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THE IMPACT OF MICRO SCALE COMBUSTION OF BIOMASS FUELS ON ENVIRONMENT

WPŁYW SPALANIA BIOMASY W UKŁADACH MIKROSKALOWYCH NA ŚRODOWISKO

Abstract: This paper shows the results of works aimed to determine the impact of biomass combustion in micro scale devices on the environment. The impact of burning conditions on the level of CO, CO_2, SO_2 and NO_x emissions were determined using the stove-fireplace with accumulation. Based on the analysis of its typical operation (when incomplete combustion of CO has occurred), the air distribution system was modified and new control system, based on the PLC controller, was introduced. These modifications allowed to obtain a level of CO emission required by the Ecodesign Directive.

Keywords: clean combustion, stove-fireplace with accumulation, biomass, micro scale systems

Introduction

One of the most popular heat sources in residential sector are biomass-fired devices, such as central heating boilers and room heaters (fireplaces, stoves and stove-fireplaces with accumulation). These devices are assessed due to the emission of different pollutants to the atmosphere. Boilers are classified using EN 303-5:2012 standard. The highest class units emit no more than 700 ppm of carbon monoxide (in the case of manually feeding system) or 500 ppm (in the case of automatic feeding system). The EN 303-5:2012 standard includes also requirements for boilers' efficiency and limits of the dust and volatile organic compounds (VOC) emission. Determination of the concentration of nitrogen oxides in flue gas is not obligatory, but is indicated if possible. On the other hand, the room heaters are validated by the EN 13229:2001, Ecodesing and BImSchV 2 standards. The first one standard limits the CO emission at the level of 3345 mg/m^3. Much more restrictive are the other two documents. Due to the European Directive 2009/125/WE (Ecodesign) the CO concentration in the flue gas

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must not exceed 1500 mg/m^3, when the Austrian BImSchV 2 standard indicates the maximum CO concentration at a level of 1250 mg/m^3. In both cases, the CO emission is calculated to the 13% of O_2 concentration.

The analysis of the operation of the existing devises shows the strong dependence of the CO emission with their construction and a level of their automation. The formation of pollutants during the combustion process (*eg* CO) results mainly from incomplete combustion of fuels and is generally correlated with a local lack of O_2. Incomplete combustion occurs mainly in a simple, manually controlled furnaces. It may also occur also in automatically controlled units in the starting phase of combustion process or in the case of wrong operation of the automation system. In the case of good mixing of flue gas with air, properly low emission may be achieved.

State of the art

The literature sources consist interesting results of studies carried out in the area of clean combustion in the fireplaces and stoves (but actually not in the case of the stove-fireplaces). The main physical characteristics and operating conditions of commonly used in the domestic heating fireplace and stove were determined during works described in [1]. The combustion of softwood (from pine) and hardwood (from eucalyptus) was divided into three main periods, differing by specific flue gas composition. These results were confirmed by other experimental studies, where the CO emission during the ignition phase was about 3–4 times higher than in the combustion phase [2]. Also in the case of investigations performed in terms of number of particles and the size distribution, the number emissions were in strict relationship with the combustion conditions in the fireplace [3]. The results of other studies carried out in order to evaluate non-steady phase contribution to the total emissions of a pellet stove, once again shown that the ignition phase, even though it lasts only 10–20 min, can contribute to pollutant emission. In this investigation, CO and NO emission factors in ignition phase were differ from other operating conditions: NO emission factor was lower, while CO was much higher (it was a product of incomplete combustion) [4].

To avoid a problem with high CO emission caused by incomplete biomass combustion, the modifications of the furnace construction were proposed in [5]. Proposal was based on the results obtained in a way of mathematical modeling. Two-dimensional turbulent flow model with homogeneous chemical reactions has been developed. Accuracy of the model has been previously confirmed with experimental data obtained on the existing furnace [6]. Also other mathematical models have been developed. The models reflect all relevant parts of the furnace and may be subsequently used for the design of the control unit [7].

Taking into account all of mentioned above aspects, a new general strategy for automatic control of the primary and secondary air streams for firewood combustion was applied in [8]. The design consists in two in situ gas sensors (oxygen and CO/HC) and gives consideration to the combustion temperature. Such configuration of the controller enabled to reduce the CO/HC-emissions to the level of about 50% (central heater) and 15% (tiled stove) in comparison to the use of the typical controller, provided by manufacturer.

The significant impact on the carbon monoxide and other pollutants emission has also the proper choice of the wood species. During tests carried out to determine the effect of ignition technique, biomass load and cleavage on carbon monoxide, total hydrocarbon, particulate matter (PM10) and particle number emissions from a wood-stove, the pine and beech wood were burned. The highest CO and total hydrocarbon emission factors were observed, respectively, for pine and beech, for high and low fuel loads [9]. Another seven fuels (four types of wood pellets and three agro-fuels) were tested in an automatic pellet stove. Particulate matter emission factors and the corresponding chemical compositions for each fuel were also obtained. The CO emission factors ranged from 90.9 ± 19.3 (pellets type IV) to 1480 ± 125 mg/MJ (olive pit) [10].

Presented above studies may be only in some part related to the stove-fireplace with accumulation. Therefore, the impact of the burning conditions on the level of CO, CO_2, SO_2 and NO_x emissions were determined using the stove-fireplace with accumulation equipped with a 550 kg accumulative furnace and a 1050 kg accumulative exchanger located next to the furnace. Basis on the results of previously studies [11], the improvements in the air distribution system and combustion process control system were applied.

Experimental set-up

The experimental set-up with the stove-fireplace with accumulation is equipped with modular PLC controller combined with the set of measurement elements and actuators:

– temperature sensors placed inside the furnace, accumulative mass and chimney as well as on the external side of accumulative exchanger;

– thermoanemometers to measure the flow rate of the air blown into the furnace area;

– platform scale equipped with 4 strain gauges with the resolution of 0.1 kg to measure the weight loss of fuel during the combustion process;

– flue gas analyser to measure the concentration of O_2 (using the electrochemical method) and the concentrations of CO, CO_2, NO, NO_2 and SO_2 (using NDIR method);

– servo-mechanisms to control the air throttles positions.

The monitoring and process data acquisition system was performed in the CoDeSys environment. It allows to observe the real time variations of the measured values, archive measurement data and control the system operation [12].

The main elements of control and measurement system, used during described studies, are presented in Fig. 1.

The proposed control system is different from originally used combustion optimizer, which operation rule is very simple – the system controls the combustion process and keeps the ember phase using the air damper. Due to lowering the combustion curve in the phase of temperature raise and raising the combustion curve upon decrease in temperature, the optimizer prolongs the process of burning.

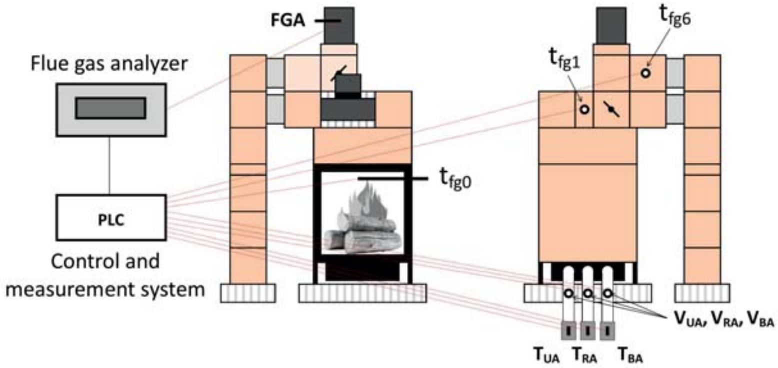

Fig. 1. The main elements of control and measurement system (FGA – flue gas analyser, t_{fg0}, t_{fg1} and t_{fg6} – temperature sensors, T_{UA}, T_{RA} and T_{BA} – respectively upper, rear and bottom air throttle, V_{UA}, V_{RA} and V_{BA} – respectively upper, rear and bottom air speed sensors)

The combustion optimizer controls the level of damper opening based on temperature measurement and an internal control algorithm. The algorithm divides the process of combustion into several phases. The sample combustion curve has been presented in Fig. 2.

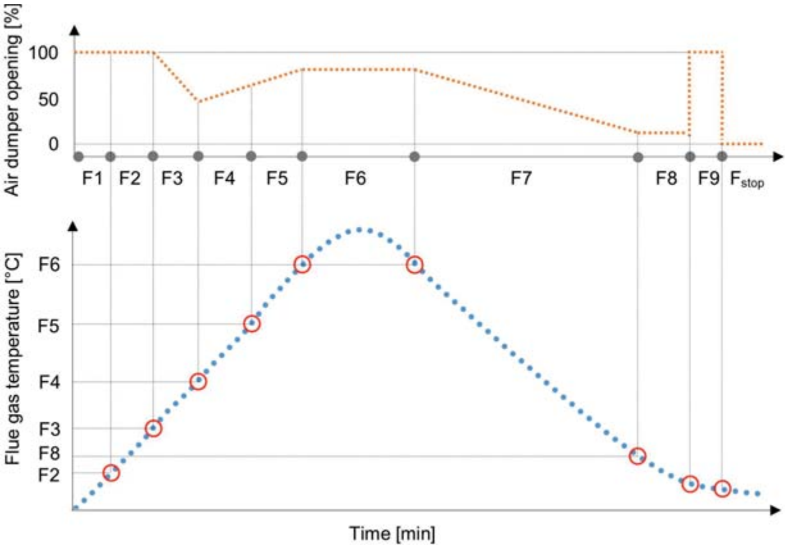

Fig. 2. Theoretical combustion curve with combustion phases marked

The proposed control system is based on the use of PLC controller which allows to control the operation of three air dumpers basis on the CO and O_2 measurements. The introduction of an additional air streams blown to the furnace area from the bottom and rear sides is a follow-up solution in relation to the basic control system of the considered devices. Providing an additional air streams may be really beneficial to the combustion process, causing better burning-out of fuel and decreased emission of carbon monoxide to the atmosphere (this is especially significant in the first and the last phase of the combustion process, in which the peaks of carbon monoxide emissions occur). The control of the operation of a system of three dampers should be performed by means of a specially developed control algorithm which is capable of controlling three devices.

Experimental results

The first part of presented studies was performed using typical optimizer connected with an upper air throttle. In this case, the air was blown into the furnace using a gap

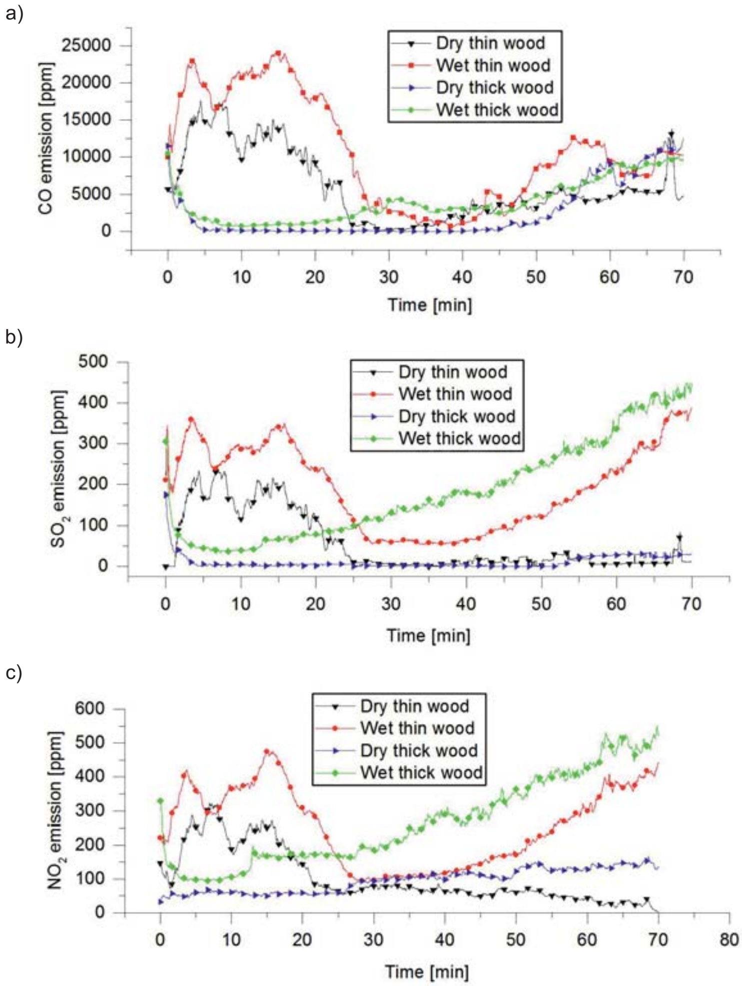

Fig. 3. The variations of the concentration of a) CO, b) SO_2 and c) NO_x in flue gas

located over the door (the air inlet was directed towards the pane to keep it clean). The level of the throttle opening was dependent from the predefined heating curve and the current flue gas temperature (measured at the outlet from the furnace).

During this part of studies, as a fuel was used a hardwood (mixed beech and oak wood). In each from four combustion processes, divided into two series, a wood characterized by different parameters was burned. It was respectively: i) dry thin wood, ii) wet thin wood, iii) dry thick wood and iv) wet thick wood. The variations of the emissions of CO, SO_2 and NO_x were shown in Fig. 3a–3c.

As we can see in Fig. 3, the size of the wood pieces has a significantly greater impact on the clean combustion, than their humidity. The lowest emissions were obtained during combustion of dry thick wood, when the average concentration of the carbon monoxide was less than 1800 ppm. Comparing this value to other measured concentrations of CO, we have 2 times less emission than in the case of burning wet thick wood, 3 times less emission than in the case of burning dry thin wood and 5 time less emission than in the case of burning wet thin wood. In general, the trends for SO_2 and NO_x emission were the same, but the measured values and differences between them were visibly lower.

Detailed analysis of data presented in Fig. 3 shows, that the highest emissions occurred in the ignition phase. One of the reasons was limited access of the air to the wood bed. Significantly lower values were measured in the combustion phase. The average CO emission in this phase was lower than 500 ppm in the case of burning dry thick wood. On the other hand, the CO emission in the case of burning wet thin wood was more than 20 times higher. The values obtained in the afterburning phase (starting between 40 and 50 minute) show the increasing trends, but there are not representative (the high amount of the oxygen is connected mainly with the fact, that the fire has died out).

The improvements in the stove-fireplace construction

Based on above results, two ways to improve efficiency of the starting phase of combustion process and reduce the average emission of CO were proposed: i) introduce additional air inlets and ii) develop new control system. Additional air inlets (allow to delivery air in the periods of a time, when the carbon monoxide burning is incomplete), were located under the pane and on the rear wall of the furnace. In opposite to upper air inlet, there were directed towards the fuel bed. The impact of their application on the CO emission has been shown in Fig. 4. As before, 12 kg of thick wood with was burnt during combustion process. The furnace was preheated and therefore fuel was ignited from the ignition layer.

The analysis of the CO emission during combustion process shows, that air supplied from inlet located under the pane limited the carbon monoxide emission in its ignition phase. In this phase, the opening of upper-air throttle was insufficient, while the supply of air from the rear inlet had any impact on the CO emission. On the other hand, the use of rear air inlet had a really positive impact in the combustion phase.

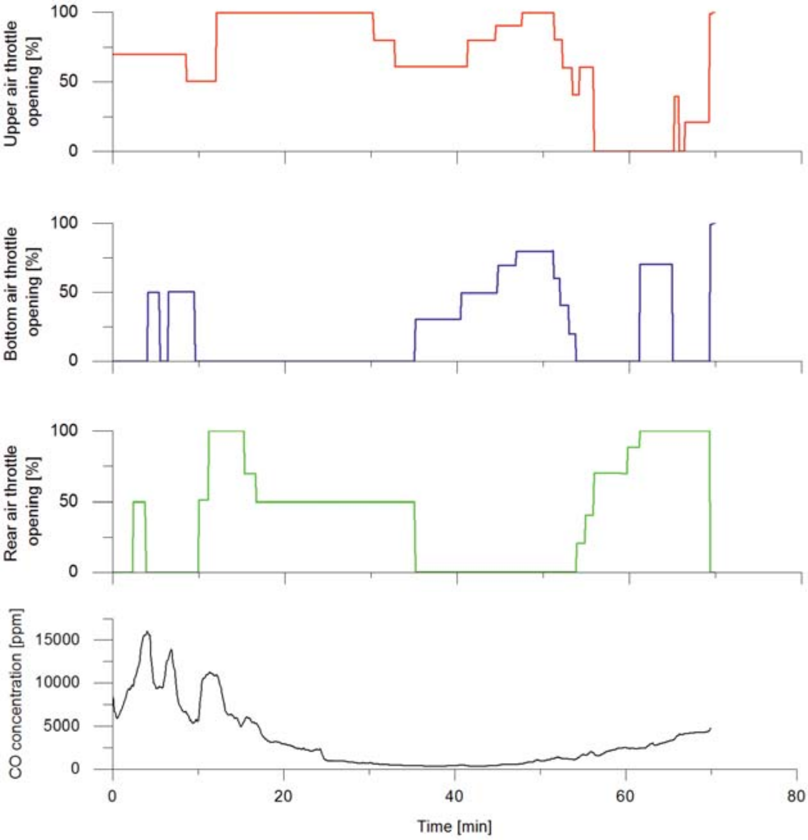

Fig. 4. The variations of the concentration of CO in the case of using three air inlets

If we compare a level of CO emission from the typical stove-fireplace with only one air throttle and a level of CO emission from modified unit with three air throttles, we can see that the new device is more environmental friendly. The improvements in its operation is connected with better air distribution allows to limit incomplete combustion of the wood. On the other hand, construction changes were complemented by develop new regulator replacing non-efficient optimizer provided by manufacturer.

Introduction of the new regulator

The new regulator was developed in the CoDeSys software using such programming languages as CFC (Continous Function Chart) and ST (Structured Text). The signals from temperature sensors (t_{fg0}, t_{fg1} and t_{fg6}) and flue gas analyzer (CO and O_2) have been connected to the analog input modules of the PLC controller and used to control the level of the air throttles opening (T_{UA}, T_{RA} and T_{BA}). The volume of O_2 and volume of CO emissions have been coupled respectively with upper and rear air throttles opening control. Bottom air throttle was controlled separately and it was used in the ignition phase.

The throttles were opening and closing depending on actual values of the O_2 and CO concentrations and boundary conditions (minimum set content of oxygen in the flue gas and the maximum set content of carbon monoxide). The emission of CO in the case of using new developed regulator was shown in Fig. 5.

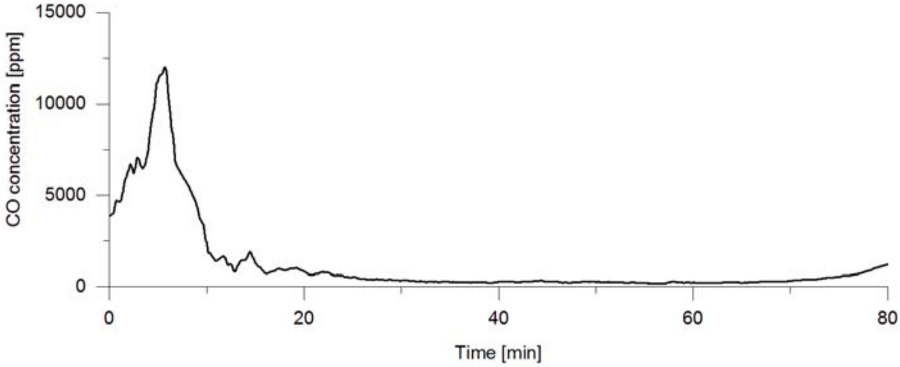

Fig. 5. The variations of the concentration of CO in the case of using new regulator

The use of additional air inlets and developed regulator limited CO emission in the ignition phase. As a result, the average CO emission during whole combustion process was lower than 1200 ppm. Expressing this value in the milligrams per cubic meter it is about 1 450 mg/m^3 (in comparison to the level of 2 156 mg/m^3 in the case of the typical unit). Of course, proposed solution is still developing in order to further reduce CO emission (mainly in the ignition phase).

The amount of NO_x and SO_2 emissions, measured during this part of study, were also on the acceptable level. The variations of NO_x and SO_2 emissions were shown in Fig. 6.

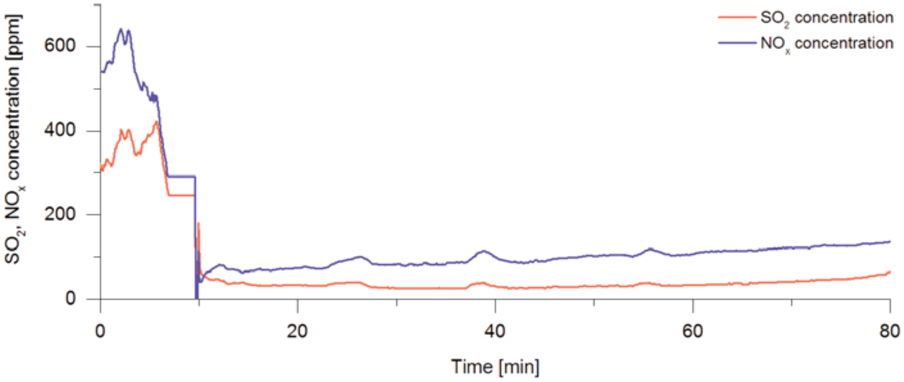

Fig. 6. The variations of the concentration of NO_x and SO_2 in the case of using new regulator

Analyzing histogram presented in Fig. 6 we can conclude that concentrations of NO_x and SO_2 were quite high only in the ignition phase. In the combustion phase emissions were significantly lower – respectively lower than 100 ppm (NO_x) and lower than 200 ppm (SO_2).

Conclusions

The introduction of the a new air distribution system and regulator allowed significantly reduce CO emission to the atmosphere and preserve NO_x and SO_2 emissions at satisfactory level. The average concentration of CO in the flue gas during whole combustion process meets the restrictive requirements of Ecodesign standard.

On the other hand, if we take into account the fact, that combustion process took about 80 minutes and heat accumulated in the heat exchanger was transferred to the room for the next 6–8 hours after fire died out, the average value of CO emission calculated for this time is lower than 200 mg/m^3. Such a low value definitely meets the BImSchV 2 requirements.

Further development of the proposed air distribution system and regulator will allow to achieve even better results (further decrease of the CO and other pollutants emission to the atmosphere). However, in order to productize the developed solution, it is necessary to apply cheap CO sensors or to change the CO signal with another signal (due to high costs of the circuits for the measurement of carbon monoxide concentration in flue gas). The further research should thus address the possibility of applying only a lambda probe (or another sensor measuring the indicated value) as the element sufficient for the proper control of the operation of the stove-fireplace with accumulation.

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WPŁYW SPALANIA BIOMASY W UKŁADACH MIKROSKALOWYCH NA ŚRODOWISKO

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Abstrakt: W artykule przedstawione zostały wyniki badań, których celem było określenie wpływu spalania biomasy (drewna) w jednostkach mikroskalowych na środowisko naturalne. Badania przeprowadzone zostały na stanowisku badawczym wyposażonym w piec ceramiczny z wymiennikiem akumulacyjnym – urządzenie stanowiące połączenie typowego kominka z tradycyjnym piecem akumulacyjnym. Bazując na analizie typowej pracy piecokominka, podczas której następowało niezupełne spalanie węgla zawartego w biomasie i powstawanie tlenku węgla, opracowany został dodatkowy układ doprowadzania powietrza, który zlokalizowano na tylnej ścianie paleniska. W kolejnym kroku opracowano system kontrolno-pomiarowy, oparty na zastosowaniu sterownika PLC oraz własnego algorytmu sterującego, który rozwija możliwości standardowych regulatorów procesu spalania. Otrzymane wyniki obejmujące emisję CO, CO_2, O_2, SO_2 i NO_x pokazują, że wprowadzenie opisanych zmian pozwala na znaczącą redukcję wpływu spalania biomasy na środowisko naturalne (szczególnie w aspekcie emisji tlenku węgla).

Słowa kluczowe: czyste spalanie, piecokominek, biomasa, systemy mikroskalowe