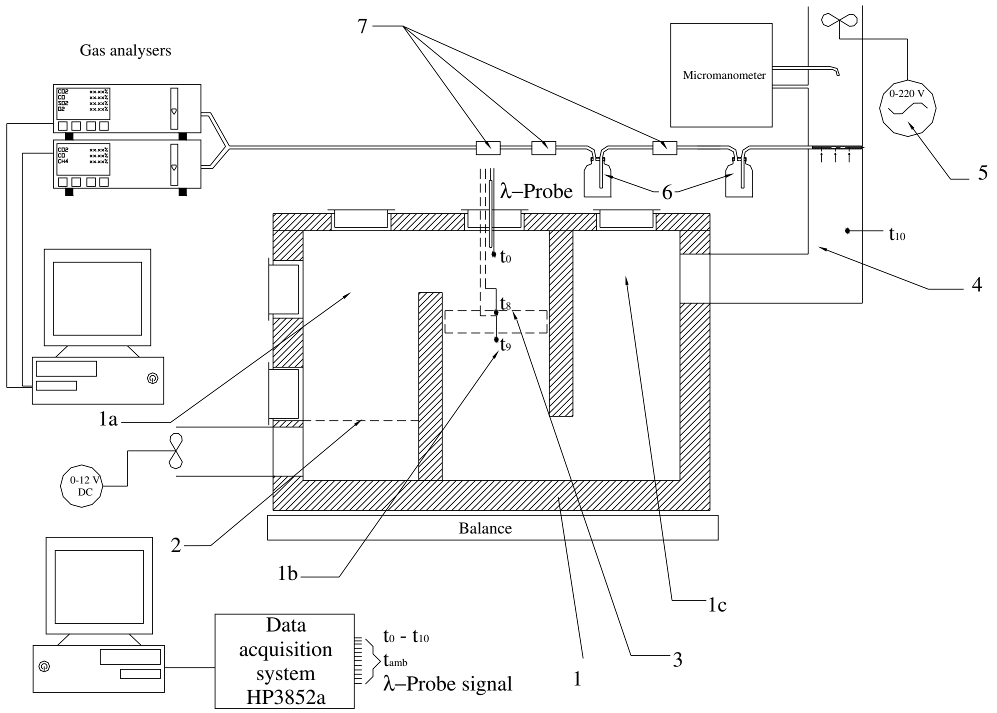

Fig. 2. Heat storage solid fuel-fired furnace with installed equipment for measurement: 1 – furnace; 1a – combustion chamber; 1b – middle flue; 1c – third flue; 2 – grate; 3 – catalyst (optional); 4 – stack; 5 – flue gas fan with a variable AC source; 6 – flue gas condensate vessels; 7 – filters.

the stack (4). The stack is also used as a measuring path, used for flue gas sampling, temperature and flow rate measurement. The combustion air enters the furnace through the ash bin opening, under the grate. The basic method for controlling the air flow rate is by adjusting the draft in the furnace – by changing the flue gas fan speed. This fan is connected to a variable (0–220 V) AC source (5). For additional, precise air flow rate control, another fan was used, which blew the air through the ash bin opening, under the grate (Fig. 2). This fan was connected to a variable DC source (0–12 V). The furnace as a whole was placed on a high-precision balance (±10 g), in order to monitor the weight loss between consecutive fuel feedings, i.e., the combustion dynamics.

Measurements were performed in three different operating regimes of the furnace, with wood used as fuel. During experiments in the basic regime without air excess control (Regime W1), when the furnace had reached a steady state (after the initial firing period), the AC voltage was kept constant, which enabled the whole amount of fuel in the chamber to burn out until the next fuel feeding, in 1 h, with only incandescent char left on the grate. Average fuel consumption in Regime W1 was $B = 1.05$ kg/h, which equals the obtained average thermal power $P = 4.9$ kW (with the estimated efficiency $\eta = 0.8$).

In the regime with air excess control (Regime W2), the air flow rate was adjusted primarily by changing the AC voltage, supplying the flue gas fan, in a very wide range, in accordance with the values of oxygen content in the flue gases, measured by the gas analysers. A smaller fan, blowing the air under the grate (Fig. 2), was used for fine control of the air flow rate. The furnace was without the catalyst in regimes W1 and W2. In Regime W3 (air excess control with the presence of the catalyst in the middle flue), the air flow rate control was performed in the same manner as in Regime W2. The catalyst was positioned as depicted in Fig. 2 (a dashed-line rectangle). The average obtained thermal power in regimes W2 and W3 was 7 kW, for fuel consumption of 1.5 kg/h.

Gas samples were continuously taken from the stack (4) and analysed during experiments. The gas sampling probe, made according to the EN 12815 Standard [13], was water-cooled on the outside of the stack, in order to dry the flue gas samples. The gas sampling line was also equipped with vessels for collecting the condensate (6), and filters (7) for protection of gas analysers (both types Saxon Junkalor Infralyt 50) from particles and tar in the flue gases. Gas analysers were continuously controlled by a PC, with memorizing the measured concentrations data every 3 s.

Temperatures were measured with type K, class I thermocouples, at the following points: t_0 – temperature at the top of the middle flue (Fig. 2), t_1 – combustion chamber wall temperature (Fig. 3), t_2 – middle flue wall temperature (Fig. 3), t_3 – third flue wall temperature (Fig. 3), t_4, t_5, t_6 and t_7 – ceramic tiles temperatures (Fig. 3), t_8 – flue gas temperature at the catalyst section entrance (Fig. 2), t_9 – flue gas temperature at the catalyst section exit (Fig. 2), t_{10} – furnace exit flue gas temperature, t_{amb} – surrounding air temperature.

Together with the temperatures, the λ-Probe (zirconia probe) signal, in volts, was measured, in order to obtain a basis for the planned development of an automatic air excess control system. Temperatures and the λ-Probe signal were measured with a digital voltmeter on the HP3852a data acquisition system, and memorized every 5 s.

In all regimes of operation, the fuel was fed to the furnace in shorter intervals – 1 h or 30 min, which was found to be optimal from the pre-tests of the furnace. Furnace operation was continuously monitored for several hours with the data acquisition system, and the flue gas contents, temperatures and λ-Probe signal were measured and memorized.

In order to compare furnace operation regimes with different air excess coefficients, measured CO concentration values in dry flue gases were converted to concentration values at reference oxygen content in the flue gases, according to the formula in Eq. (1):

$$\mathrm{CO}_{\text{ref}} = \frac{20.9 - \mathrm{O}_{2\text{ref}}}{20.9 - \mathrm{O}_{2\text{meas}}} \cdot \mathrm{CO}_{\text{meas}}. \tag{1}$$

The reference oxygen content in the flue gases, according to the EN 12815 Standard, is $\mathrm{O}_{2\text{ref}} = 13\%$. The CO concentration at reference oxygen content was converted to mg/Nm^3 as follows:

$$\mathrm{CO}_{\text{ref}}[\text{mg/Nm}^3] = \mathrm{CO}_{\text{ref}}[\text{vol.\%}] \cdot 10\,000 \cdot 1.25. \tag{2}$$

Released carbon monoxide in time was calculated as:

$$\dot{m}_{\mathrm{CO}} = \dot{V}_{\text{fg}}[\text{m}^3/\text{s}] \cdot \mathrm{CO}_{\text{ref}}[\text{mg/Nm}^3]. \tag{3}$$

Mass of CO released in 3 s is

$$m_{\mathrm{CO}}(3\ \text{s}) = 3 \cdot \dot{m}_{\mathrm{CO}}. \tag{4}$$

Since gas samples analysis data are memorized every 3 s, the cumulative CO emission from the beginning of the test until the moment observed $\tau - E_{\mathrm{CO}}(\tau)$ is calculated by the expression in Eq. (5):

$$E_{\mathrm{CO}}(\tau) = \frac{1}{1000} \sum_{0}^{\tau} m_{\mathrm{CO}}(3\ \text{s}). \tag{5}$$

The heat loss with the flue gases was calculated as

$$Q_{\text{g}} = (t_{10} - t_{\text{amb}}) \left[\frac{c_{p\text{m}}(\mathrm{C} - \mathrm{C}_{\text{r}})}{0.536(\mathrm{CO}_{\text{meas}} + \mathrm{CO}_{2\text{meas}})} + 1.91 \frac{9\mathrm{H} + W}{100} \right], \tag{6}$$

$$q_{\text{g}} = 100 \frac{Q_{\text{g}}}{\mathrm{H}_{\text{d}}}, \tag{7}$$

and the heat losses due to incomplete combustion are

$$Q_{\text{h}} = 12\,644 \frac{\mathrm{CO}_{\text{meas}}(\mathrm{C} - \mathrm{C}_{\text{r}})}{0.536(\mathrm{CO}_{2\text{meas}} + \mathrm{CO}_{\text{meas}})100}, \tag{8}$$

$$q_{\text{h}} = 100 \frac{Q_{\text{h}}}{H_{\text{d}}}. \tag{9}$$

The thermal power of the furnace is calculated as

$$P = \frac{\eta \cdot B \cdot H_\mathrm{d}}{3600}. \tag{10}$$

The heat losses were determined using the average values of corresponding parameters (t_{10}, t_amb, c_pm, $\mathrm{CO_{meas}}$, $\mathrm{CO_{2meas}}$) during the intervals between two fuel feedings. Calculations were made under the assumption of $C_\mathrm{r} = 0$. The assumption for wood seemed to be realistic, since the material left in the ash bin after several hours of tests resembled completely burnt out ash. The heat losses due to combustibles in the unburnt that falls through the grate are supposed to be $q_\mathrm{r} = 0.5\%$.

The furnace efficiency η is calculated as

$$\eta = 100 - (q_\mathrm{g} + q_\mathrm{h} + q_\mathrm{r}). \tag{11}$$

4. Results and discussion

The ultimate and proximate analyses of wood used in experiments are given in Table 1, with respect to the mass percentages.

In the basic operation regime – W1, less air than needed was supplied into the furnace deliberately, in order to show that an already proved efficient furnace, if not operated the correct way, can give non-satisfactory results, regarding CO emission and combustion quality. In the beginning of this regime, wood was supplied to the furnace every 30 min (0.750 kg), in order to avoid the grate to be completely covered with fuel and "choked". It turned out during the experiment that this amount of fuel was optimal for 40 min of operation, and fuel feeding was adjusted accordingly. Measured (Fig. 4), as well as average values (Fig. 5) of CO concentration in this regime of operation, where the furnace was deliberately supplied with lower amounts of air than needed, were at times somewhat higher than 1%, the maximum allowed by the EN 12815 Standard [13]. This points to the importance of correct furnace operation (guiding of the combustion process). Previous investigations [16] have shown that furnace, if operated properly, completely fulfills European environmental norms and requirements. Concentration values shown in Fig. 5 were averaged over periods between fuel feedings.

For assessing the influence of combustion air flow rate control on furnace efficiency and CO emission, investigations were done in the Regime W2 (air excess control without the catalyst) and the Regime W3 (air excess control with the catalyst). During these experiments, the aim was to keep the oxygen content in the flue gases in a relatively narrow range (11–14%). This equals to air excess coefficient

Table 1
Ultimate and proximate analyses of wood

Fuel	Carbon (%)	Hydrogen (%)	Oxygen (%)	Nitrogen (%)	Sulfur (%)	Ash (%)	Moisture (%)	Lower heating value (kJ/kg)	Fixed carbon (%)	Volatile matter (%)
Wood	43.25	5.17	37.53	0.44	0.00	1.66	11.95	20983	9.28	77.12

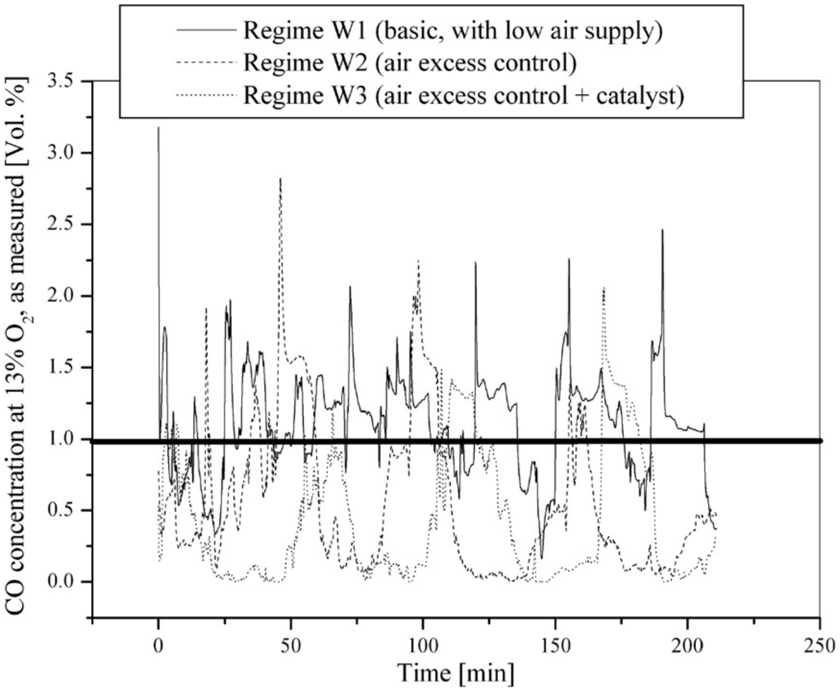

Fig. 4. CO concentration at 13% O_2 in different regimes of operation.

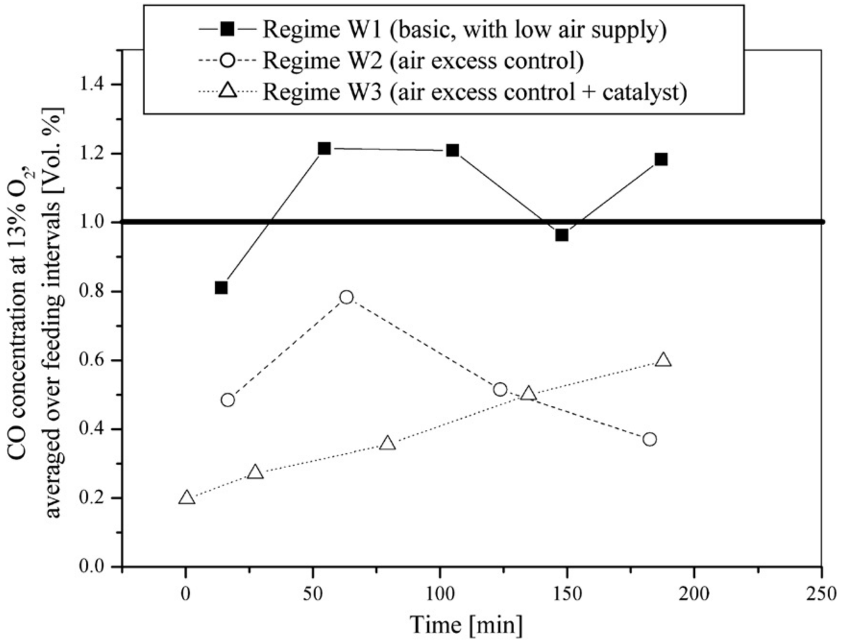

Fig. 5. CO concentration at 13% O_2, averaged over fuel feeding intervals.

values of 2.1–3, which were during the pre-tests found to be optimal for furnace operation, with respect to combustion quality and CO emission. For most of the time between two fuel feedings, flue gas oxygen content was about 12% (equal to 2.33 for air excess coefficient). In both regimes, average CO concentration in the flue gases, converted to 13% O_2, was lowered to values significantly under the permitted 1% (Fig. 5), which proved that air excess control contributed to the furnace performance.

The comparison of the influences of air excess control and catalyst installation is easier to be carried out by observing the cumulative CO emission during the experiments (Fig. 6). The air excess control itself considerably reduces CO emission, when compared to Regime W1, and this influence becomes more and more obvious during the experiment. The presence of the catalyst improves the effects of air excess control and reduces CO emission further. After 200 min of operation, the cumulative CO

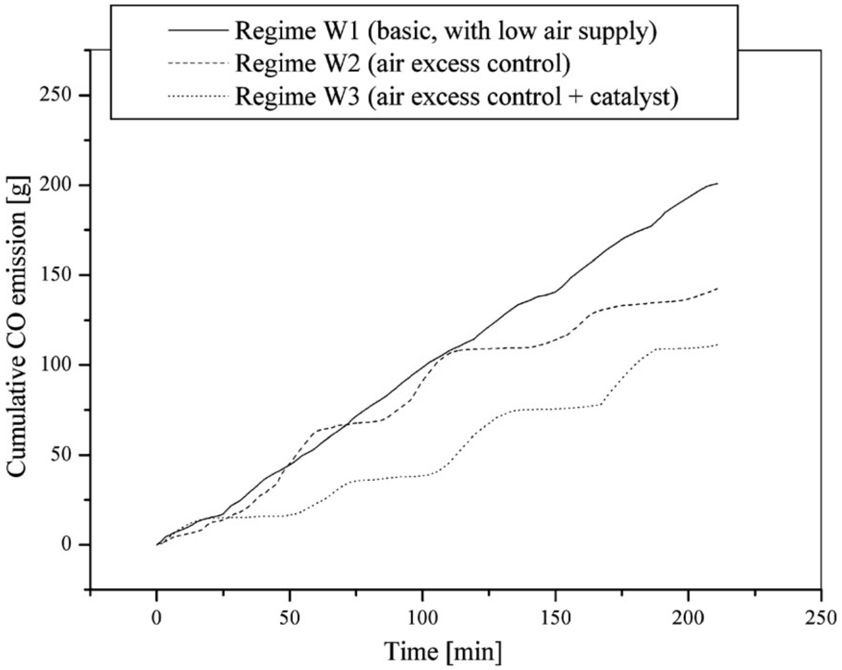

Fig. 6. Cumulative CO emission in different regimes of operation.

emission in Regime W2 was 30% lower than in Regime W1. By placing the catalyst in the middle flue, an additional 10% decrease of CO emission was achieved, at the same moment in time.

In the case of Regime W3, with the catalyst, the experiments were performed with the rest of the conditions being essentially the same as in the Regime W2, to emphasize the possibility of the furnace efficiency improvements by adding the catalyst. The results are shown in Fig. 7 and Fig. 8. Due to the harsh flow and combustion conditions in Regime W3 (with catalyst placed in the upper part of the middle flue, which significantly disrupts flow conditions in the flue), the exit flue gas temperature was somewhat lower than in Regime W2, and it changed differently in time – moments when wood was supplied cannot be spotted (Fig. 7). Correspondingly, calculated efficiencies (Eq. (11)) were higher in Regime W3 than in Regime W2, not only for the reason of decreased CO emission (Eq. (8)), but also due to a decrease of the exit flue gas temperature (t_{10} in Eq. (6)). In both regimes, efficiencies were higher than 85% (Fig. 8), which is an excellent result for a heating device of this kind. When calculating the furnace thermal

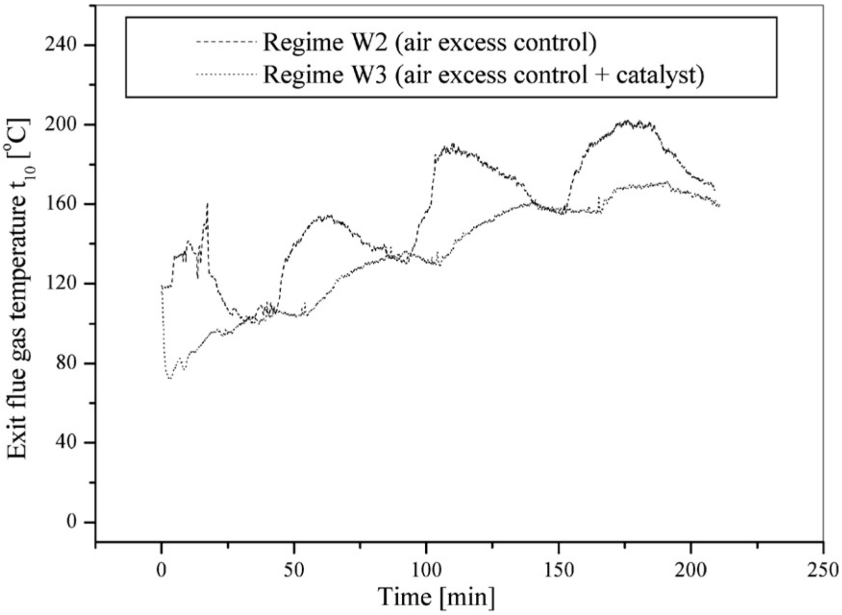

Fig. 7. Exit flue gas temperature in different regimes of operation.

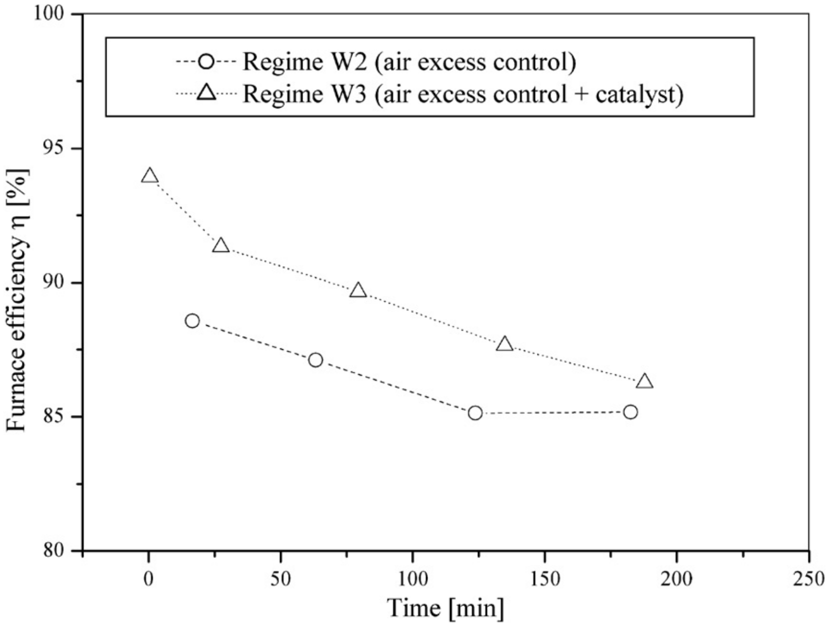

Fig. 8. Furnace efficiency.

power before the experiments, for a given coal consumption of 1.5 kg/h, it was assumed that the efficiency was 80%. The experiments showed that this assumption was not an exaggeration.

5. Conclusions

An innovative concept of the energy efficient and environmentally friendly heat storage solid fuel-fired furnace, aimed for residential heating purposes, is presented. The furnace enables high-combustion efficiency, considerable energy savings, low-emission of pollution, possibility of firing both low- and high-rank solid fuels and a pleasant heated ambient. The existence of convective air ducts, between furnace inner refractory walls and the outside wall made of ceramic tiles, makes heating with this furnace much more pleasant, due to increased convective heat transfer and lower outside wall temperature (lower radiative heat transfer to the heated room). The furnace has been experimentally tested in detail, with the main aim to assess the possibilities to improve the combustion quality by controlling the air excess. These tests have shown that air excess control contributes to significant CO emission reductions, by optimizing combustion conditions in the furnace. The presence of the catalyst in the middle flue helps in decreasing CO emission further. The catalyst also helped in bringing down the exit flue gas temperature and increased the furnace efficiency, thus additionally improving the overall effect of the air excess control. The assessment of the possibilities for furnace operation control is to be continued, with the aim to develop an automatic air excess control system, by using the signal of the zirconia probe, installed in the furnace.

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