EXPERIMENTAL FACILITY FOR ANALYSIS OF BIOMASS COMBUSTION CHARACTERISTICS

by

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The objective of the present article is to present an experimental facility which was designed and built at the Faculty of Technical Sciences in order to study the combustion of different sorts of biomass and municipal solid waste. Despite its apparent simplicity, direct combustion is a complex process from a technological point of view. Conventional combustion equipment is not designed for burning agricultural residues. Devices for agricultural waste combustion are still in the development phase, which means that adequate design solution is presently not available at the world market. In order to construct a boiler and achieve optimal combustion conditions, it is necessary to develop a mathematical model for biomass combustion. Experimental facility can be used for the collection of data necessary for detailed modelling of real grate combustor of solid biomass fuels. Due to the complexity of the grate combustion process, its mathematical models and simulation software tools must be developed and verified using experimental data. This work highlights the properties required for the laboratory facility designed for the examination of biomass combustion and discusses design and operational issues.

Key words: *combustion in bed, experimental facility, straw, biomass*

Introduction

Although burning biomass in order to produce heat energy is as old as mankind, the use of energy crops in combustion industry is relatively novel. Even though this kind of fuel is different from coal in its combustion characteristics and, due to its high volatile content and alkali content of ash that can cause various problems, it is also regarded as problematic, it has natural advantages for the generation of electricity and heat, especially in local communities as a renewable and environmentally friendly energy source.

Conventional combustion equipment is not designed for burning agricultural residues, therefore the furnace and boiler used for this purpose have to be specially designed to cope with potential problems so as to minimize the risk of corrosion and passage blockage. Since the combustion of straw for power generation is a relatively new concept, the equipment design and operating conditions are not fully optimized. That is why grate-fired boilers burning straw are often associated with high emission levels and relatively poor burning of fuel.

There is still a lack of detailed and systematic theoretical study on the packed bed burning of biomass and municipal solid wastes. For the purpose of properly designing and oper-

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ating straw fired power plant it is important to have detailed knowledge of the characteristics of fuel combustion and the effects of varying operating conditions. In the past, the development of combustion systems was based on experience, that is, years of data collection from different systems. However, this kind of development is limited by the applicability and generality of the available data, which makes it difficult to assess crucial process parameters change. In addition, for large industrial scale units, detailed measurements of flow temperature and concentration of gas species inside a furnace are impossible and normally limited to flue gas measurements.

However, data obtained using laboratory units provide valuable information on specific processes included in the overall performance. Furthermore, experimental and simulated results showed that analogy exists between combustion in a fixed bed and on a grate. Therefore a fixed bed reactor can be used as a simplified system to simulate the moving bed. The ignition and burning rates acquired from the packed bed tests are of practical interests, and they can be used for the design and operation of moving beds.

General combustion behavior of biomass fuels in packed beds have been studied by numerous researchers. The effects that various fuel properties and operating conditions have on the ignition and burning rates have been reported in the literature for various wastes and biomass materials. Crucial combustion parameters, primary air flow rate, have been widely studied by researchers such as [1-5]. Khor *et al*. [6] present an experimental investigation into the combustion behavior of straw in a fixed bed combustor and compared the effects of primary air flow rate on three herbaceous biofuels: straw, switch grass, and reed canary grass. Gort [7] conducted a series of tests on the combustion of wood chips under different operating conditions. He suggested that the fuel bed is partially gasified, fully gasified or combusted depending on the ignition rate and air flow rate. Ronnback *et al.* [8] studied the influence of primary air flow and particle properties on the ignition front, on its temperature and on the composition of the exiting gases in a biomass fuel bed. Saastamoinen *et al*. [9] investigated the propagation of ignition front in beds of wood particles where the effect of air flow, moisture, particle size, density, and wood species were considered. Ryu *et al.* [10] investigated the fixed bed combustion of two segregated wastes for different air flow rates. Cardboard and waste wood samples were burned in a batch reactor and the key combustion characteristics including the ignition and burning rates were evaluated using the experimental data. A mathematical model developed for the fixed bed combustion was used to predict the combustion of the two samples for wider range of air flow rates. Yin *et al*. [11] established a reliable baseline CFD model for a thermal 108 MW grate-fired boiler burning biomass. A sensitivity analysis was carried out on the basis of the design conditions of the boiler to evaluate the effects of different factors in CFD modeling of grate boilers.

The studies mentioned are not intended to represent an exhaustive analysis of the current situation of biomass combustion research. They are selected because they represent examples of different aspects and tendencies of inquiry into this area.

The present work focuses on the biomass combustion in a bed. This work is part of a larger research program aiming at a complete simulation of a biomass fired power plant. For that purpose an experimental facility that enables the study of combustion of different sorts of biomass and municipal solid waste has been designed and built at the Faculty of Technical Sciences. The analysis presented in this paper is based on our own experimental results.

Experimental facility

As it has been mentioned earlier, in the past the development of combustion systems was based on experience. Empirical operating experience can be obtained during long periods of operation and it is helpful, but its application is only valid for the conditions under which it has been obtained.

These problems are especially manifested in biomass combustion, due to the highly variable composition of biomass as a fuel, and the fact that minimal changes in the composition (*e. g.* fuel moisture) greatly change the kinetics of combustion.

Thus, detailed knowledge of straw combustion characteristics and the effects of varying operating conditions are important for properly designing and operating straw fired power plant.

The focus of this article is on presenting an experimental facility (shown in fig. 1) which offers an effective way to simulate grate combustion in a real facility. The experimental facility represents first step in the new facilities construction as well as in the reconstruction the old ones. Data obtained using laboratory units provide valuable information on specific processes included in the overall performance. By measuring the temperature along the bed during combustion process, it is possible to monitor different sub-processes in the bed, as well as the development of the reaction zone along the bed under different conditions (air velocity, bed density, fuel type, and quality). This makes it possible to determine the impact of different parameters on combustion process which would be impossible in a real facility.

Figure 1. Photograph of the experimental facility

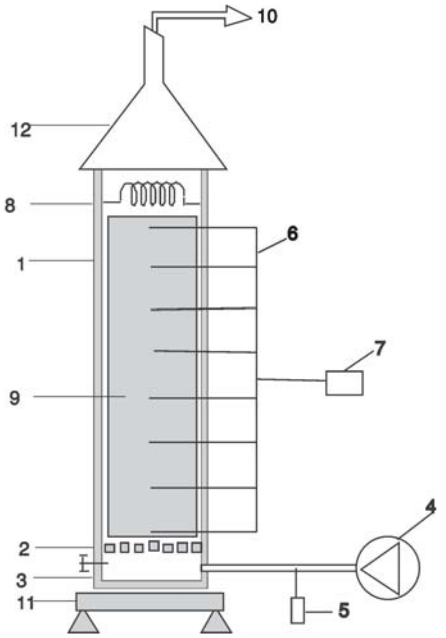

Figure 2. Schematic diagram of the experimental facility
1 – reactor, 2 – grate, 3 – ash tray, 4 – fan with potentiometer, 5 – anemometer, 6 – 8 thermocouples, 7 – data logger, 8 – electrical radiation heater, 9 – fuel (straw bed), 10 – smoke gases, 11 – weighing scale, 12 – chimney

Figure 2 shows a schematic diagram of the experimental facility which was constructed in order to study the combustion of different sorts of biomass and municipal solid waste. The combustion facility consists of a cylindrical fixed-bed combustion chamber made of chromium steel alloy. That material was chosen because of its resistance to corrosion at high temperature and its ability to withstand the high temperature of the combustion, which is expected to reach 1500 K. The chamber is 1080 mm high with an internal diameter of 230 mm and a 2 mm thick wall.

The chamber is thermally insulated by 50 mm thick ceramic wool which is able to withstand temperatures of up to 1500 K and covered by a thick layer of external casing. The stainless steel grate is located at the bottom of the chamber and primary air is fed from the bottom of a fixed-bed reactor through the grate without preheating. An electrical radiation heater is placed on top of the reactor. A chimney, through which smoke gases could be taken to the flue gas analyzer, is placed at the top of the reactor. Thus, combustion efficiency can be monitored by means of smoke gas analyzer.

The chamber is equipped with ten K-type thermocouples placed at the central line of the reactor, 100 mm apart, starting from 100 mm above the grate. They enable continuous measurement of the primary air temperature, the temperature in the bed at ten levels and the temperature of the flue gas above the bed while data logger records the measured temperatures every 50 s. As the reaction proceeds in the bed, the temperature distribution along the bed is measured continuously. In this way it is possible to determine combustion front velocity. Propagation velocities are calculated from the time it takes for the front to pass between two thermocouples.

By measuring the temperature along the bed during the combustion process, it is possible to monitor temperature change in the bed as well as to indirectly determine the rate of mass loss by determining combustion front velocity. Direct measurement of mass loss during process is possible by using a weighing scale.

Fuel and procedure

This study investigates the fixed bed combustion of straw at three different bulk densities for different air flow rates. The experiments were carried out using wheat straw, collected from the fields near Novi Sad, as a fuel. Whole straw taken from straw bales was used as fuel without any treatment (cutting or rolling) which means that they were cylindrical in shape. The straw had moisture content of about 15%. The wheat was treated with standard agro technical measures. Simple random sampling plan was used in order to get samples from the collecting warehouse immediately after harvest during the period of dry weather, so that the straw was not exposed to different climate influences.

The fuel was loaded on the grate to the thickness of 1050 mm. The weighing scale used has a resolution of ±100 g, while the initial sample feed was varied and three cases were considered: 1250 g, 2000 g, and 2500 g, and the bulk density of the fuel material in the packed state in the three cases was around 30, 48, and 60 kg/m^3. Care was taken to fill the reactor as uniformly as possible.

In this type of reactor, biomass burns on top of a fixed grate with primary air supplied from below. The reactor is open at the top and an electrical radiation heater is placed a few centimeters above the top of the bed in order to ignite the fuel. In that way, an electrical heater simulates the radiation environment from the chamber above the bed in a real furnace. Thus, the fresh biomass ignites by radiation from the hot gas phase above the bed.

When the temperature of the gas phase above the bed reaches the combustion temperature *i. e.* as soon as the reaction front reaches the upper thermocouple and the temperature starts to rise, the radiation heater is switched off in order to measure the self-sustaining propagation front without the disturbance by the heater. At the same time the fan is switched on and combustion air is supplied from the bottom of the furnace. The rate of primary air flow into the bottom of the bed is varied as shown in tab. 1.

Table 1. Experimental investigation of straw combustion

Bulk density [kgm^{-3}]	Mass of straw in the bed [kg]	Air flow velocity [ms^{-1}]	Average ignition front velocity [mms^{-1}]	Average burning rate [kgm^{-2}s^{-1}]
30	1.25	0.144	2.667	0.080
		0.230	2.667	0.080
		0.423	2.667	0.080
48	2	0.144	1.667	0.080
		0.300	1.667	0.080
		0.450	1.583	0.076
60	2.5	0.126	1.333	0.080
		0.239	1.250	0.075

In that way, the straw bed on the grate is crossed by an upstream air flow and submitted to radiation heating on its upper surface and a flame front formed at the top surface slowly progresses downwards, against the gas flow. As the ignition front passes one of the thermocouples in the bed, the volatiles from the burning particles ignite and form local flames around them and above. This results in the rise of temperature from room temperature to around 900 °C within a few minutes. The heat released from the reaction of volatiles and char with air transfers downwards toward the fresh particles (below the ignition front). This heat is then consumed for further evaporation and heating up. By varying fan speed and straw density it is possible to achieve different combustion conditions. Since oxygen is consumed first by the volatile gases, at low air flow rates, a layer of char accumulates above the ignition front as it propagates downwards. In that case, the burning rate is slower than the ignition rate, but continues to increase and attain the level of ignition rate at the air flow rate of 0.2 m/s for average burning rate of 0.08 kg/m^{2}s.

Results and discussion

Figures 3-10 show the mass loss rate as a function of time for the wheat straw samples in the described conditions. After switching on the radiation heater to initiate the burning process, as a first step, the top of the bed is vigorously heated and moisture is evaporated. That first step can be detected as a slow mass loss at the beginning of the process.

Except that first step, the flame front propagation speed is relatively constant during the entire experiment. This indicates that the mass loss rate is roughly constant during this time period. A steady combustion stage is reached rapidly. A linear decrease in the total mass of the bed material is observed during this period. The duration of complete burning period ranged to around: 330 s in the case of 1250 g, 530 s in the case of 2000 g, and 660 s in the case of 2500 g – initial sample feed. In all cases, the reaction

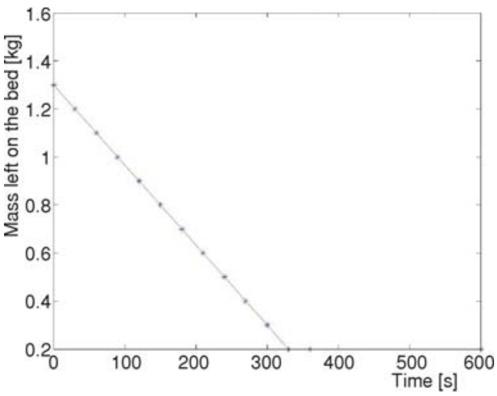

Figure 3. Mass loss as a function of time: bulk density 30 kg/m^3, air flow velocity 0.144 m/s

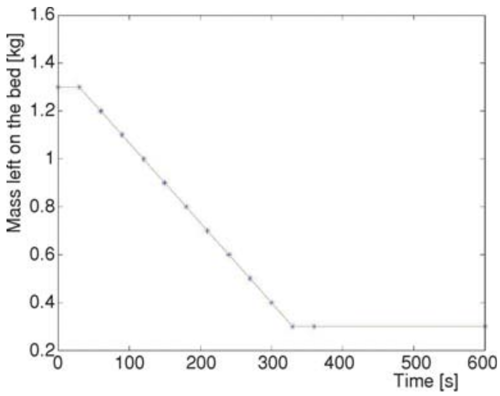

Figure 4. Mass loss as a function of time: bulk density 30 kg/m^3, air flow velocity 0.230 m/s

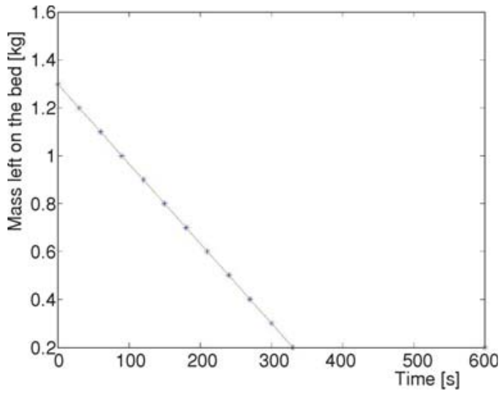

Figure 5. Mass loss as a function of time: bulk density 30 kg/m^3, air flow velocity 0.423 m/s

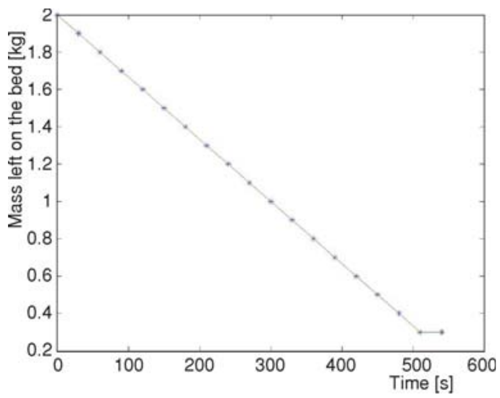

Figure 6. Mass loss as a function of time: bulk density 48 kg/m^3, air flow velocity 0.144 m/s

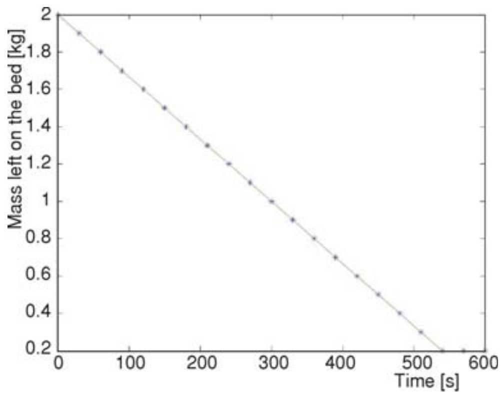

Figure 7. Mass loss as a function of time: bulk density 48 kg/m^3, air flow velocity 0.300 m/s

front moves down through the bed layer with velocity (of around 0.08 kg/m^{2}s) that does not dependent on bulk density (see tab. 1).

However, when air flow velocity increases, a slow decrease in the burning rate can be detected. To the explain that fact, it is important to note: for average burning rate of 0.08 kg/m^{2}s for the complete combustion process it is important to achieve air-flow of 0.2 m/s at the bottom of the grate. For higher air-flow velocity cold air breezing the bed cools the fuel and so decreases the burning rate.

For lower air-flow velocity, after intensive devolatilization process in the reaction zone, oxygen is consumed by the reacting volatile material and then by the char. As the amount of oxygen is not sufficient for the complete combustion process of devolatilization products, the volatile material leaves the reactor through the chimney as thick smoke, and its color (ochre) indicates huge concentration of volatiles in flue gases, figs. 3, 6, and 9.

Ignition front velocity can be directly observed by setting thermocouples at the center line of the reactor. The distance between two thermocouples divided by the time that the reaction front needs to get though from one thermocouple to the next represents the average burning rate, [mms^{-1}], tab. 1.

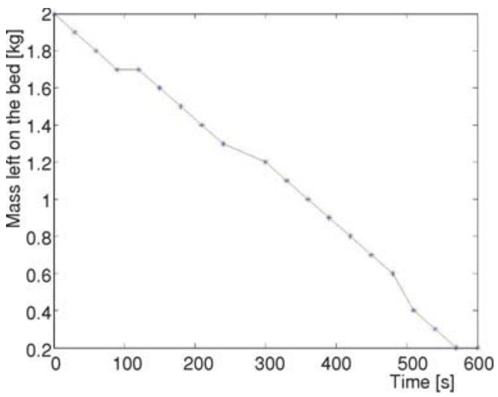

Figure 8. Mass loss as a function of time: bulk density 48 kg/m^3, air flow velocity 0.450 m/s

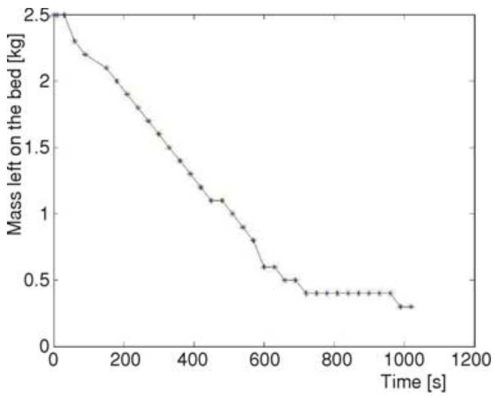

Figure 9. Mass loss as a function of time: bulk density 60 kg/m^3, air flow velocity 0.126 m/s

These results agree well with the results reported by other researchers. Table 2 contains experimental and simulated results of fuel consumption available in the literature [6, 12].

Ignition front velocity can be visually observed during the experiment if the reactor isolation is removed. When exposed to the high temperature of reaction front, the reactor steel tin changes temperature and as a consequence the color of the tin is changed. But, after the combustion process is finished and the reactor cools, the tin returns to its original color. In that way, it is possible to determine the distance that front passes in the specified period of time. Figure 11 shows the photos of the experimental fa-

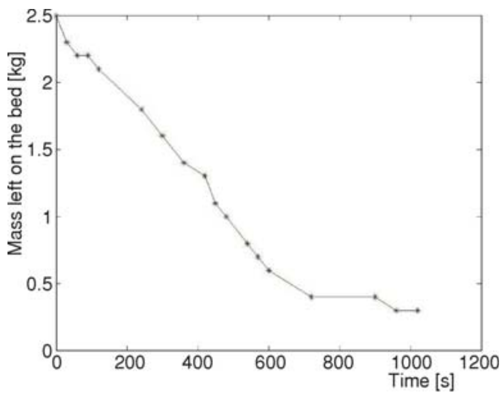

Figure 10. Mass loss as a function of time: bulk density 60 kg/m^3, air flow velocity 0.239 m/s

Table 2. Experimental and simulated results available in the literature

	Bulk density [kgm^{-3}]	Air flow velocity [ms^{-1}]	Average burning rate [kgm^{-2}s^{-1}]
Straw (cut) [6]	52	0.053	0.0128
	60	0.106	0.0303
	41	0.159	0.0619
	41	0.212	0.0469
	65	0.265	0.0486
Straw (uncut) [6]	27	0.053	0.00916
	39	0.159	0.05160
Straw (uncut) (simulated model) [12]	15	0.016	0.026

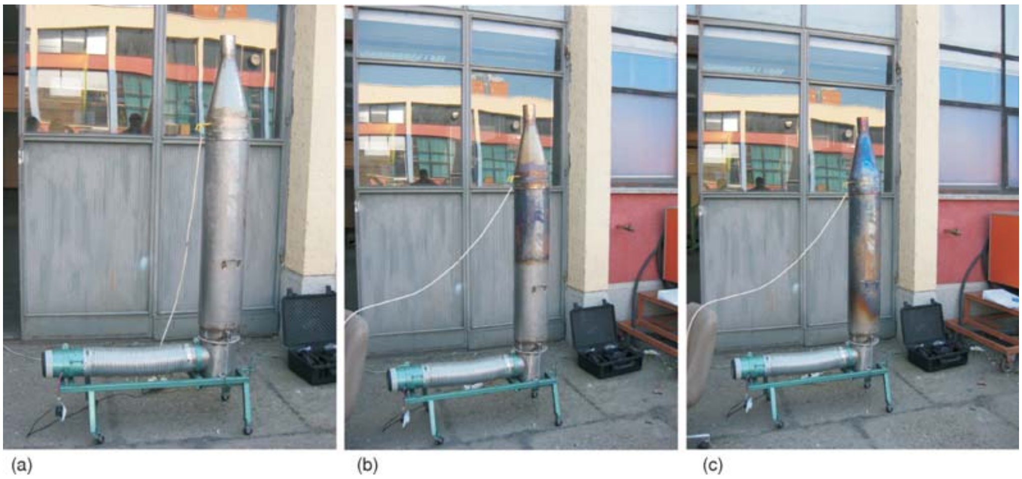

Figure 11. Photograph of experimental facility during the process; (a) at the beginning, (b) after 300 s and (c) after 540 s

cility (without isolation) at different points of the process: at the beginning, after 300 s and after 540 s, while fig. 12 shows the photos of the experimental facility made during the process using a thermal camera.

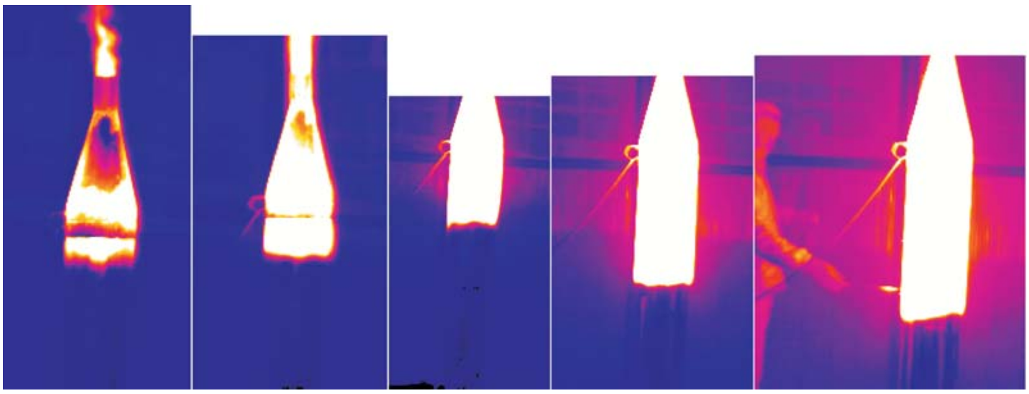

Figure 12. Photos of experimental facility during the process made by using a thermal camera

It is also interesting to note the development of the reaction zone along the bed. The thickness of the reaction zone is defined as the distance from the bed top downward to the position where the bed temperature starts to rise from the room temperature. The local temperature in the upper layers of the bed rises quickly to around 900 °C, whereas the lower layers remain cool. The reaction zone stays very thin during the process. This is because the solid bed has low thermal conductivity and the air supplied at the bottom of the bed continuously cools the bed. The flame front thus propagates downwards, against primary air flow, and it can be observed with the rise in temperature measured by the ten thermocouples.

In that steady combustion stage, the total mass loss from the bed is dominated by moisture evaporation and volatile release from the waste solid. After the steady combustion stage, as the reaction time increases, the rate of bed mass loss slows down. In that period char combustion is the dominant process. At the end of the process, unburned fuel that consists of ash and unburned fuel components, indicated by the dark color of ash, remains on the grate, Figure 13. In order to perform a detailed analysis of combustion, it would be necessary to do a chemical analysis of the ash.

Figure 13. Photo of the ash on the grate, at the end of combustion process

Conclusions

This article is not intended to represent an exhaustive study of biomass combustion. Instead, it focuses solely on representing an experimental facility. The development and use of this type of reactor in order to more effectively assess the kinetics of combustion is new.

Experimental facility is required to provide data necessary for detailed modelling of grate combustion of solid biomass fuels, like weight loss rate, flame front velocity or drying and devolatilization rates. The construction of boilers differs according to the kind of fuel.

The present article presents an experimental facility that was designed and constructed at the Faculty of Technical Sciences in Novi Sad. This facility is intended for investigating the combustion of different sort of biomass and municipal solid waste.

Combustion experiments with wheat straw are carried out in a fixed bed reactor. The effects of different primary air staging as well as different kinds and quality of fuel can be studied. Selected results obtained in a packed bed for different combustion conditions are presented in this paper. Present reported experimental results and experimental and simulated results of the other authors have been compared. Good agreement can be observed for the velocity of the reaction front, as well as for the maximum temperature reached.

These results show a lot of potential for predicting the relevant parameters of combustion process in a real facility and thus provide the basis for obtaining a clear image of the overall process of burning biomass in a real facility.

This work is part of a larger research program aiming at a complete simulation of the biomass fired power plant.

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