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Development of a Boiler for Small Straw Bales Combustion

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1. Introduction

In terms of sustainable energy development in Serbia, as well as in the whole world, there is a growing need for using the alternative energy sources. Alternative energy sources are, in most cases, renewable: biomass, wind power, solar energy, hydro-power and geothermal energy. A need for the utilization of this kind of energy sources is dictated by the market, on one side, as well as by environmental protection, on the other. Prices of fossil fuels grow proportionally to the decreasing of fossil fuel reserves. Since available reserves of fossil fuels in Serbia, especially those of high quality, are relatively limited, this problem becomes even more emphasized. On the other hand, it is necessary to harmonize the energy production legislation and practice in Serbia with the directives of the European Union, in the sense of intensifying the utilization of renewable energy sources and thus reducing pollution and greenhouse effect formation.

Biomass is one of key renewable energy sources (van Dam et al., 2007). This is the reason for the development of cheap thermal devices (boilers and furnaces) burning biomass from agricultural production, as quite available and cheap energy source. These devices could be used primarily in villages, small towns and small businesses processing agricultural goods (greenhouses, dairy farms, slaughterhouses, etc.). The devices could also find use heating schools, hospitals and other institutions.

Boilers and furnaces should utilize baled biomass which has not been adequately used and should have complete combustion control. The most favorable combustion organization for this type of devices is based on the principles of burning of a cigarette. The development of these devices should be simultaneous with the solving of the problem of low ash melting temperature and damaging of boiler metal parts and walls. At the same time, environmental aspect of combustion should be kept in mind.

2. Basic potentials and characteristics of biomass

Serbia has ample biomass energy resources, consequently in the total energy balance of the country biomass represents a true energy potential. Usually, biomass is divided into forest and agricultural types. In table 1, the estimate of biomass potential of Serbia is shown (Ilic at al., 2003). Biomass from agricultural production represents about 60% of this potential.

The potential role that agricultural biomass could play in meeting Serbian energy consumption, can be overviewed by comparing its energy potential to the potential of the coal consumed for the production of electricity in the utilities of the Electric Power Industry of Serbia (EPS), shown in table 2. Some basic data on physical characteristics of various types of biomass are given in table 3 (Oka, 1992). It can be seen that the ranges are quite huge for some values, for example for heating value.

No	Biomass residues	TJ/year
1	Forest	43000
2	Agriculture	65076
2.1	Grain growing	40000
2.2	Fruit and grapevine production	25000
2.3	Cattle breeding	76
	Total	108076

Table 1. Energy potential of biomass in Serbia

No	Type of coal	Consumption (t/year)	Energy potential (TJ/year)
1	Lignites (Obrenovac and Kostolac thermal power stations)	35 000 000	248 000
2	Higher quality coals (underground exploitation)	624 000	10 700
	Total		258 700

Table 2. The consumption of coal used for electricity production in Serbia

Although biomass is close to local lignite, considering the heating value, relatively low energy density has a great influence on transport, storage space, and fuel feeding equipment costs. Moisture content influences biomass combustion behaviour, causing different adiabatic combustion temperature and volume of gaseous products. In the case of higher moisture the drying process is longer, so volatiles releasing and char combustion are delayed, requiring larger furnace space.

In the process of production of various agricultural crops produced biomass that remains in some kind of residues are up to three times the amount produced culture. These residues can be baled, so today in Serbia producers of baled biomass are mainly farmers who receive baled biomass in the form of a by-product along the main product. In practice there are two basic types of straw bales: small bales (usually square 40x50x80 cm), and large bales (cylindrical, ø180x120 cm, or square 80-120x70x150-250 cm).

Advantages and disadvantages of some forms of bales are reflected in the following. Small conventional bales have a number of advantages: low cost presses, binders moderate price, the need for a smaller tractor, good storage, a favourable agreement on the means of transport, easy disintegration and fragmentation means lower prices, the possibility of firing whole bales and others. Disadvantages are: manual manipulation, usually by hand using storage aids, relatively high consumption of binders, and lower reliability than other presses.

Characteristic	Range
Heating value	5-20 MJ/kg, depending on moisture
Density	400-900 kg/m^3
Heating value per m^3	700-12000 kJ/m^3
Moisture content	8-50%
Ash content	1-10%
Volatile content	50-70%
Ash sintering temperature	800-1100^{0}C

Table 3. Values of physical characteristics for various kinds of biomass

Baled biomass can be used in cattle breeding, as food supplement, or stall cover. There are few boilers and furnaces burning baled biomass at the moment in Serbia, and their technical level could be considered as low (Martinov et al., 2006). Most of the straw is reverted to the fields, burned and ploughed. Although this treatment of biomass residue is unacceptable, it is widespread, because there are no adequate sanctions. The main reason for avoiding straw baling and using it as fuel is that there is no organized market and no sufficient number of users. Additionally, low ash melting temperature causes problems during biomass combustion.

There is a keen interest of agricultural producers in utilizing biomass residues, in order to use it at their own farms, or to find a market for it. It is anticipated that if baled biomass were used close to its source and the problems mentioned above were solved, it would become the most prospective alternative fuel in Serbia. It is perceived that intensive utilization of this kind of biomass would streamline agricultural production, because energy originating from biomass could be used for improving agricultural technologies. At the present level of the market, technology and prices, it is estimated that utilities with direct biomass combustion would be the most efficient.

2.1 General characteristics of biomass

Biomass fuel is a very good quality but with specific characteristics that make it different from fossil fuel and cause a variety of ways of its use. There is a big difference in the characteristics of biomass from the viewpoint of the benefits of its application in practice. Burning biomass from the standpoint of convenience, or applications, can be divided into two main groups, namely: a) forest biomass b) biomass from agricultural production. The main difference between these two types of biomass is in the ash characteristics or ash melting temperatures (sintering (shrinkage) temperature, deformation temperature, hemisphere temperature and the flow temperature).

Sintering temperature is very important for the process of biomass combustion. It is the temperature at which ash shows preference for the start gluing. If any fuel is used in installations where drainage of liquid slag is missing, sintering temperature can not be exceeded in the furnace.

Unfavourable circumstance for the application of biomass from agricultural production is that the ashes of that biomass usually has a strong tendency to sticking, and sintering temperature of ash from agricultural biomass production is much lower than the sintering temperature of ash from forest biomass. This phenomenon is not accidental but it is a result of application of fertilizers in the cultivation of agricultural crops. The application of fertilizers involves increasing the concentration of the contents of potassium (Ka) in the mineral part of plant (ash). On the other hand, the basic mineral content of plants, or one of the main components, is the SiO2 silicon dioxide - quartz sand. SiO_2 melting temperature is 1400-1500°C, but with the addition of potassium or sodium the temperature can drop below the 800°C. Described phenomena are also the cause of the pronounced tendency toward gluing the ashes of biomass from agricultural production.

In addition to the fibrous structure of biomass it is very difficult to cut and prepare it for the mechanized and controlled heating. When it comes to mechanized and controlled heating usually refers to the fragmented biomass burning or combustion of briquettes or pellets that are made of fragmented biomass. With all this before mentioned, biomass also must be dried if the humidity exceeds its limits, and usually exceed. So the classical system implementation of biomass from agricultural production had to be applied: drying, chopper, grinder, briquette (pellet), and a special system for fuel dosage or insufflations. Primarily from the energy point of view, and also from an economic, which are not negligible, it reduces the effects of use biomass from agricultural production. Applied technical solutions must meet all required environmental aspects.

3. Biomass combustion technologies

The main problems that occur when burning straw that is biomass from agricultural production are related to (Strehler, 2005): the quality of combustion, combustion efficiency, workload plants, the cost of equipment, applied materials (thermal and chemical stability of the material). Although the straw is widespread fuel it is used negligible compared to other types of biomass. The main reasons for this are the problems caused by physical and chemical characteristics of the straw. Also, the energy density of straw is low so it is not economical to transport it to greater distance, which limits the possibility of securing large quantities of straw in the boilers of greater powers.

For the combustion of straw can be used all developed technologies that are used for solid fuel. One of the main criteria for the selection of combustion technology is the size of plant that is built so that they can distinguish between small plants with thermal power of 15 kWt, the average thermal power plants up to 1 MWt power and industrial plants over 1 MWt.

Small furnaces (boilers) are used in the household sector for heating water and rooms up to 15 KWt. Plants of up to 1 MWt are used for commercial purposes. These are furnaces (boilers) that burn biomass in baled form or another, and where the products of combustion discharge into the environment via the chimney. Thermal power plants over 1 MWt is used for heating, heat or steam production that is used in a technological process or the combined plant for the production of heat and electricity.

The technology for optimal utilization of biomass is determined by biomass characteristics. Reported technologies of biomass conversion are (Obernberger, 1998): fixed bed combustion, combustion on a grate, fluidized bed combustion and, finally, gasification. All these technologies are described in detail in the literature (Merick, 1984), and have their pros and cons. The basic advantages of these technologies are in the fact that they can be used for various types of fossil fuels, and that there is an extensive range of producers (including local ones) of utilities of this kind, etc. The main disadvantages are short life, inflexibility and lack of proved combustion technologies for agricultural biomass. Apart from being used as primary fuel, biomass is often used in co-combustion with fossil fuels, even in large-

scale utilities (thermal power plants for instance), and experiences with this kind of biomass utilization are reported and described in detail (Leckner, 2007).
Whereas forest biomass utilization is quite simple, the use of agricultural biomass for energy production faces quite a lot of difficulties (Zabanitou et al., 2007). One of the most disadvantageous is that its ash has an excessive inclination towards melting, and problems with slagging and fouling in biomass-fired facilities are present even in case of co-combustion (Tortosa et al., 2003). Low ash sintering temperature is caused by using the chemical fertilizers during plant growth. On the other side, fibrous structure of biomass affects its grinding and preparation in the forms of pellets and briquettes. This leads to conclusion that agricultural biomass should be combusted as collected from the fields - in baled form.
Technologies recommended for various type of the biomass combustion for the heating purposes is presented in table 4. Cigar burner combustion system of baled biomass has also been recognized by the European Union as the most suitable method to be utilized for burning baled agricultural residue (Kavalov & Peteves, 2004). For straw combustion cigar burner technology is very appropriate and without any reserves (Mladenovic et al., 2009).

Technology	Wood	Wood chips	Wood powder	Pellets	Briquetess	Straw
1. Open fireplace	0	-	-	-	0	-
2. Manual stove	+	-	-	-	+	-
3. Automatic burner	- -	+	-	+ +	- -	+
4. Batch combustion	0	- -	- -	- -	-	+
5. Fixed inclined grate	- -	+	-	+	-	-
6. Travelling grate	- -	+ +	-	+ +	-	+
7. Vibrating grate	- -	+	-	+	-	+
8. Underfeed stoker	- -	+	-	+	- -	-
9. Dust burner	- -	- -	+	- -	- -	-
10. Cigar burner	- -	- -	- -	- -	- -	+ +
Legend: (- -) Not possible; (-) Not appropriate; (0) The penalties are compensated to a given extent by the advantages; (+) Appropriate; (+ +) Very appropriate Combustion systems (1-3) are suitable for small-scale applications, while combustion systems (4-10) are appropriate for large-scale facilities.						

Table 4. Biomass for the heating purposes

4. The boiler burning baled biomass

The experimental boiler burning small soybean, corn or wheat straw bales, with 0.8x0.5x0.4 m in size, has been designed and built (Djurovic et al., 2008). The combustion has been organized on the principles of cigarette burning (Kraus, 1985). In Fig. 1, the scheme of the experimental boiler is shown (Repic et al., 2008a). Baled straw is introduced through the inlet (1) into the combustion zone (7). The inlet is supplied by cover (2) to prevent air suction and provide stable combustion conditions (Fig. 2). Furnace walls (4) have been made of

refractory material – chamotte, with thermal insulation (5). In the combustion zone a mobile chamotte plate (6) has been placed, serving as combustion (air amount) regulator.
The primary and secondary air flows (divided by a screen) are supplied through the mesh (10), which is also used for positioning the bale in the combustion zone. The tertiary air is supplied through the inlet (12), and is previously heated by flowing inside the walls (13). In the zone (14) is carried out the process of final combustion of the bale. The heat produced by combustion of biomass is transferred by the gas-to-water heat exchanger (15). After passing through the channels (16) to the flue gases collector (17), the flue gases leave the boiler through the smokestack (18), equipped with the flap (19), and through the cyclone-type particle precipitator (Fig. 3). Ash is collected in ash collectors (20, 21, and 22). A mobile tube for ash removal (23) has been placed inside the furnace, as well as a tube for pneumatic transport of ash (24). The boiler has a revision opening (25) for manual ash removal.

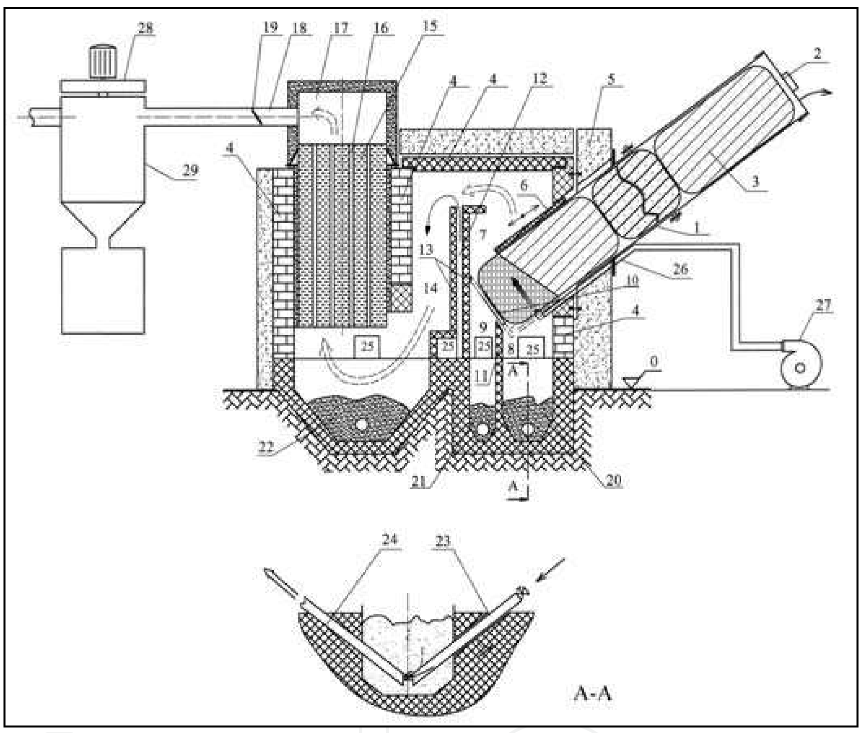

Fig. 1. The scheme of the experimental boiler. 1. fuel feeding, 2-cover, 3-baled biomass, 4-insulation, 5-heat insulation, 6-regulation of combustion zone, 7-combustion zone, 8-primary air supply, 9-secondary air supply, 10-grate, 11-compartment between primary and secondary air, 12-tertiary air introduction, 13-tertiary air channels, 14-burnout zone, 15-heat exchanger, 16-flue gas channel, 17-flue gases collector, 18-smokestack, 19-flap, 20,21,22-ash collector, 23-air tube for ash removal, 24-ash removal tube, 25-revision opening, 26-air distributor, 27-air fan, 28-flue gases fan, 29-cyclone separator with bunker.

After the first examination of the boiler some changes were carried out in the distribution of air (Repic et al., 2008b, Djurovic et al., 2009), so that after this change the air for combustion is inserted into the space through the distributor (26) which is connected to a fan of fresh air (27). By changing the position of the air distributor (Fig. 2) can be regulated the part of the bale involved in combustion and thus indirectly is regulated the heat output of the boiler. Also, a several types of biomass feedings were made: shorten (Fig. 2), inclined (Fig. 4) and horizontal (Fig. 5).

In order to obtain to plant work at nominal power, heat accumulator (thermal reservoir, with volume of 5 m^3) has been installed (Fig. 6). In this way it is ensured that no matter what the current needs for heating buildings, boiler always works with the nominal power (Mladenovic et al., 2008). The transitional periods (spring, autumn), for example, the need for heating usually amount to 20-40% rated power boiler, which would mean a much lower level of utility plant. Thermal scheme of distribution facilities is shown in Fig. 7. For it can be seen following thermal circles: a) Hot water from the boiler goes directly into a building that is heated, b) Hot water from the boiler goes into heat only tank, c) Hot water from the boiler going at the same time in the building and heat reservoir, d) Hot water tank from the heat goes into the building. Also, the boiler is equipped with appropriate management and control system (Figs. 2 and 3).

Fig. 2. The picture of the experimental boiler

Fig. 3. The cyclone-type particle precipitator

The thermal power of the boiler has been regulated with: the amount of straw engaged in the combustion process, the air excess and the fuel feeding rate. This experimental boiler could be scaled, since it satisfies the similarity requirements in (Beer, 1966): geometry, flow patterns, thermal load, thermal flux, adiabatic temperature, average temperature and flue gases content.

5. Some results of the boiler investigation

Biomass combustion in the boiler has been experimentally investigated. The experiment groundwork consisted of biomass sample preparation. The sample biomass was soybean and wheaten straw. The proximate and ash analysis of straw used in tests is given in table 5.

Fig. 4. Inclined fuel feeding

Fig. 5. Horizontal fuel feeding

The sum of six tests was done. A summary of main test parameters is given in table 6. Experiments trough 1-5 was performed with inclined bale feeder, and 6 with horizontal feeder. Experiments trough 1-4 was performed using soybean straw, and 5-6 using soybean and wheaten straw as fuel.

Experiments with both type of biomass have been successful, and showed that straw is suitable for cigarette-type combustion technology. Especially, soybean straw is very suitable for this technology of straw combustion because the ash melting temperature is so high (table 5). A picture of the cigarette flame of baled biomass is shown in Fig. 8.

Fig. 6. Heat accumulator (thermal reservoir)

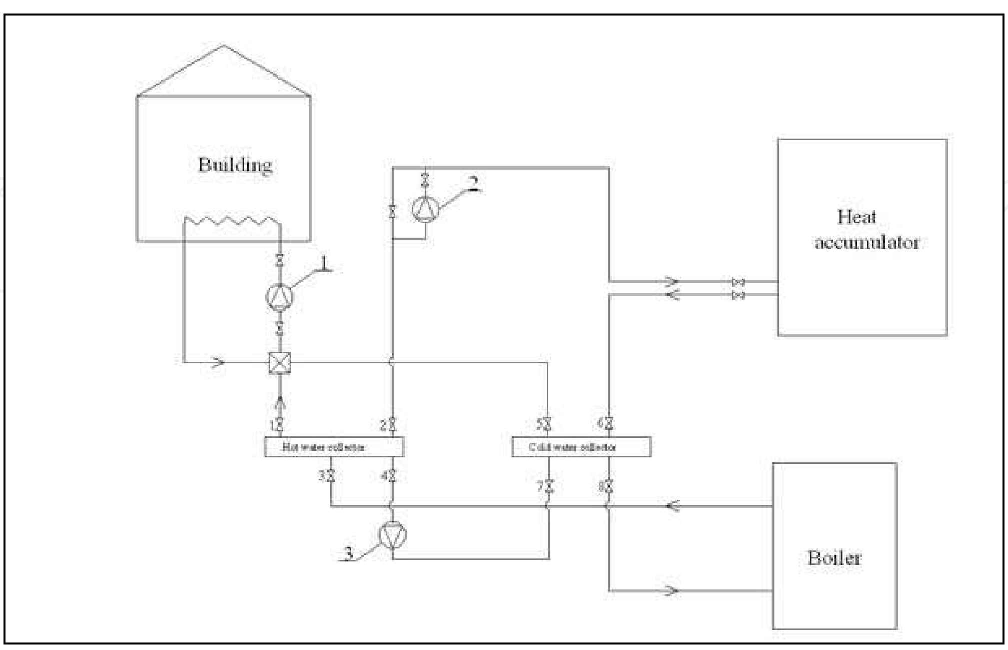

Fig. 7. Thermal scheme of distribution facilities

Fig. 8. Cigarette flame of baled biomass

Element	Unit	Wheat straw	Soybean straw
Proximate analyze			
Moisture	%	9.90	18.80
Ash	%	11.29	5.66
Combustible matter	%	78.81	75.54
Volatile matter	%	62.33	59.08
Fixed carbon	%	16.48	16.46
Char	%	27.77	22.12
Net calorific value	kJ/kg	14.242	14.318
Solubility of the ash			
Sintering (shrinkage) strat temperature	°C	880	1185
Deformation temperature	°C	1020	1310
Hemisphere temperature	°C	1125	1420
Flow temperature	°C	1170	1450

Table 5. The proximate analysis of straw used in tests

Test	1	2	3	4	5	6
Number of used bales	2,0	2,0	5	6	12	11
Amount of straw (kg)	24,6	27,7	61,3	75,9	166	144
Average fuel consumption (kg/h)	21,1	16,6	18,4	19,8	20,8	17,3
Total air flow rate (m^3/h)	169	143	187	173	166	169
Calculated thermal power (kW)	71,3	49,4	53,5	57,4	60,3	50,2
Air excess coefficient measured at the furnace exit l (-)	1,38 -2,35	2,23 -5,35	1,45 -4,27	1,62 -4,27	1,35 -2,52	1,09 -2,82
Test duration (min)	75	100	200	230	480	560

Table 6. Test parameters

Short and long tests have been carried out, with average fuel flow rates of 16,6 to 21,1 kg/h (table 6). The thermal power of the boiler changed in the range from 49,4 to 71,3 kW. The boiler power has been regulated using the regulatory distributor of air excess. Air excess coefficient measured at the furnace exit varied in the range of 1,09-5,35. This shows that there were significant suctions of air from the outside into the furnace, especially in the period when new bales were led into the channel. There was no ash sticking on boiler walls, as well as on the heat exchanger, which was checked after the experiments (Fig. 9).

In order to obtain valid information on the operation of the facility, the following parameters were measured (Fig. 10):

- flue gas temperatures (in the furnace - t_1, in the burn-out zone - t_2, and behind the heat-exchanger - t_3),
- water temperatures (at the outlet - t_4 and at the inlet - t_5), and
- flue gas contents at the boiler outlet (amount of O_2, CO and NOx). Gas sampling was done with a probe placed in the gas duct. Gas samples were discontinuously analyzed since the gas analyzer used is not meant for continuous measurement.

Fig. 9. The view of the furnace inside

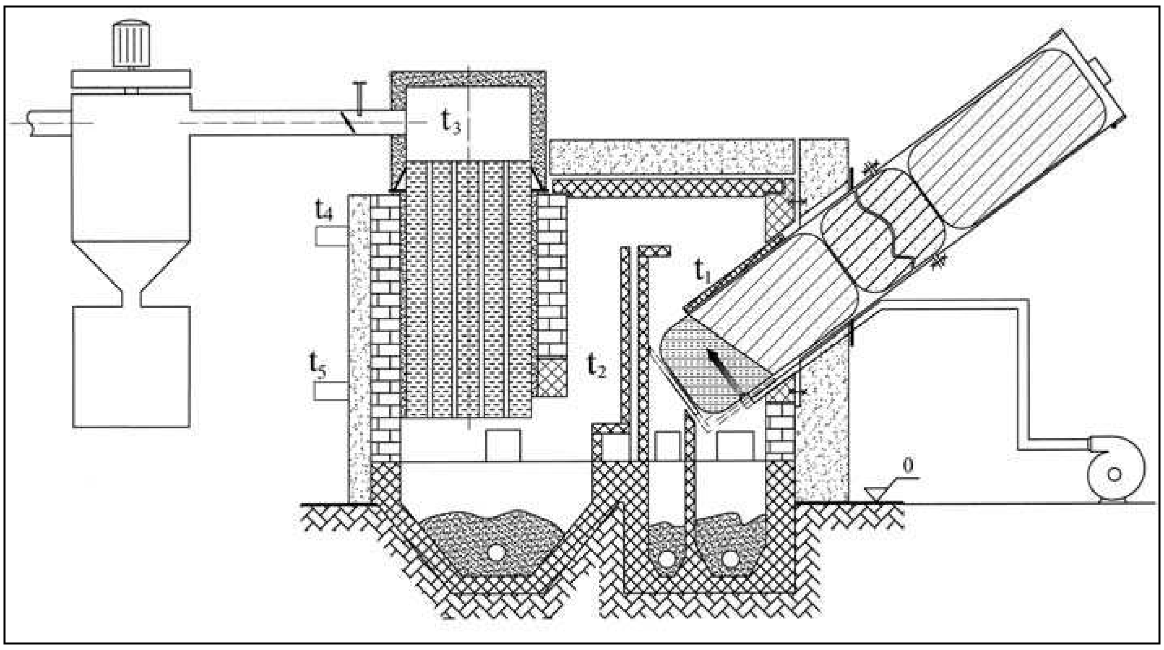

Fig. 10. Measured scheme

In Figs. 11 and 12 flue gas and water temperatures are presented, for two regimes of operation. It can be seen (Fig. 11) that gas temperature in the furnace rose up to 1000^{0}C, in the burn-out zone up to 850^{0}C, and on the boiler outlet up to 220^{0}C, during the operating regime 2. During the operating regime 6 (Fig. 12), the gas temperature in the furnace was about 900^{0}C, in the burn-out zone up to 800^{0}C, and at the boiler outlet up to 220^{0}C. According to the temperature histories, it could be concluded that soybean and wheat straw combustion was satisfactory. Also, the measured water temperatures at the outlet and at the inlet (Figs. 11 and 12) have been in accordance with the values recommended for the heating of objects. The hot water temperature reached values of 95^{0}C, while the water temperature at the inlet reached 70^{0}C.

As mentioned earlier, during all experiments the contents of the flue gases at the boiler outlet was measured. For the reason of instrument used (instrument with electrochemical cells), gas samples were discontinuously analyzed – several times for 10-20 minutes – during all regimes of operation. The results obtained for O_2, CO and NOx contents in the exit flue gases, for operating regimes 2 and 6, are presented in Figs. 13 to 16. Oscillation in the O_2 and CO contents are a consequence of several influences: unsteady feeding of baled biomass, which is caused by gravitational feeding and introduction of the bales into the furnace space; periodical opening of the cover at the back side of the bale channel, which caused rapid suction of false air into the boiler furnace. Measurement of NOx shows smaller oscillations in measured emission values.

Measurement of the oxygen content in exit flue gases has shown a range of 10-17%, depending on the combustion regime. In Fig. 13, the oxygen content in the flue gases for a chosen sequence of measurement at stable operating conditions, for operating regime 2, is shown. Simultaneously, CO and NOx content in the flue gases have been measured (Figs. 15 and 16).

The Book of Regulations on emission limitations, issued by Serbian Ministry of Environmental Protection (1997) recommends that furnaces and boilers burning wood, briquettes and waste biomass should satisfy certain values of CO and NOx oxides

limitations. Although the investigated boiler has small capacity, and not subjected to emission limitations (Book of Regulation, 1997), it has been anticipated that in the future small capacity boilers will have to meet some limitation requirements. During the investigations, CO emission varied in a wide range. When stable regime of operation was established, CO emission was in the range between 81 mg/m^3 and 243 mg/m^3 (at 11% O_2 in the flue gases), which is below Serbian emission limitation (for furnaces and boilers with power 1-50 MWt it is 250 mg/m^3, calculated for 11% O_2). Nitrogen oxides emission was in the range between 311 mg/m^3 and 384 mg/m^3 (at 11% O_2 in the flue gases), which is below the 500 mg/m^3 legislative limit.
The experimental investigation of the boiler has provided necessary parameters (ratio of primary (67-82% of total air), secondary (12-21%) and tertiary air (6-12%), temperatures in the furnace, at the inlet/outlet of the heat exchanger and at the boiler outlet) for the calculation and design of higher capacity boilers, burning baled biomass.
Boiler efficiency was determined according to recommendations (Brkic et al., 1999), and the values of the elements that are of importance for efficiency calculations are given in table 7.

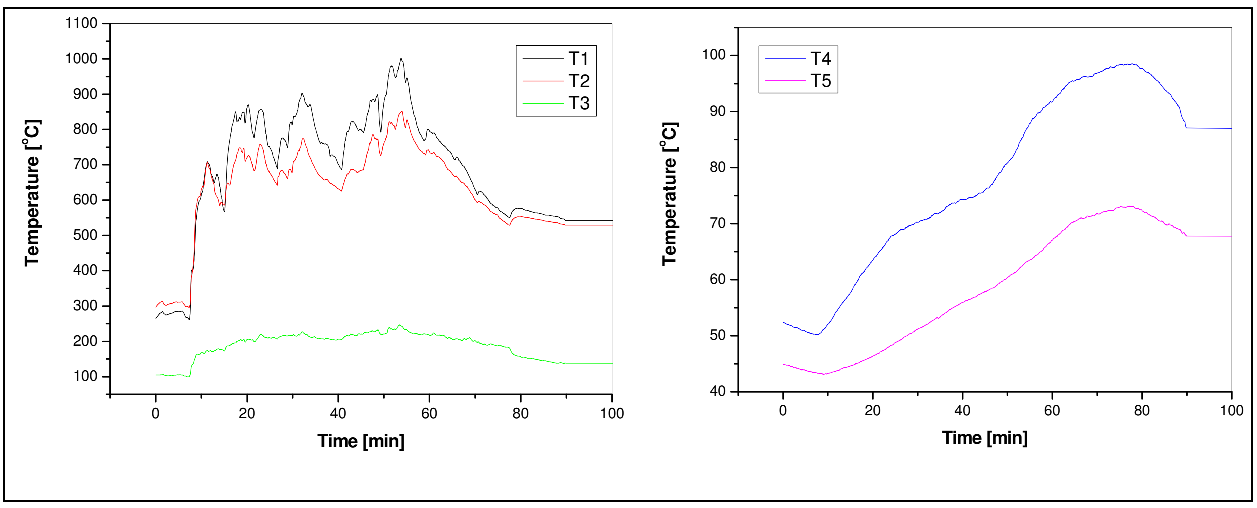

Fig. 11. Measured gas and water temperatures (operating regime 2)

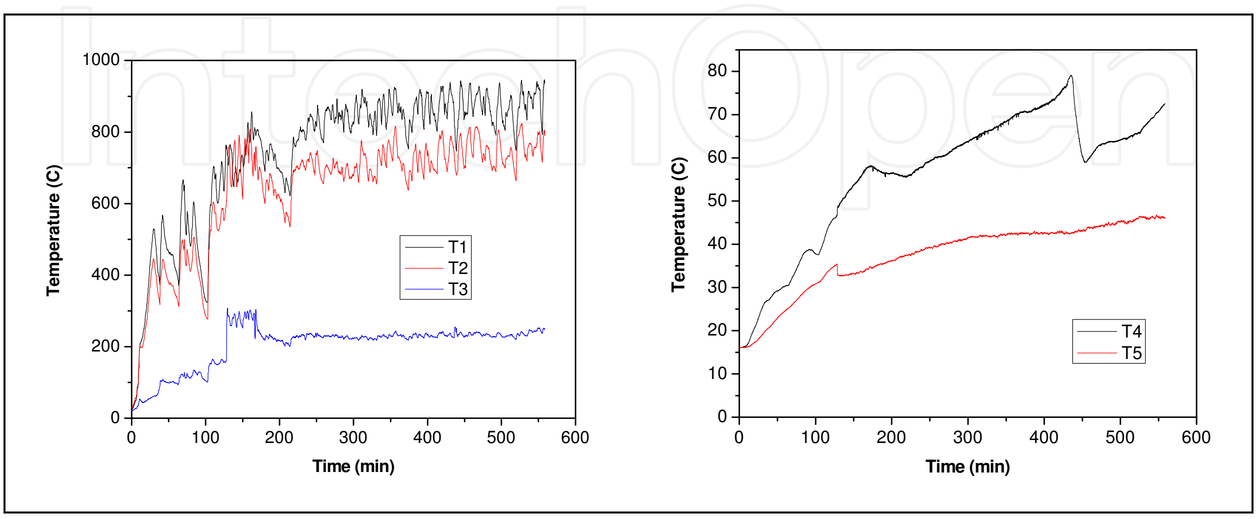

Fig. 12. Measured gas and water temperatures (operating regime 6)

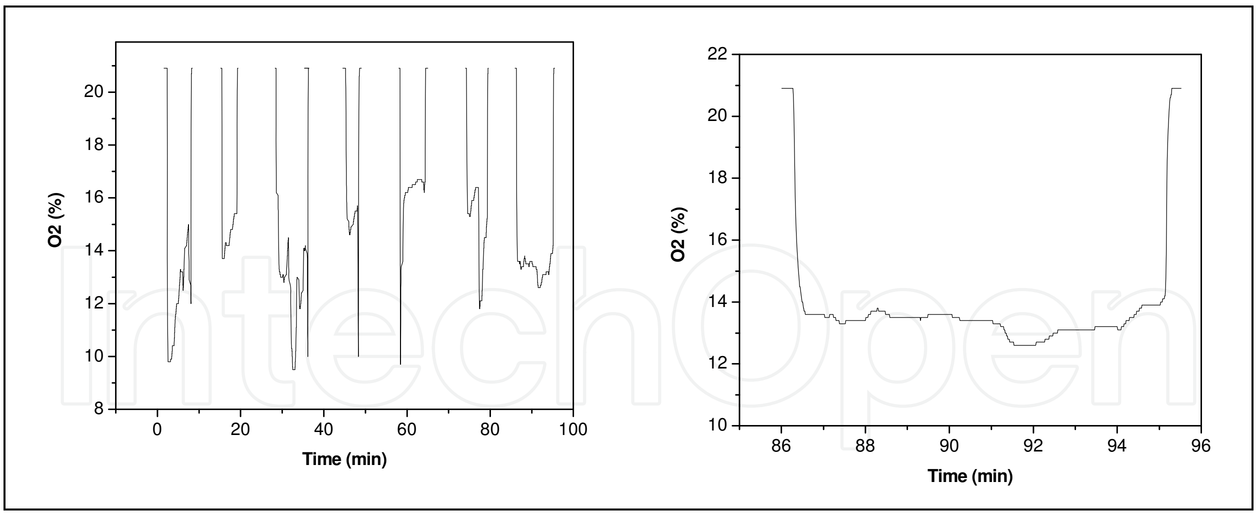

Fig. 13. Change of O_2 concentration in exit flue gases – operating regime 2

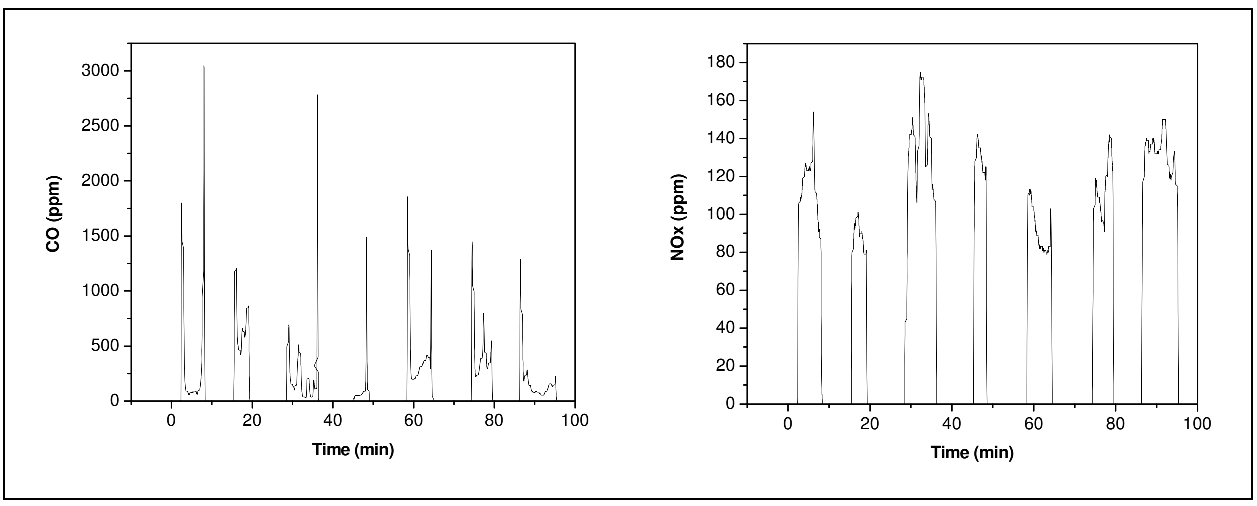

Fig. 14. Emission of the flue gases products (CO and NOx) – operating regime 2

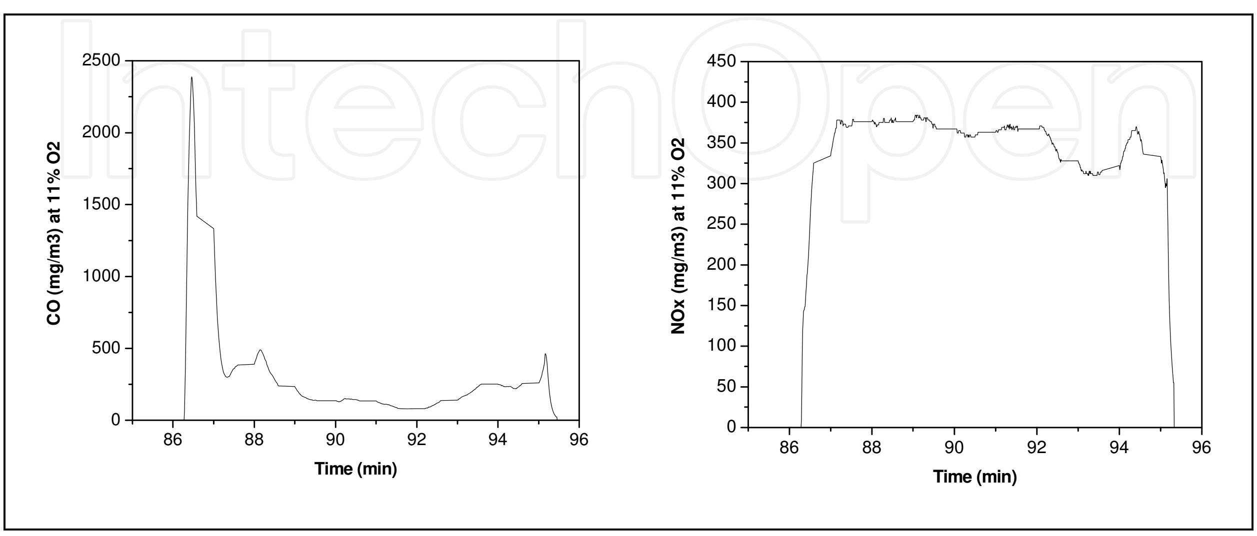

Fig. 15. Emission of the flue gases products (CO, NOx) – a sequence in operating regime 2

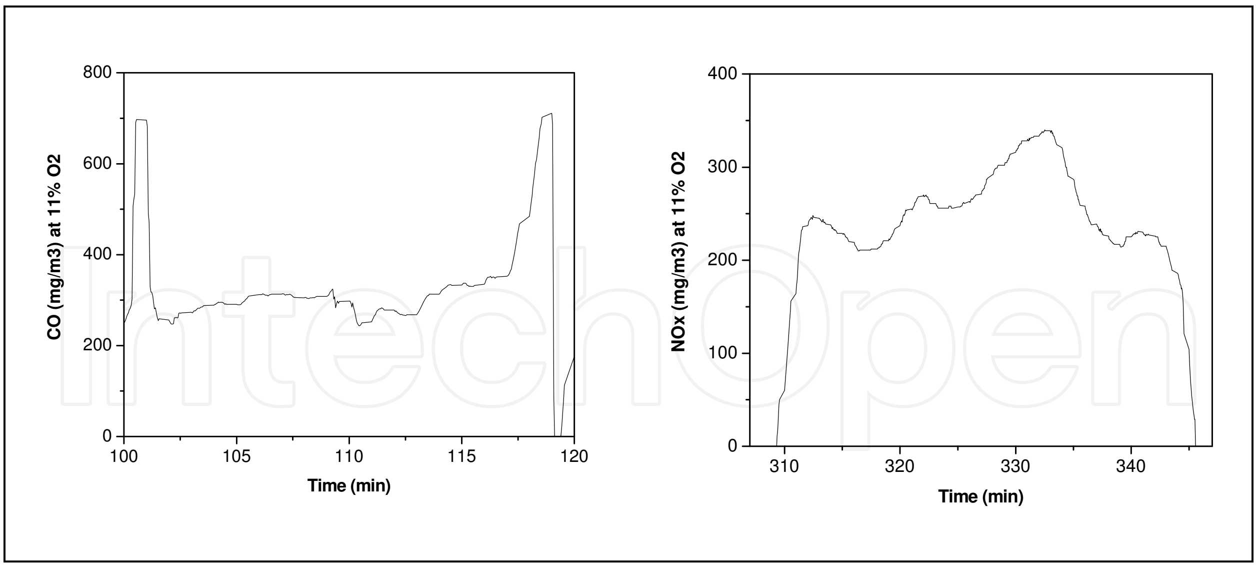

Fig. 16. Emission of the flue gases products (CO, NOx) – a sequence in operating regime 6

Element	Unit	Value
Lower heating value	kJ/kg	13 686
Available heat	kJ/kg	13 686
Air excess coefficient at the boiler exit	-	2,8
Combustion (fresh) air temperature	°C	30
Enthalpy of the theoretical amount of combustion air	kJ/kg	140,61
Exit flue gas temperature	°C	220
Exit flue gas enthalpy	kJ/kg	3240,97
Heat loss due to mechanical incompleteness of combustion	%	4
Loss with the flue gas	%	19,97
Heat loss due to chemical incompleteness of combustion	%	0,5
Heat loss due to boiler cooling from the outside	%	2
Heat loss due to the physical heat of slag	%	0,2
Boiler efficiency	%	73,33

Table 7. Calculation of the boiler efficiency

6. Conclusions

The results of the development of the experimental boiler burning baled biomass have been presented in the paper. The combustion has been organized on the principles of cigarette burning. Basic features and advantages of this kind of combustion have been shown, as well as some essential test results. The investigation proved that with agricultural biomass combustion:

- ensures high enough temperatures in the boiler combustion zone,
- water in the heat exchanger can be heated to nominal temperature, and
- CO and NOx emissions are low enough.

Investigations were performed using soybean and wheaten straw as fuel. Experiments with both type of biomass have been successful, and showed that straw is suitable for cigarette-type combustion technology. Especially, soybean straw is very suitable for this technology of straw combustion because their ash melting temperature is so high. In the next time investigations with other type of straw (corn and rape seed) will be performed. All data collected during these experimental tests were used for designing and building-up of a 1.5 MW hot water boiler for greenhouse heating, also based on cigarette type combustion using large baled biomass.

7. Acknowledgements

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Paths to Sustainable Energy
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The world's reliance on existing sources of energy and their associated detrimental impacts on the environment- whether related to poor air or water quality or scarcity, impacts on sensitive ecosystems and forests and land use - have been well documented and articulated over the last three decades. What is needed by the world is a set of credible energy solutions that would lead us to a balance between economic growth and a sustainable environment. This book provides an open platform to establish and share knowledge developed by scholars, scientists and engineers from all over the world about various viable paths to a future of sustainable energy. It has collected a number of intellectually stimulating articles that address issues ranging from public policy formulation to technological innovations for enhancing the development of sustainable energy systems. It will appeal to stakeholders seeking guidance to pursue the paths to sustainable energy.