SOYA STRAW BALES COMBUSTION IN HIGH-EFFICIENT BOILER

by

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There is a growing need for the use of alternative and renewable energy sources, in terms of sustainable energy development. One of the potentially biggest renewable energy sources in Serbia is agricultural biomass, quite available and cheap at the moment. For many years, the Vinča Institute of Nuclear Sciences, Laboratory for Thermal Engineering and Energy, has been working on the development of clean technologies for efficient utilization of biomass, and as a result utilities and equipment (boilers and furnaces) with wide range of use have been developed. These devices have complete combustion control and primarily burn baled biomass with no adequate utilization. The results of the development and of the tests of an experimental demonstrativel boiler burning small bales of soya straw have been presented in this paper. In the boiler, the combustion has been organized on the "cigarette burning" principle, and fuel feeding has been done by gravity. The technical scheme of the boiler and the results of preliminary tests carried out in real operation conditions have been given.

Key words: *boilers, agriculture residue, biomass, straw, combustion*

Introduction

In terms of sustainable energy development in Serbia, as well as in the whole world, there is a growing need for using 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 [1]. This is the reason for the development of cheap thermal devices (boilers and furnaces) burning biomass from agricultural production, which is a vastly available and a cheap energy source. These devices could be used primarily in villages, small towns and small businesses processing agricultural goods (greenhouses, dairy farms, slaughterhouses, *etc.*), and could find use for heating of schools, hospitals and other objects as well.

Boilers and furnaces should utilize baled biomass which has not been adequately used until now, 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, the environmental aspect of combustion should be kept in mind.

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 tab. 1, an estimate of biomass potential of Serbia is shown [2].

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 Serbian Electric Power Industry (EPS), shown in tab. 2.

Table 1. Energy potential of biomass in Serbia

No.	Biomass residues	TJ per year
1	Forest	43000
2	Agriculture	65000
2.1	Grain growing	40000
2.2	Fruit and grapevine production	25000
2.3	Cattle breeding	76
	Total	108076

Table 2. The consumption and the energy potential of coal used for electricity production in Serbia

No.	Type of coal	Consumption [t per year]	Energy potential [TJ per year]
1	Lignites (Obrenovac and Kostolac thermal power stations)	35000000	248000
2	Higher quality coals (underground exploitation)	624000	10700
	Total		258700

Some basic data on the physical characteristics of various types of biomass are given in tab. 3 [2, 3]. It can be seen that the ranges are quite huge for some values, for example for heating value.

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 [2]. Moisture content influences the behaviour of biomass during combustion, causing variations of the adiabatic combustion temperature and of the volume of gaseous products. In the case of higher moisture the drying process is longer, which causes the release of volatiles and char combustion to be delayed, requiring larger furnace space [2].

The production of cereals leaves straw residue, which, in some cases, exceeds grain quantity up to three times. Baled straw is a secondary agricultural product, with a considerable energy potential. The straw is most commonly packed in the form of small bales (usually square-shaped, 40×50×80 cm) and large bales (cylindrical, ∅180×120 cm, or square 80-120×70×150-250 cm).

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 [4]. 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.

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

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	800-11000 °C

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.

Biomass combustion technologies

The technology for optimal utilization of biomass is determined by biomass characteristics. Reported technologies of biomass conversion are [5]: fixed bed combustion, combustion on a grate, fluidized bed combustion and, finally, gasification. All these technologies are described in detail in the literature [6] , 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 [7].

Whereas forest biomass utilization is quite simple, the use of agricultural biomass for energy production faces quite a lot of difficulties [8]. 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 [9]. 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.

The boiler burning baled biomass

The experimental boiler burning small soya or corn straw bales, with 0.8×0.5×0.4 m in size, has been designed and built. The combustion has been organized on the principles of cigarette burning [10]. In fig. 1, the scheme of the experimental boiler is shown [11]. 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. Furnace walls (4) have been made of refractory material – chamotte, with thermal insulation (5).

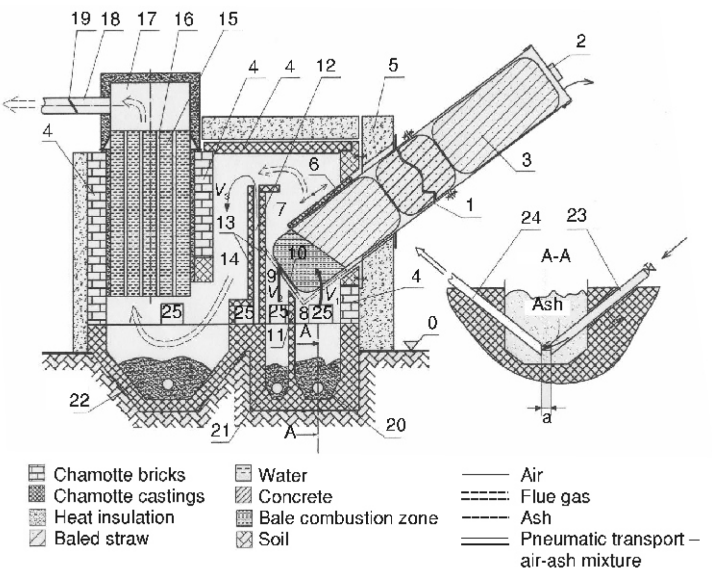

Figure 1. The scheme of the experimental boiler
1 – fuel feeding, 2 – cover, 3 – baled biomass, 4 – insulation, 5 – heat insulation, 6 – regulation of combustion zone, 7 – combustion zone, 8 – primary air supply, 9 – secondary air supply, 10 – grate, 11 – compartment between primary and secondary air, 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 – valve, 20, 21, 22 – ash collectors, 23 – air tube for ash removal, 24 – ash removal tube, 25 – revision opening

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). The burnout of straw occurs in the zone (14).

The heat produced by combustion 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 valve (19), and through the cyclone-type particle precipitator. Ash is collected in ash collectors (20, 21, 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.

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 [12]: geometry, flow patterns, thermal load, thermal flux, adiabatic temperature, average temperature, and flue gases content.

Some results of the experimental tests of the boiler

Biomass combustion in the boiler has been experimentally investigated. The experiment groundwork consisted of biomass sample preparation. The sample biomass was soya straw. The proximate analysis of soya straw used in tests is given in tab. 4. The results of ash analysis gave data on the following: the initial deformation temperature – 1185 °C, the softening temperature – 1310 °C, the hemisphere temperature – 1420 °C, and the fluid temperature – 1450 °C.

Table 4. The proximate analysis of soya straw used in tests

Moisture [%]	Ash [%]	Char [%]	Fixed carbon [%]	Volatile matter [%]	Combustible matter [%]	Net calorific value [kJ/kg]
18.80	5.66	22.12	16.46	59.08	75.54	14318

Five tests were done, and a summary of the most important test parameters is given in tab. 5.

Table 5. Test parameters

Test	1	2	3	4	5
Number of used bales	2	3.5	0.5	5.5	3
Amount of straw [kg]	27.7	51.6	7.9	77.5	41.5
Average fuel consumption [kg/h]	16.6	17.3	23.6	18.6	17.8
Total air flow rate [m^3/h]	143	149	183	160	154
Calculated thermal power [kW]	49.4	51.6	70.3	55.5	53.1
Air excess coefficient measured at the furnace exit l [–]	2.23-7.75	2.34-5.36	2.64-3.54	2.11-4.27	2.30-5.18
Test duration [min.]	100	120	20	250	140

Experiments with soya straw have been successful, and showed that soya straw is suitable for cigarette-type combustion. A picture of the flame is shown in fig. 2. Short and long tests have been carried out, with average fuel flow rates of 16.6 to 23.6 kg/h (tab. 5). The thermal power of the boiler changed in the range from 49.4 to 70.3 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 2.11-5.36. 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. 3).

In order to obtain valid information on the operation of the facility, the following parameters were measured:

- 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

Figure 2. Cigarette flame of baled biomass

Figure 3. The view of the furnace inside

– flue gas contents at the boiler outlet (amount of O_2, CO, and NO_x). 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.

In figs. 4-7 flue gas and water temperatures are presented, for two regimes of operation. It can be seen (fig. 4) that gas temperature in the furnace rose up to 1000 °C, in the burn-out zone up to 850 °C, and on the boiler outlet up to 220 °C, during the operating regime 1. During the second operating regime (fig. 5), the gas temperature in the furnace was about 800 °C, in the burn-out zone up to 700 °C, and at the boiler outlet up to 200 °C. According to the temperature histories, it could be concluded that soya straw combustion was satisfactory. Also, the measured water temperatures at the outlet and at the inlet (figs. 6-7) have been in accordance with the

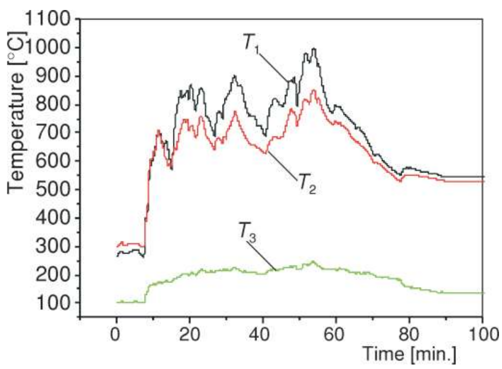

Figure 4. Measured gas temperatures (operating regime 1)

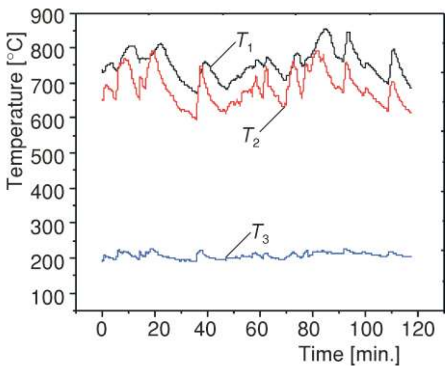

Figure 5. Measured gas temperatures (operating regime 2)

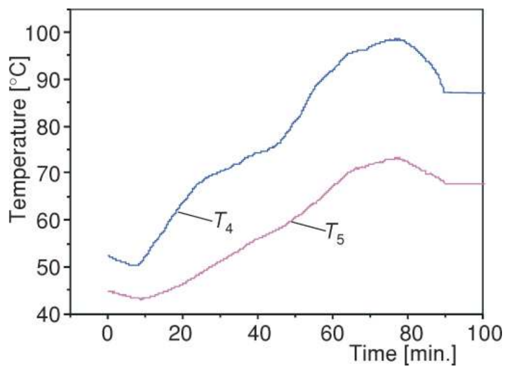

Figure 6. Measured water temperatures (operating regime 1)

values recommended for the heating of objects. The hot water temperature reached values of 95 °C, while the water temperature at the inlet reached 70 °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 5-10 minutes – during all regimes of operation. The results obtained for O_2, CO, and NO_x contents in the exit flue gases, for operating regime 1, are presented in figs. 8-10. 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 NO_x shows smaller oscillations in measured emission values.

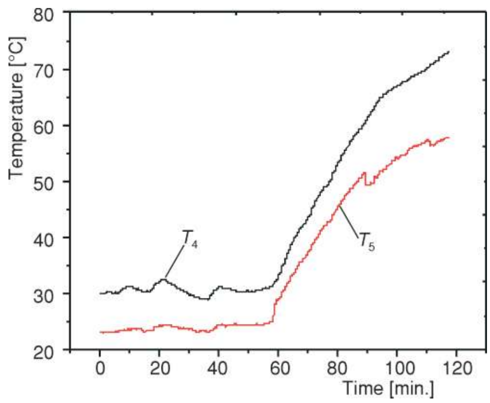

Figure 7. Measured water temperatures (operating regime 2)

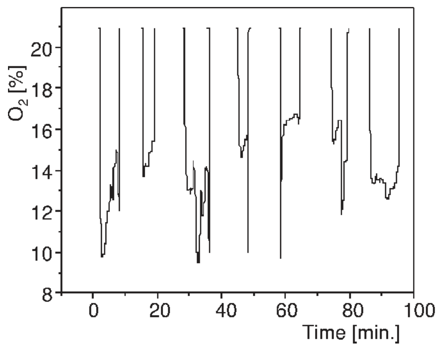

Figure 8. Change of O_2 concentration in exit flue gases – operating regime 1

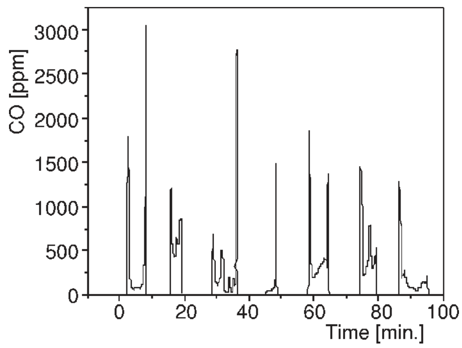

Figure 9. Flue gas emissions (CO) – operating regime 1

Measurement of the oxygen content in exit flue gases has shown a range of 10-17%, depending on the combustion regime. In fig. 11, the oxygen content in the flue gases for a chosen sequence of measurement at stable operating conditions, for operating regime 1, is shown. Simultaneously, CO and NO_x content in the flue gases have been measured (figs. 12 and 13). The Book of Regulations on emission limitations, issued by Serbian Ministry of Environmental Protection [13] recommends that furnaces and boilers burning wood, briquettes, and waste biomass should satisfy certain val-

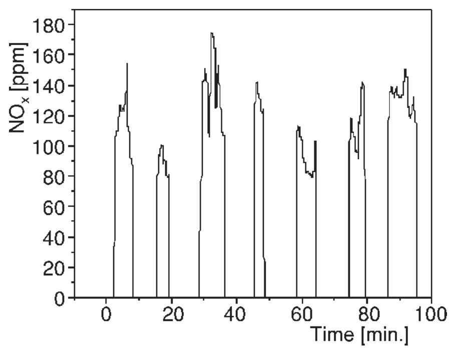

Figure 10. Flue gas emissions (NO_x) – operating regime 1

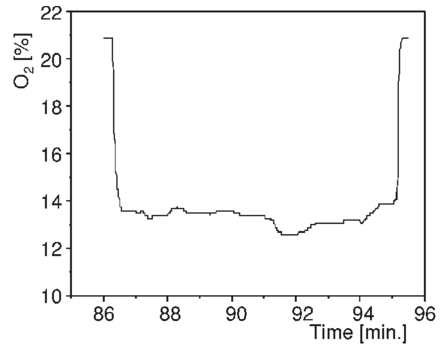

Figure 11. Change of O_2 concentration in exit flue gases – a sequence in operating regime 1

ues of CO and NO_x oxides limitations. Although the investigated boiler has small capacity, and not subjected to emission limitations (according to [13]), 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 MW 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.

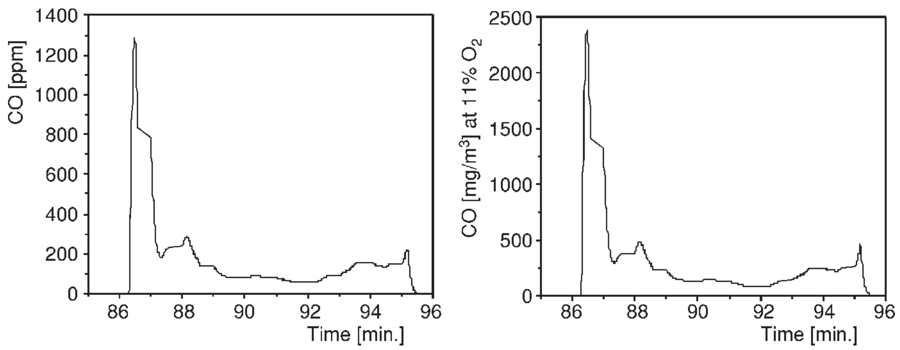

Figure 12. Emission of the flue gases products (CO) – a sequence in operating regime 1

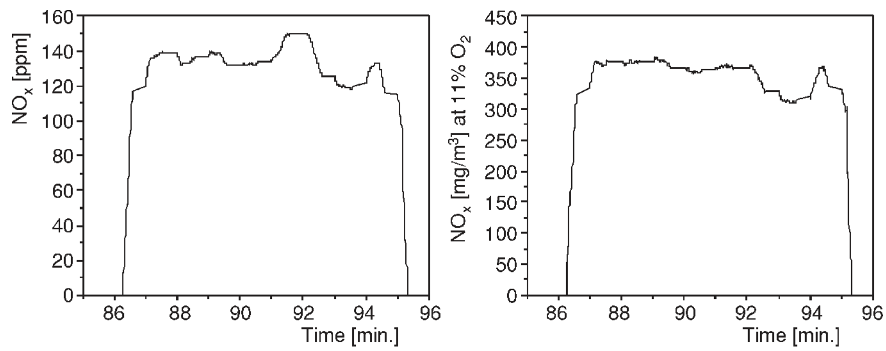

Figure 13. Emission of the flue gases products (NO_x) – a sequence in operating regime 1

Boiler efficiency was determined according to recommendations given in [14], and the values of the elements that are of importance for efficiency calculations are given in tab. 6.

Table 6. Calculation of boiler efficiency

Element	Symbol	Unit	Value
Lower heating value	H_d	kJ/kg	13686
Available heat	Q_r^r	kJ/kg	13686
Air excess coefficient at the boiler exit	α_{iz}	–	2.8
Combustion (fresh) air temperature	t_{hv}	°C	30
Enthalpy of the theoretical amount of combustion air	I_{hv}^o	kJ/kg	140.61
Exit flue gas temperature	t_{iz}	°C	220
Exit flue gas enthalpy	I_{iz}	kJ/kg	3240.97
Heat loss due to mechanical incompleteness of combustion	q_4	%	4
Loss with the flue gas	q_2	%	19.97
Heat loss due to chemical incompleteness of combustion	q_3	%	0.5
Heat loss due to boiler cooling from the outside	q_5	%	2
Heta loss due to the physical heat of slag	q_6	%	0.2
Boiler efficiency	η	%	73.33

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:
– high enough temperatures in the boiler combustion zone can be reached,
– water in the heat exchanger can be heated to nominal temperature, and
– CO and NO_x emissions are low enough.

The experimental boiler has worked more or less satisfactorily with calculated capacity. However, instabilities and fluctuations were observed in flue gas contents (figs. 8-13) and gas temperatures (figs. 4 and 5). This unsteadiness in all regimes of operation are a consequence of a very short channel for bale feeding, which was caused by the actual on-site condition and insufficient space in the boiler house and around it. Hence only one and half bale was placed inside the channel at a time, and the channel cover (position 2, fig. 1) had to be opened frequently in order to supply new bales. This provoked sudden and frequent fluctuations and disturbances in the combustion regime and in flue gases emissions. This sort of problems with unstable conditions is not expected on a real boiler facility. All the data collected during these experimental tests were used for designing and building-up of a 1.5 MW hot water boiler for greenhouse heating [15].

Acknowledgments

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