Chapter 3

Development of the Technology for Combustion of Large Bales Using Local Biomass

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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 [1-3]. 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 [4]. 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.) [5]. The devices could also be used for heating schools, hospitals, prisons and other institutions.

Annual energy consumption in the Republic of Serbia currently reaches 15 million tons oil equivalent (Mtoe), out of which 7.4 Mtoe represents the net consumption and 3 Mtoe is electricity consumption. According to the official date of Ministry of Infrastructure and Energy of Republic of Serbia [6], Serbia is in dispose of 4.3 Mtoe of renewable energy sources, while biomass is represented with 2.7 Mtoe. 60% out of registered biomass potential are residuals from agricultural production, and the rest is wood biomass. Currently, only a small portion of waste biomass is being used in energy production mostly for heating (not taking into account burning in the individual households, in small ovens), for several reasons: low electricity price and non-resolved problems in biomass gathering. Also, there is no regulated biomass market, and no developed technologies for its utilization as fuel. Besides, small financial power of potential buyers have to be mentioned, as well as costly commercial credits and total absence of state subsidizing of biomass facilities.

This biomass is a cheap and available fuel, but its utilization is linked to the problems of its collection, preparations for its transportation (cutting, tying into haystacks, baling), transportation and storage [7]. The best way for utilizing residual agricultural biomass for energy production in industrial or district heating is to be used close to place of its gathering - in large agricultural companies. That is the optimal solution, from energy, as well as economic point of view. Agricultural biomass is usually collected in form of bales, varying in size and shape, so it is most convenient to use it in that form. One of the most efficient ways, recommended by many institutions worldwide, is the combined heat and power (electricity) production – CHP [8], which use residual biomass as fuel, and have least as possible own power consumption.

Two technologies are currently used for the combustion of biomass bales. The first is based on whole-bale combustion in the combustion chamber, while the second considers combustion of biomass bales in “cigar” burners. The “cigar” firing technology provides better quality of the combustion process, resulting in lower pollutant emissions and increased plant efficiency. This technology was found to be very suitable for straw combustion and was deemed not to be associated with any process limitations.

2. Research path

In the process of production of different crop residues that occur in some species exceed three times the amount of crops produced. These residues can be baled and still used. Today in Serbia the producers of baled biomass are mainly farmers who receive biomass in baled form as by-products of primary production. In practice there are two basic types of bales: small square bales (0,40x0,50x0,80 m) and large cylindrical bales (ø1,80x1,20 m) or rectangular shape (0,80-1,20x0,70x1,50-2,50 m).

Advantages and disadvantages of specific types of bales are the following [9]. Small conventional bales have many advantages: low cost of presses, binders moderate prices, the need for a smaller tractor, good storage, a favorable agreement on means of transport, simple disintegration and chopping by means of lower prices, the possibility of firing the entire bales and others. Deficiencies are inevitable manual operation, by hand using auxiliary storage means, a relatively high usage of the binder, the lower reliability than other presses etc.

The advantages of large cylindrical bales are moderate presses price, simple and fully mechanized manipulation, in the case of unwinding a simple and inexpensive device, conveniently storing for own needs on medium farms, the opportunity to work with medium power tractors etc. The disadvantages of this bundle are: the highest consumption of binder, the lower performance because of the need to halt the bale tying and ejection from the workspace, the sensitivity of trusses on the quality of the binder, the deformation under the bonding quality, lower transportability because the empty space, need more storage space etc.

Large square bales have the following advantages: high pressure compression, high performance, low consumption of binder, best transportability, good storage conditions, the whole mechanization and the lowest price of manipulation, the lowest consumption of binder etc. The disadvantages are reflected in the following: high initial cost of machinery, required a large tractor, requires special means for manipulation, machinery sensitive to the application of low-quality binders, need of special funds for the disintegration etc.

Furnaces and boilers that would use baled biomass from agricultural production can be a wide power range from 0.1 to 2 MW or more. Baled biomass as a fuel does not require big investments in preparation because balers have nearly every farmer. These are not expensive and complicated machines and do not require high energy consumption per kg of baled biomass. On the other hand, neither of which would be the biomass used as fuel, not far from the place of origin nor transport is not a major problem. Storage can be a problem, but as there is plenty of farmland damage caused by his occupation is insignificant, and increased investment costs to build a warehouse to quickly pay the difference in price between the liquid or gaseous fuels and biomass. In addition, profit get from the green credits - benefits that are obtained in the case of renewable energy usage are paid this facilities only through the benefits in a very short period of time.

In the Laboratory for Thermal Engineering and Energy of the "Vinca" Institute in Belgrade, efforts have been made to develop a clean technology for utilizing baled biomass for energy production. The initial set of analyses carried out in the research investigation conducted focused on the combustion of small, 40x50x80 cm straw bales in cigar burners. For the said purpose, an experimental, 75 kWth hot water boiler was designed and constructed [9]. The furnace was built entirely out of an insulating material providing favorable biomass combustion conditions. Appropriate boiler tests were conducted in order to properly determine required design parameters. Although the boiler assembly examined was a small-scale facility intended to be used by individual farm owners and utilized for space heating, it provided a good basis for development of large, industrial scale straw-fired facilities.

Following the initial set of analyses, combustion of rolled, ø180x120 cm straw bales in cigar burners was analyzed in the next investigation phase. In order to assess the combustion quality and obtain data needed for proper design of the straw-fired hot water boiler, a 1 MWth demonstration furnace was designed, constructed and tested [10].

As a result of the specified investigation efforts, a pilot plant capable of burning large, 0.7x1.2x2.0 m straw bales was designed and built [11]. A 1.5 MWth industrial-scale hot water boiler was constructed and installed in the Agricultural Corporation Belgrade, where it was used for heating 1 ha of vegetable greenhouses belonging to the agricultural complex mentioned. The boiler house was built in the immediate vicinity of the greenhouse complex.

3. Materials and methods

Technologies enabling biomass use for energy generation are mainly dependant on biomass characteristics. Different biomass conversion technologies available on the market include: fixed-bed combustion, combustion on the grate, combustion in dust burners, fluidized bed combustion and gasification [12]. Utilization of agricultural biomass faces a lot of challenges. One of the main disadvantages associated with combustion of agricultural biomass is a tendency of biomass ash to melt [13]. Two technologies are currently used for the combustion of biomass bales. The first is based on whole-bale combustion in the combustion chamber, while the second considers combustion of biomass bales in so called “cigar” burners. Cigar burner technology was found to be very suitable for straw combustion and was deemed not to be associated with any process limitations. The research investigation described herein was focused on developing a cigar burner combustion system suitable for the combustion of bales of various sizes and shapes and their utilization for energy production.

3.1. An efficient boiler burning small straw bales

The experimental boiler burning small soya, corn, rape seed or wheat straw bales, with 0.8x0.5x0.4 m in size, has been designed and built [10, 14-16]. The combustion has been organized on the principles of cigarette burning [17]. Thermal power of the boiler is around 75 kW. In Figure 1, the scheme of the experimental boiler is shown. Baled straw is introduced through the inlet (3) into the combustion zone (7). The inlet is supplied by devices for continuous bale feedings and provides stable combustion conditions (Figures 2 and 3). Furnace walls (4) have been made of refractory material – chamotte, with thermal insulation (5).

Under the original solution fresh air is injected through two channels, the primary air through channel (8), and secondary air through channel (9), and they are divided using compartment (11). 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.

After the first examination of the boiler some changes were carried out in the distribution of air 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 can be regulated the part of the bale involved in combustion and thus indirectly is regulated the heat output of the boiler.

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 valve (19) and flue gas fan (28), and through the cyclone-type particle precipitator (29). 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.

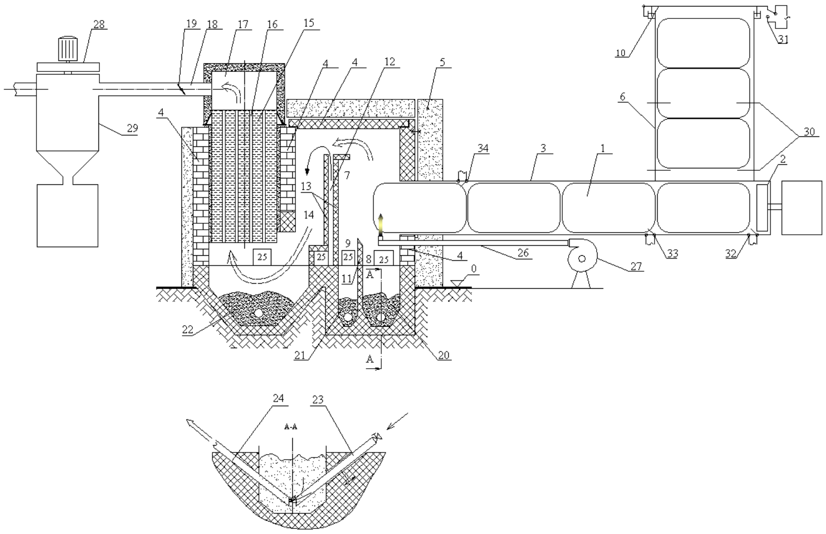

Figure 1. Scheme of the small agricultural biomass bale combustion boiler

Figure 2. Heat accumulator and bale storage and feeding system

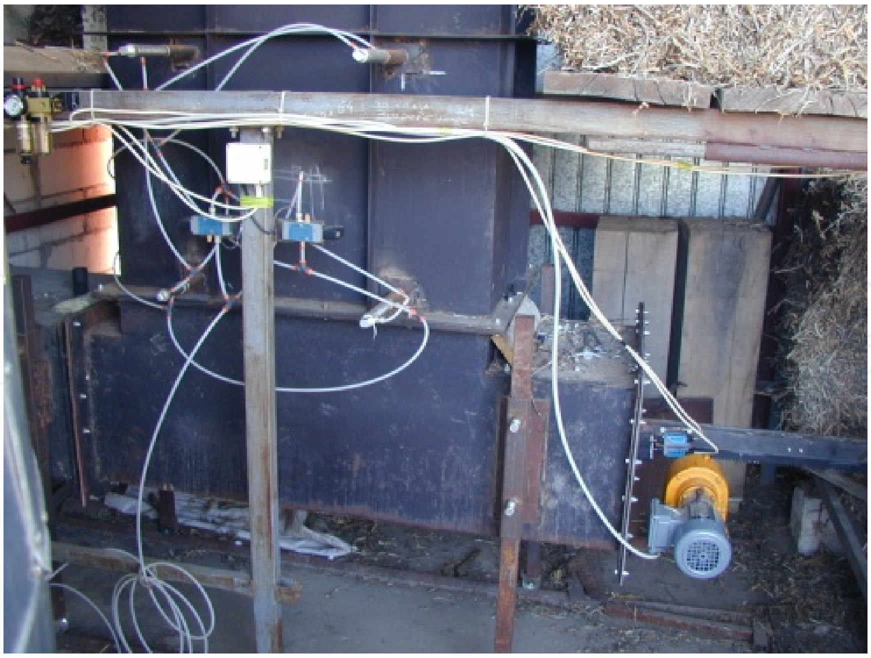

Figure 3. Bale storage and feeding system with push piston

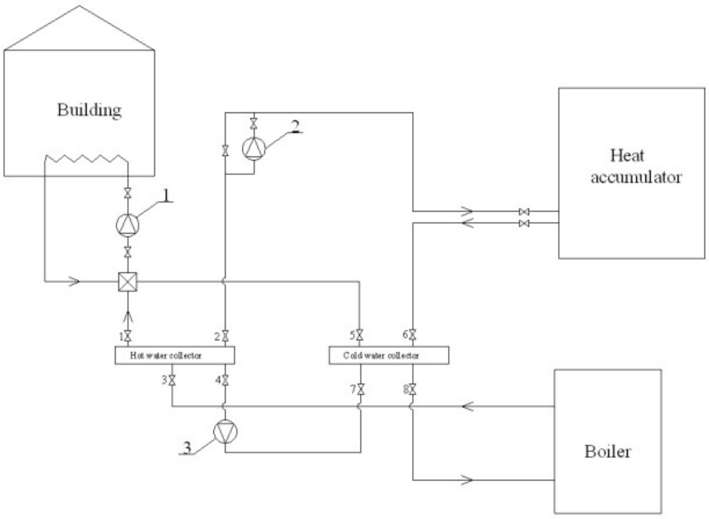

Figure 4. Thermal scheme of distribution facilities

In order to obtain to plant work at nominal power, heat accumulator (thermal reservoir, with volume of 5 m^3) has been installed (Figure 2). In this way it is ensured that no matter what the current needs for heating buildings are, boiler always works with the nominal power. 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 Figure 4. From it can be seen following thermal circles: a) Hot water from the boiler goes directly into a building that is heat-

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ed, 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 (Figure 5).

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

3.2. The demo furnace burning soya straw bales

In order to assess the combustion quality and to obtain data for the design of a soya straw-fired hot water boiler, a demo furnace with thermal power of 1 MW has been designed and built [10, 18, 19]. The appearance of the furnace, with the thermocouple probes, the primary air fan and channel, and the fuel feeding channel is shown in Figure 6. This furnace has been adopted for cylindrical bales, with 1.2-1.5 m in diameter which were available at that time. The cross is clearly visible on Figure 7 where the scheme of the experimental demonstration unit for burning large rolled soy straw bales was presented. There can be also clearly distinguish three characteristics combustion zones in the cigar burner: drying zone (6), zone of devolatilization (5) and zone of char burning (13).

Figure 5. The boiler control system and cyclone-type particle precipitator

The proximate analysis of soya straw used in testing is given in Table 1. The sum of five tests was done. A summary of main test parameters is given in Table 2. During all tests, three gas temperatures in the combustion zone were measured, with shielded type K thermocouple probes. Gas sampling was done with a probe placed near the furnace exit. Gas samples were continuously analyzed with two analyzers, collected every 5 seconds and stored on-line.

It should be noted that secondary air supply through the movable cross was not present in the first version of the demo furnace, which was examined in tests 1 and 2. The results from these tests stressed the need to introduce secondary air in the combustion zone, at the bale forehead, and the furnace with secondary air supply through the cross was examined in tests 3, 4 and 5.

Figure 6. The appearance of the demo facility for burning large rolled straw bales

Test 1 was conducted with one bale of straw placed in the feeding channel. Only temperature measurements were done, and the results showed that the temperature in the combustion zone, in steady conditions, was quite stable (730-830°C, Figure 8) for a reasonable period of time (40 minutes). It was noted that the amount of tertiary air did not contribute much to overall combustion conditions, and that in fact this air over-cooled the flue gases in the combustion zone.

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	13686

Table 1. The proximate analysis of soya straw used in the tests

In test 2, along with temperatures, gas composition was continuously measured. Less air was supplied as tertiary than in test 1. In the initial, start-up period (Figure 9), gas samples were taken directly from the combustion zone, and very high levels of CO in the flue gases were noted. After the choking of the gas sampling probe and its cleaning, and also in all following tests, gas samples were taken only from the top of the furnace. As the temperature in this period increased to approximately 1000°C, bale feeding was slowed down, and this corresponds to the temperature downfall (min. 50-75). Soon after that, stable conditions were obtained (Figures 9 and 10), primarily by adjusting bale feeding.

Test	1	2	3	4	5
Number of bales in the feeding tube	1	2	2	3	3
Amount of straw [kg]	134,6	280	327,97	458,3	554,9
Primary air [m^3/h]	1548	1548	1548	1350	1404**
Secondary air [m^3/h]	-	-	234	418,25	228,14**
Tertiary air [m^3/h]	504	252	108	259,2	259,2**
Calculated thermal power [kW]$^+$	485,2	529,3	556,5	551,7	455,7
Average air excess coefficient λ [-]	not measured	4,71	2,61	4,12*	2,92**
Test duration [min]	47	89	99	140	205

Conditions: $^+$ - The thermal power was calculated over the entire test period
* - The air excess coefficient in Test 4 was calculated for the period shown in the diagrams (Figures 13 and 14)
** - The air flow rates refer only to the period shown in the diagrams (Figures 15 and 16), since in test 5 variable speed drives were used for changing the speed of the fans. The air excess coefficient λ was calculated for the same period

Table 2. Test parameters

High level of CO concentration at the furnace top in test 2 urged the introduction of a small amount (approximately 10% of total air) of secondary air in the combustion zone, which would cool down the movable cross at the same time. It was also noted that tertiary air flow rate should be decreased, and therefore secondary air was introduced to the detriment of tertiary air. This change in design was examined in test 3, with two bales placed in the feeding channel.

The supply of the secondary air through the cross provided excellent conditions for combustion (Figure 11) – the concentration of CO was equal to zero for most of the time during the test. The air distribution (82% primary air, 12% secondary, 6% tertiary) was found to be well suited for maintaining steady conditions inside the furnace. On the other hand, the stability of the thermal output was found to depend largely on the active length of the bale immersed into the furnace.

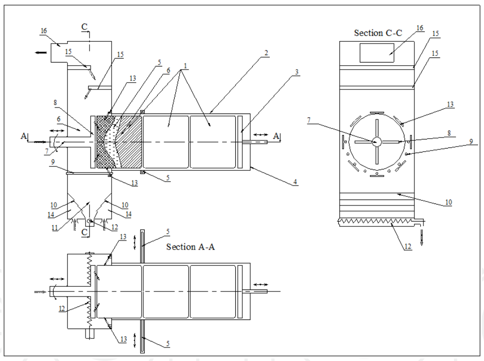

Figure 7. Schematic of the experimental demonstration unit for burning large rolled straw bales

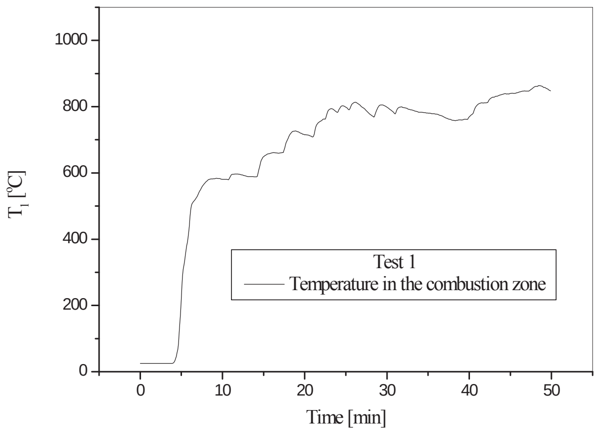

Figure 8. Test 1 – Temperature in the combustion zone

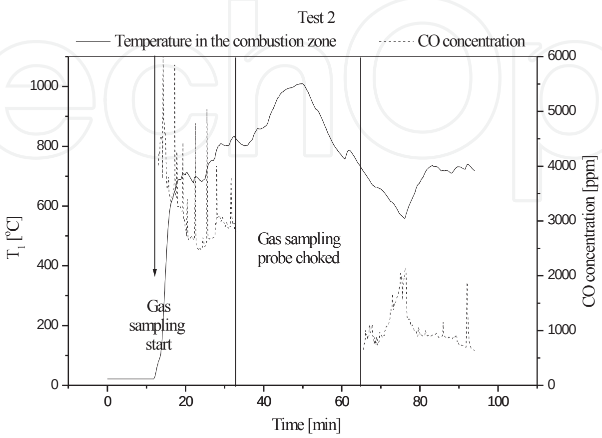

Figure 9. Test 2 – Temperature in the combustion zone vs. CO concentration

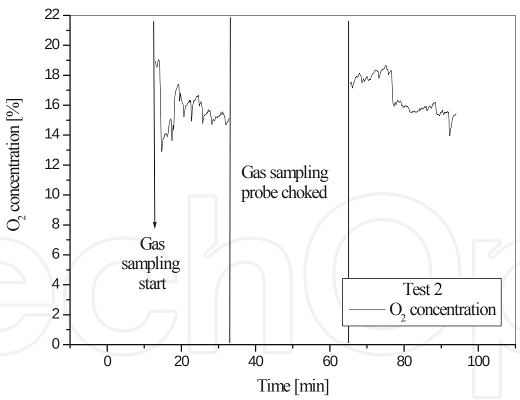

Figure 10. Test 2 – O_2 concentration at the furnace exit

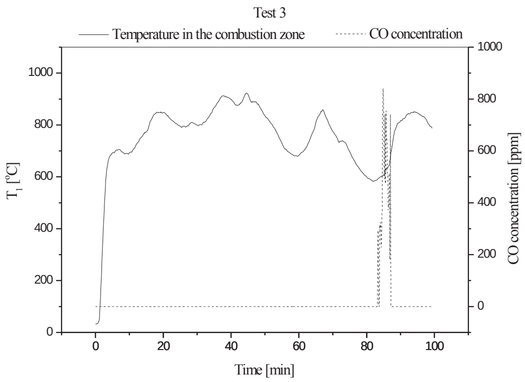

Figure 11. Test 3 – Temperature in the combustion zone vs. CO concentration

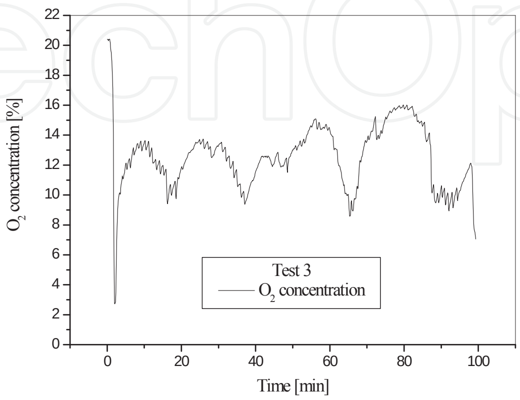

Figure 12. Test 3 – O_2 concentration at the furnace exit

Therefore, it is of great importance to feed the bale uniformly in accordance with the combustion process, and to maintain this length as stable as possible, by moving the cross accordingly. The temperature instabilities (from the minute 45 further on, Figure 11) during this test are a consequence of changes of this length. The only peak in CO concentration coincided expectedly with low temperatures during this period. Nevertheless, this test proved that the adopted concept of the furnace provided good conditions for efficient combustion of soya straw bales, with O_2 concentration ranging from 10-14% (Figure 12), and an optimal average value of λ.

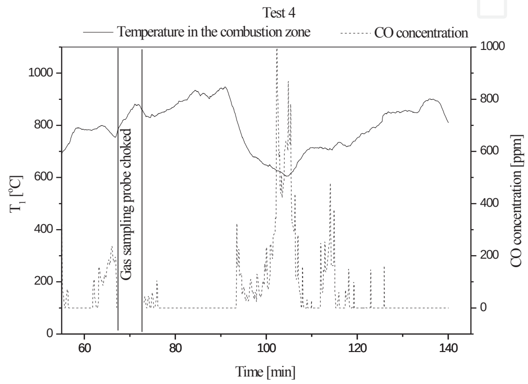

Figure 13. Test 4 – Temperature in the combustion zone vs. CO concentration

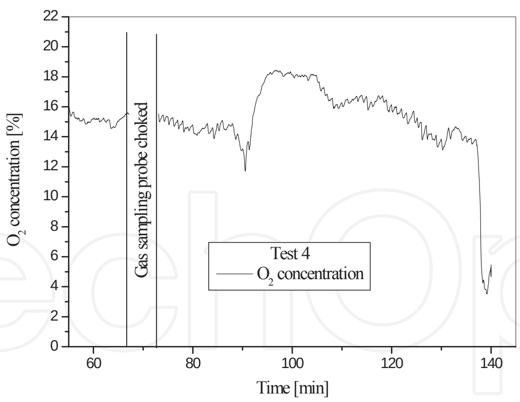

Figure 14. Test 4 – O_2 concentration at the furnace exit

The principal aim of test 4 was to assess the possibility of longer furnace operation, with three bales placed inside the feeding channel. The bales prepared for this test were approximately 1.2 m in diameter, and in order to secure stable manual feeding, the gaps between the channel wall and the bales were manually filled with more straw. Problems with feeding undersized bales caused instabilities in the first hour of the test. In the period shown in Fig-

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ures 13 and 14, the temperature was in the desired range, and CO concentration was acceptable for most of the period (up to 350 ppm), the only rise in CO occurring at the time of the temperature downfall (minutes 100-110). It was spotted by visual inspection, through the inspection openings, that the bale was not inside the furnace at the time of the downfall, due to the problems with manual bale feeding and cross positioning – the bale forehead remained inside the tube. This caused the flame to enter the tube at the time, which also occurred during test 5.

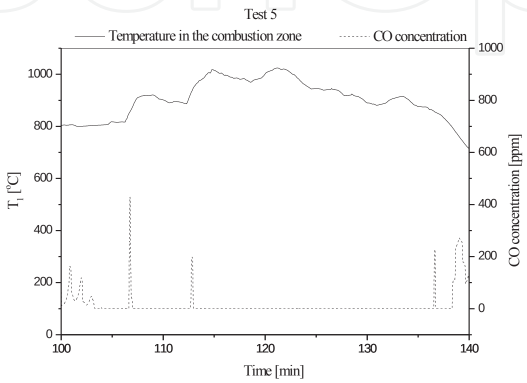

Figure 15. Test 5 – Temperature in the combustion zone vs. CO concentration

The aim of test 5 was to assess the influence of air flow rate control, with variable speed drives, on furnace performance. During a chosen period of 40 minutes (Figures 15 and 16), optimal air flow rates were obtained and bale feeding was kept stable. The concentration of CO was very low, with O_2 concentration varying in the range of 10-15%. The temperature during this period was higher than the desired 850°C (which should not be exceeded in order to avoid ash melting), which will be taken into consideration in some of the conclusions.

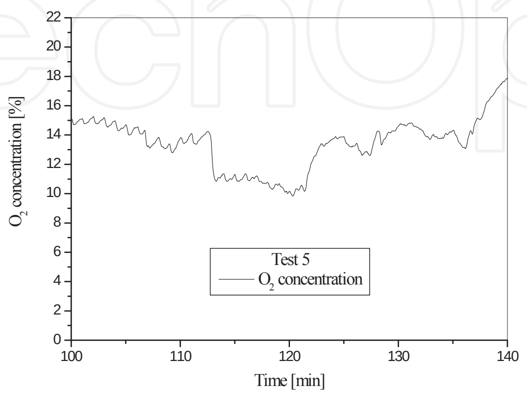

Figure 16. Test 5 – O_2 concentration at the furnace exit

3.3. Heat water boiler burning baled biomass

The use of renewable energy sources is becoming more and more important, mainly due to continuously increasing prices of fossil fuels, resource depletion and global attempts to achieve maximum feasible CO_2 emission reduction. Researches in this area are very complex and in order to obtain reliable data it is necessary to carry out theoretical and experimental research of the process. For this purpose, a 1.5 MW industrial-scale hot water boiler was constructed and installed in the Agricultural Corporation Belgrade [20-22]. The boiler is based on waste baled soybean (and other types) of straw combustion, and it is used for heating 1 ha (10000 m^2) of greenhouses. Combustion in the boiler carried on so-called "cigarette" principle [11], where 0.7x1.2x2.0 m straw bales are used as fuel. The bales have parallelepiped shapes. In Figure 17, the scheme of the experimental hot water boiler is shown.

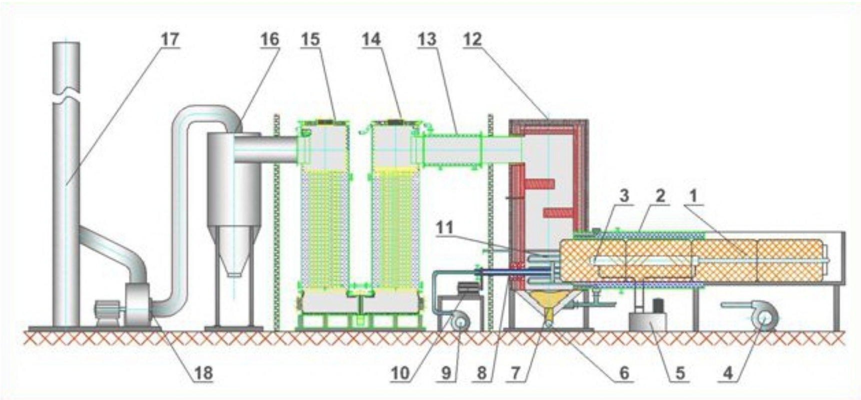

Figure 17. The scheme of the demonstrating hot water boiler with thermal power of 1.5 MW

Baled straw (Figure 17, position 1) is fed to the facility by cylinder type transporters (2,3). After entering the rectangle cross sectioned bale feeding channel (4) bales are carried by a motor driven VSD controlled conveyor (6) towards the furnace (7). The section of the channel (4) nearest to the furnace is made of multiple steel sheets (5), with primary air flowing through space between the sheets, thus cooling the sheets and being preheated at the same time. The furnace is made of refractory material (chamotte) (8), and is completely insulated (9). Ash is removed from the furnace by a transporter (10).

Preheated primary air (13) is supplied around the bale, and a portion of it also from under the grate (12), which is water cooled. Secondary air (11) is supplied through the movable cross onto the bale forehead, similarly as in the experimental furnace. The cross also serves as bale support from the forehead, for shaking-off ash from the forehead and for bale positioning inside the furnace.

Leaving the furnace chamber, the flue gases pass through a heat pipe to the first section of the gas to water heat exchanger (14), and then through a chamber with screen barrier type particle separator (15) to the second section of heat exchanger (16). After final particle removal in the multi-stage cyclone type separator (18) the flue gases, transported by the flue gas fan (19), leave the furnace through the stack (20). The view of the boiler house and heat accumulator is presented in Figure 18.

Apart from the presence of the movable cross, used for secondary air supply, which can be considered as innovative, another new concept is the existence of a 100 m^3 heat storage vessel - heat accumulator (Figure 18) with thermal insulation. It was introduced so that the whole facility could respond more appropriately to the heating needs of the greenhouses. Hot water produced in the boiler is stored in the heat storage vessel. At time when the ambient temperature is relatively high and weather conditions are mild (sunny days, without wind etc.), the boiler produces much more heat i.e. hot water than necessary for greenhouse heating. The greenhouse systems use only the amount of hat water necessary for heating, and the heat surplus is stored inside the heat storage vessel. At time when outside temperatures are below zero, on windy and cloudy days, the heat produced by the boiler might not be sufficient, but the lacking heat is then supplied from the heat storage vessel. The boiler is operated and controlled by a SCADA-based system, through a computer.

Figure 18. The boiler house, heat accumulator and cyclone type separator

A cigar firing combustion system is expected to exhibit the following advantageous features: a) combustion of whole bales and whole energy crops; b) compact combustor design; c) short start up period, good load-following performance; d) profitable operation of smaller facilities (down to 1 MWth); e) division of combustion from the heat recovery system, usable not only for the provision of steam (for heat generation or CHP), but also as a hot gas generator in industrial drying applications. Cigar burner combustion system promises a more competitive use of renewable for “green” heat and power generation as well as their use in various industrial applications.

Possible disadvantages of cigar burner combustion system include: a) a need for a “smart” and sophisticated process control system; b) thermal cracks, thermal attacks on the metal combustion chamber.

4. Experimental research

4.1. Investigation of the influence of bale quality

During experimental investigation of the boiler occasionally came to some minor problems in boiler operation. The problem was detected in the poor biomass burning. It is assumed that the main cause of problems is uneven quality of bales. Therefore, it is examined in detail the quality and moisture in bales that are stored and used in regular plant operation. It is assumed that poor bales quality could come from two reasons: a) Because of the rainy season in the period of collection of soybean straw in the fields; b) The increase in moisture content during bales storage up to their use.

Figure 19. The cover and open bales storage near the boiler house

Preparation for use baled straw in boiler is in September. According to official data of the Republic Hydrometeorological Service of Serbia [23] during the month of September at the territory of Belgrade fell more than 3 l/m^2 of rain. On this basis it can be concluded that the formed bale of soybean straw were acceptable dry before storing, or it can be said that the weather was ideal for baling straw. Shortly after baling bales were transported near the boiler room so that time needed to bales transport did not affect the increase in moisture.

5	10	15	20
4	9	14	19
3	8	13	18
2	7	12	17
1	6	11	16

Figure 20. Schematic layout of sampling straw

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Part of the bales is stored under the canopy capacity of 1200-1500 pcs bundle (Figure 19). The quantity of bales is insufficient to operate the boiler throughout the season. Therefore it had to accede to the formation of a group bales in the open, again near the boiler where the bales are placed in the open and covered with nylon.

Number of sample	% of moisture	Number of sample	% of moisture
1	14.77	12	13.78
2	45.17	13	19.44
3	11.83	14	12.34
4	15.84	15	59.73
5a	66.70	16	17.59
5b	65.83	17	16.98
6	17.17	18	20.65
7	19.63	19	15.75
8	20.05	20a	68.98
9	16.74	20b	66.62
10	62.15	21	67.86
11	11.97		

Table 3. Results of the determination of moisture content in samples of soybean straw

From several groups of bales placed at open space one was chosen for the implementation of a test. Selected group made a bundle so that in a horizontal row was passed four bales (bale lying on the site with the largest surface area). Such orders were five in height. Length of group was determined free space and it corresponded to the width of a few dozen bales. It was decided to analyze the quality of bales (determination of moisture content in bales) per cross-section of group. A special sampler which allows sampling in-depth of the bale was made. Straw sampling scheme in the cross section is given in Figure 20 where from some of the bales taken more than one sample.

Determination of moisture content in straw samples was performed in an accredited laboratory for testing fuels at the Vinca Institute. Test results of straw samples moisture is given in Table 3. The results show dramatic differences in the quality of the bales at the cross section of bale group. All straw samples from the fifth highest among the group (number of samples 5a, 5b, 10, 15, 20a, 20b, 21) show that the concentration of moisture in them is extremely high. It ranged from 60-70%. Such quality straw with so much moisture content, absolutely can not burn in any furnace. Also, if such a bale enters the combustion chamber can cause a host of other problems.

By using the appropriate computer program calculation the adiabatic combustion temperature and combustion product composition of soybean straw with different moisture content

(Table 4). Results of proximate analyze of soybean straw was used as input data for calculations. In the case of combustion of soybean straw, with a total moisture content of Wt = 68%, the theoretical calculation shows that the combustion temperature is not possible to achieve satisfactory gas temperature for a real excess air to be used in the process of bales burning. The theoretical combustion temperature of soybean straw for excess air of 2.80 would be 572°C. In the case of combustion of the same composition biomass, but reduced the moisture content of Wt = 15%, the calculation shows that it is possible to achieve significantly higher gas temperature for a real excess air. In this case, the theoretical combustion temperature was 903°C for the excess air of 2.80. Note that this is mathematical calculated theoretical combustion temperature of soybean straw, which in real terms of furnace can not be achieved so that the actual combustion temperature significantly lower. This is caused by the fact that the combustion of CO to CO_2 achieves at the minimum temperature of 680°C. When burning soya straw with high moisture content in the flue gases products is a large amount of CO which is due to low temperatures (below 680°C) can not be transformed into CO_2.

Excess air	Moisture content Wt = 15%	Moisture content Wt = 68%
α =1,60	1379	801
α=1,90	1217	728
α=2,20	1089	667
α=2,50	987	616
α=2,80	903	572
α=2,95	866	552
α=3,10	833	534

Table 4. Theoretical (adiabatic) combustion temperature of soybean straw (°C)

Also was made a bale straw moisture test on the basis of statistical data on the amount of rains on the territory of Belgrade in September, October and November. In September fell 3.9 kg rain/m² of soil, in October 98.8 kg rain/m², while in November fell 62 kg rain/ m². This means that the total per bale could fall about 386 kg of water, taking into account data from October and November. If we accept that the initial bale moisture was 10% and the average weight of bales after baling was about 200 kg by the calculation is to the point that one rain bales after October and November had a moisture content of ≈ 70%, which agreed quite well with the obtained moisture analysis of samples. So the increase of moisture in the bales stored in groups is a consequence of atmospheric rains.

Information about the theoretical combustion temperature (Table 4) confirmed the facts of bales combustion impossibility from the upper row of the crowd with such high moisture content in it. On the other hand, the vast majority of straw samples from bales, which were in the middle of the crowd (except than bale no. 2), has a moisture content ranging from 11.83 to

20.65%. This shows that such bales, with such quality, can satisfy needs of combustion in a boiler with a cigarette burning like that installed in PKB Corporation. This means that careful bales choosing avoid many problems in the boiler operation, would reduce the number of delays, to facilitate the boiler operators and that, most importantly, and would provide a safer production in the greenhouse that uses heat produced by combustion of soy bales straw.

We will point to another very important effect of increased baled biomass moisture, which is reflected in the flow, and thus indirectly on the kinetic characteristics of the biomass combustion in a boiler furnace. As is well known soybean straw baled is a porous medium, and as such unless the porosity is characterized by another feature of flow, which is permeability. Permeability is flowing layer in some fluid flow. Experiments have shown that as the permeability of porous biomass layer is less, the pressure drop i.e. flow resistance higher [24-26].

Bearing all this in mind, we can conclude that the bales moisture is essential for the applied concept of biomass combustion. During designing this boiler we calculated that the moisture content of bales shall not be greater than 25%. This is why we made this concept that the boiler is the simplest and cheapest solution for the user. For the case when one wants to burn fuel with a high content of moisture applied to the concept of boiler furnaces with higher volume and with additional support of liquid or gaseous fuel which satisfy necessary heat required for continuous combustion of fuel in the boiler furnace. It is more expensive and complicated option for users, both in design and manufacture of the boiler as well as its subsequent exploitation.

4.2. Experimental investigation in boiler furnace

Cigarette baled biomass combustion is a relatively new and unexplored technology. For this reason a complex Computation Fluid Dynamics (CFD) simulation of the combustion process at a specific procedure may be of importance for further investigation of the process of cigarette combustion. Numerical simulations process of this type of facility involves modeling the transfer of momentum, heat and substances during combustion of biomass bales, which composition is a porous medium [24, 27]. To form a mathematical model of thermo physical parameters except combustion in a porous medium, it is necessary knowledge inputs as thresholds model.

This paper describes experimental studies performed on mentioned boiler in order to determine the necessary model input parameters. When performing experiments measured the all parameters necessary to determine the global kinetics of the combustion process, the composition and temperature of flue gases at the outlet section of the space being modeled, and estimates the amount of fuel which is unburnt and which post combustion performed in a fluidized bed of its own ashes. In order to compare with the model made the determination or measurement of the temperature profile in soybean bale on its way from entering the combustion chamber to the combustion zone.

Experimental investigation on the demonstration boiler implies the measurements of the following input parameters [28]:

- mass flows of air at the entrance , $\dot{m}_1$, $\dot{m}_2$ and $\dot{m}_3$;

- temperature of the flue gas at the ash fluidized bed layer exiting T_{m3};

- mass flow of fuel (soybean straw baled $\dot{m}_4$);

- flue gas temperature at the exit cross section of model T_g;

- flue gas composition, at the exit intersection of model (CO_2, O_2, CO, NO).

Schematic of the experimental tests is shown in Figure 21. Measurement of mass flow of air at inlet cross sections was done indirectly through the measurement of velocity in the channels using Pitot-Prandtl's probe. Temperature of the flue gas exiting the fluidized bed of its own ashes, and the temperature at the outlet cross section were measured continuously by thermocouples type K. During experiments the acquisition of measurement data using corresponding instrument was performed.

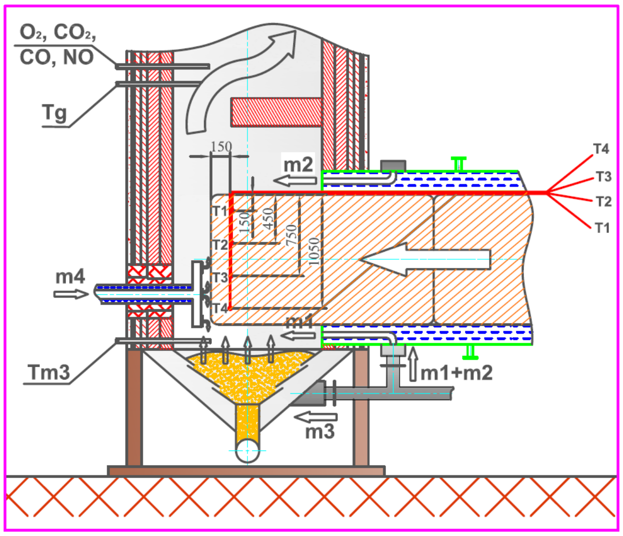

Figure 21. Measurements scheme at demonstrating hot water boiler furnace

Bales feeding were done discontinuous so that the cycle of 1 min the number of seconds the ball travels to the furnace and the rest to 1 min ball is at rest. Therefore, it is done recording the relative position of the bale in relation to entering the combustion chamber and time, which is based on data received on its secondary mass flow $\dot{m}_{fu}$. Composition of dry flue gas at the exit cross section was measured using a gas analyzer. Based on the measured air flow at the entrance to the ash layer $\dot{m}_{fu}$ and the temperature difference T_{m3} between inlet and outlet flue gases it is possible to determine the degree of conversion of coke residue, based on the energy balance between the energy of combustion of carbon, which falls on the fluidized bed and the enthalpy difference above the entrance of air and flue gas exit from the fluidized bed.

Also, were carried out experimental studies to determine the temperature profile in the central plane of soya straw bales, which participates in the combustion process. For this experiment, four thermocouples were placed in the central plane of height, according to the scheme at Figure 21. The experiment was performed in a stationary regime of the furnace operation and the temperature measured in function of the position of thermocouples. The appearance of soya straw bales with thermocouples placed in the median plane, just before entering the bale feeding system is shown in Figure 22. Experiments were performed at the maximum capacity of the furnace of 1.57 MW. Proximate and ultimate analysis of combusted soybean straw is provided in Table 5.

Ultimate analysis				**Proximate analysis**				
C [%]	H [%]	N [%]	O [%]	W [%]	Vol. [%]	C_{fix} [%]	A [%]	H_d [MJ/kg]
45.2	7.0	0.5	47.3	11.35	60.73	20.91	7.049	13.981

Table 5. Ultimate and proximate analysis of soy straw used in tests

4.3. Results of the experimental investigation

Experimental tests were carried out at a temperature in the furnace between 850-900°C, which is the optimum temperature for combustion of soybean straw. This temperature is high enough for complete combustion of straw, and safe from the point of ash melting. The stationary measurement regime remain several hours, but here will be presents the results of measurements for 1 h. It is enough to perform the necessary conclusions about the quality of combustion and comparisons with the proposed model. Data whose values are not changed during the experiment are shown in Table 6.

Figure 22. Thermocouples on the bale in feeding system

Temperature of air and fuel inputs (T_1, T_2, T_3, T_4, T_{fu}) has not changed during experiments, and for simplicity, adopted their size of 300 K, because any error will not have much impact on the accuracy of the results.

Variable	Air mass flow on inlet, [kg/s]				Fuel mass flow, [kg/s]
	Inlet 1	Inlet 2	Inlet 3	Inlet 4	
Value	0.2632	0.2263	0.2371	0.05	0.112143

Table 6. Data of experimental values

Flue gases temperatures at the outlet section of the model at input 3 were measured continuously during the experiments and their values in a representative period of time are shown in Figure 23. It can be seen that the average temperature of gases at the outlet section was 889°C, and temperature of flue gases at the entrance to model 3 was ~420°C.

Based on the known average temperature T_{m3}, air mass flow and air temperature at the inlet 3, it is possible determined the amount of fixed carbon which burn off in a fluidized bed of its own ashes, according to the methodology presented earlier. This amount essential represents a part of unburnt primary fuel that burns in the porous layer, and on the basis of this information can be concluded about the global kinetics of the process based on the mass flow of fuel and the degree of conversion. The mass flow of fictitious components of volatiles and fixed carbon burning in the porous layer, calculated according to the proposed methodology are shown in Table 7.

Variable	m, [kg/s]			
	C_3H_8	CO_2	H_2O	C_{fix}
Value	0,0166	0,0185	0,0323	0,0188

Table 7. Volatile and fixed carbon mass flow values

The global kinetics of the process is not only defined by the degree of conversion of coke residue, but also by the degree of conversion of combusted gases in volatiles. From that reason measuring of the concentration of components in dry flue gas at the exit cross section was performed (Figure 21). The values of the measured concentration of CO_2, O_2, CO and NO are shown in Figures 24 and 25 for a period of one hour.

From Figure 25 it can be seen that the concentration of nitrogen oxides is around 160 ppm, which is converted in mg/m^3 for the reference value of oxygen in the flue gas of 11% [29], is approximately 350 mg/m^3. The concentration of carbon monoxide was, at first view, very high, but we should bear in mind the fact that the observed cross section in which the measured concentration of the combustion process does not end, but it is continuing inside the chamber for burn of.

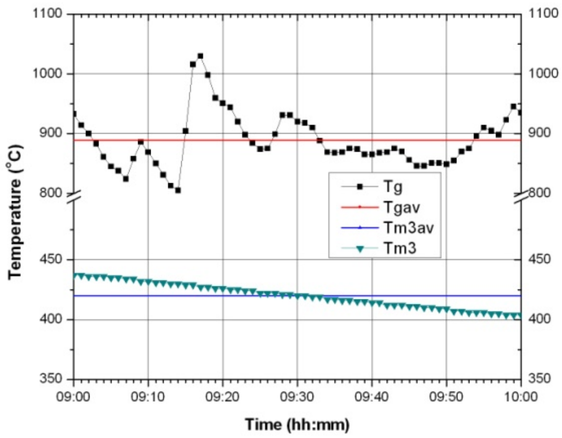

Figure 23. Flue gas temperature T_g and T_{m3} (T_{gav} = 889°C and T_{m3av} = 420°C)

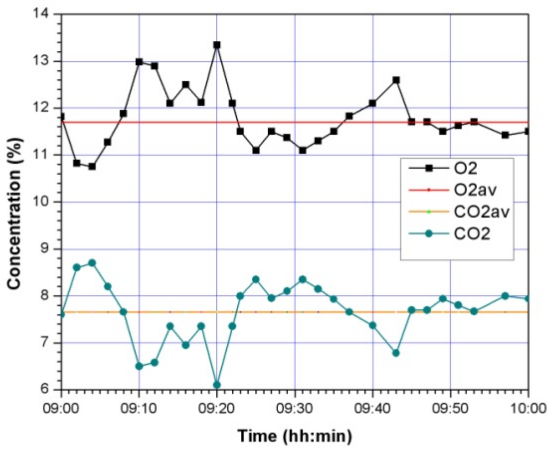

Figure 24. Carbon dioxide and oxygen concentration in dry flue gas on the outlet

The second part of the experimental research was related to determine the temperature field inside the soybean straw bale on its way from entering the furnace to the combustion zone. Graphical presentation of this measurement is shown in Figure 26.

It is important to note that the feeding rate of bale was not continual. In a determined time the bale was traveling to the combustion zone (working interval), and in determined period of time the bale was in pause (interval mode). Here it is clear that the average bale speed, if it is continuously moving, was less than the speed of movement in the working intervals. This statement is very important from the point of adoption of relevant temperature in the interval mode, because it is a case of unsteady heat conduction, so in the diagram can be seen more value of the temperature in one position. If the movement of the bale was uniformly and continuously, then the temperature is in a position that corresponds to the interval mode must have been between maximum and minimum measured values. Unfortunately, can not say with certainty whether the value was closer to the maximum, minimum or mean value. For the bale zero position we adopted the position of the combustion zone.

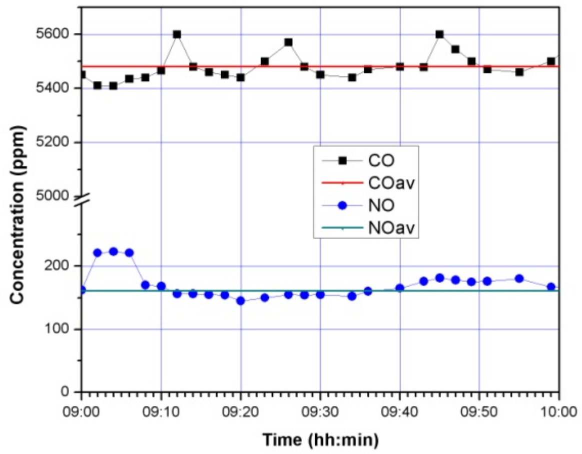

Figure 25. CO and NO concentration in dry flue gas on the outlet

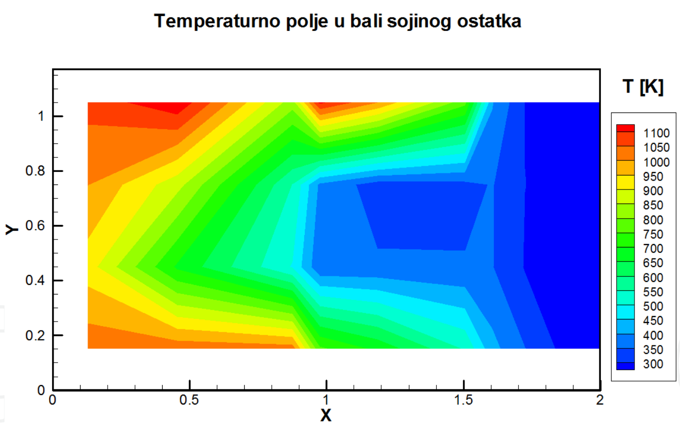

Figure 26. Measurement temperature profiles inside the soybean straw bale

4.4. Small scale plant for combined heat and power generation

The best way for utilizing residual agricultural biomass for energy production in industrial or district heating is to be used close to place of its gathering - in large agricultural companies. That is the optimal solution, from energy, as well as economy point of view. One of the most efficient ways, recommended by many institutions worldwide, is the combined heat and power

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(electricity) production - CHP, which use residual biomass as fuel, and have as least as possible power consumption. Proposed facility, analyzed here, meets those requirements in total. This is going to be the first CHP facility in Serbia, using residual agricultural biomass.

a) Present situation

Agricultural Corporation "Belgrade" - PKB is the largest agricultural enterprise in Serbia (≈ 22.000 ha of arable land), with agriculture and livestock as main domain of work. Crops (≈ 25.000 t/year of corn, wheat, barley, ≈ 5.760 t/year of soya, rapeseed and sugar beet), milk and vegetables are the main products. Each year after the harvest, a huge amount of soy straw (≈ 3.000 t/year) and corn stack (10-15.000 t/year) remain on the fields. The thermal facility with 1.5 MW power built for heating 1 ha greenhouses, has been working for five years already, using soy straw as main fuel. In the boiler, an original cigarette type combustion technology has been applied.

The energy efficiency of the straw utilization cycle is mainly affected by process of its preparation (balling, chopping, bundling), thus, the most justifiable is to use it close to the place of growing and gathering, and in form in which it is collected from fields. To utilize the remaining balled straw and meet thermal needs of surrounding objects, it is desirable to build a new boiler facility with an efficient and environmentally considerate combustion technology. The most efficient way is a combined heat and power (CHP) plant [30-32].

The planned facility would heat several objects: two greenhouses, the greenhouse office building, a school, and a hospital. An overview of the objects, their installed or required thermal capacity and current heating modus are given in Table 8.

Object	Area [m^2]	Fuel	Annual fuel consumption/ Thermal power
Greenhouse 1	1 ha	Soy straw or light fuel oil	1.5 MW
Greenhouse 2	1 ha	No heating	1.5 MW
Greenhouse office building	130 [m^2]	Soy straw	25 kW
School	4025 [m^2]	Light fuel oil	110 t/year (600 kW)
Hospital	8600 [m^2]	Heavy fuel oil	300 t/year (1.3 MW)

Table 8. Heating in Padinska Skela - present situation

b) Projected solution

The project consists of the substitution of existing boilers fed by fossil fuel by a CHP biomass facility, to heat public buildings and greenhouses as well as generate electricity. This will contribute to the reduction of CO_2 emissions and to the improvement of the general living conditions of the local inhabitants. As a pilot project, it has the potential to serve as an example for profitable green energy production facilities with replication potential.

The project covers a new boiler house with cogeneration facility. The boiler house comprise following main elements, included in the business plan (Table 9.). In addition to the mentioned units of the CHP facility, there are other infrastructural elements of the described technology, which have not been included in the business-plan, listed in Table 10.

The planned CHP facility is based on the two proven technologies:

a. The balled straw combustion technology (developed in Laboratory for Thermal Engineering and Energy of Vinca Institute of Nuclear Sciences, in cooperation with Company Tipo-Kotlogradnja, Belgrade), which has been applied in existing 1.5 MW facility used for heating greenhouses in PKB.

b. Organic Rankin Cycle (ORC) for electricity generation. ORC technology is based on turbines driven by silicone oil steam (although, steam of other liquids can be used).

Functional scheme of the CHP facility with the proposed combustion technology and the heat into electricity energy conversion technology is shown in Figure 27. The combustion technology (based on the cigarette type burning) has been described in detail in numerous papers [9, 10, 20], and has been developed up to industrial application, largely with help of Ministry of Education and Sciences of Republic of Serbia. Beside the cigarette combustion, this technology comprises some original technical solutions, considering the organization of biomass combustion completion in fluidized bed. This technology enables using balled agricultural residues (in form it has been collected on fields), with no additional transformation (chopping, grounding), which decreases fuel cost and pollution, and contributes to energy efficiency. This type of combustion has been marked as the most suitable way of combustion of agricultural biomass in EU [13]. This technology, proven in operation in PKB, is going to be applied for CHP facility and the supplemental (reserve) biomass boiler.

The cogeneration technology is ORC - Organic Rankin Cycle based. There are a number of well known producers of the equipment. The technology is used exclusively for power generation in CHP facilities, with electric efficiency is up to 20% and overall efficiency of over 80%. More than 100 of facilities like that have been installed in EU, thus the technology could be considered proven.

Combining these two technologies would give the first experimental, demonstrational and industrial facility of the kind. It is going to be a good reference for all companies involved in the project. The facility is going to be built in PKB Company, and the company is going to supply it with the fuel (soy straw, rapeseed straw and cornstalk), which is a very convenient because they have an experience in operation with a similar boiler. Public Company "Belgrade Plants" also owned by the city of Belgrade, should take part in design and construction of the necessary infrastructure (connecting the existing system with the new one). It is necessary to note that a heat accumulator (hot water reservoir) is going to be built in scope of the boiler house in order to cover the peaks in energy consumption. It has been proven in operation with the existing cigarette type boiler in the PKB.

Boiler house element	Preliminary data and description
CHP biomass facility with the auxiliary equipment	3000-4000 kW thermal + 400-600 kW electric (net)
Hot water heavy fuel oil (or light fuel oil) boiler with the whole auxiliary equipment	3000-4000 kW (as a reserve)
Heat accumulator	Matching the peaks in energy consumption
The boiler house building (the new boiler house is going to be connected to the existing one)	Building for the accommodation of the equipment
Reconstruction of the existing boiler house and connection it with the new one	Connecting the existing and new boiler house into a functional unit
Automated bale storage and equipment for the bale manipulation	Next to the boiler house, week bale storage is planned

Table 9. The main project elements

Infrastructural element	Preliminary data and description
Pipeline for connecting the consumers with the new boiler house	≈1000 m pipeline
Heating installations in the new greenhouse	Same heating system as in the existing greenhouse
Connecting the facility to the electric grid	Installation of necessary electric poles and equipment
Communicational roads	Hard material roads
Building of a central roofed storage of biomass for annual needs	The existing storage does not meet present requirements
Machinery for gathering and transport of the biomass	Machinery for provisioning the biomass reserves in optimal conditions

Table 10. Infrastructural elements, not comprised by the business-plan

c) *Project Implementation*

Construction project subjected to the CHP plant, in the suburb of Padinska Skela, near Belgrade, presents the continuing efforts from Laboratory for thermal engineering and energy of Vinca Institute and Central European Initiative (CEI) to build such a plant in Serbia. CEI associates through implementation of projects BIOMADRIA and BIOMADRIA 2 recognized the importance of the construction of such a facility, as similar projects can be transferred to many places in Serbia, as well as in the surrounding countries, which also has an intensive agricultural production.

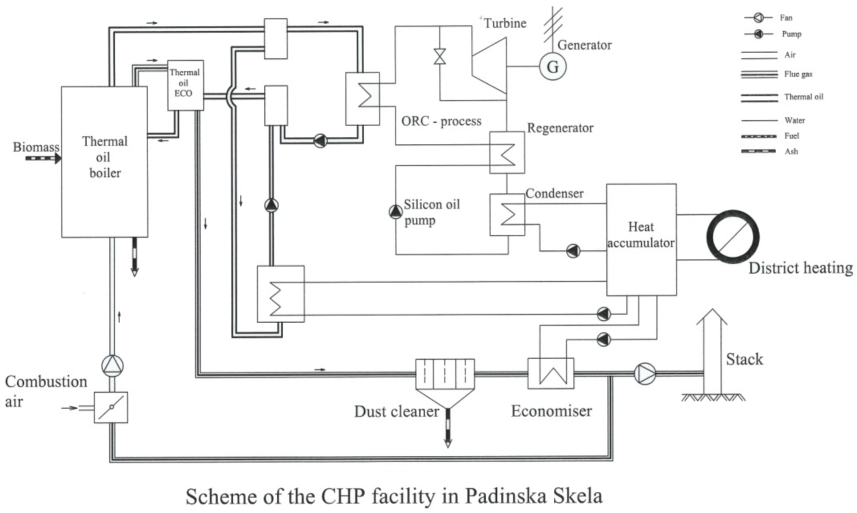

Figure 27. Functional scheme of the combined heat and power facility

The time needed for the full implementation of the project is 1.5 years starting from the date of loan approval and the first disbursement (6 months for preparations, obtaining all necessary permissions and licenses, and designing; 8 months for the building the facility, and 4 months for its commissioning). The service lifetime of the CHP plant would be 25 years, which is a commonly accepted lifetime with proper maintenance.
d) CHP facility parameters

Plant parameters are determined on basis of heat demand. In this case, the analysis is complicated by different heating dynamics of the consumers (greenhouses, office building, school, hospital). The school has a different heating dynamic compared to the hospital, and all this is completely different from the dynamics of greenhouse heating system, e.g. the greenhouse needs heating at night while hospitals and schools are heated during the day. The consumers' heat demand has been carried out in the three steps:

a. Analysis of the heat demand in the objects where people are staying: it's been carried out on the basis of data on average monthly fuel consumption, provided by Public Company "Belgrade Plants" (October and April 5%, November 11%, March 14%, December and February 20% and January 25%).

b. Analysis of the heat demand in the greenhouses: carried out on the basis of the heat demand, as well as the plants which are grown in the greenhouses. The data are averaged for a three-year period, and it show that average fuel consumption are varied between 4% in September up to 20% in January and April.

c. Analysis of the needed active power during the heating season: In order to calculate optimal power of the planned facility, the analysis of the minimal, maximal and average heat demand have been carried out for each object, as well as the overall calculation. After that, the installed thermal power of the facility can be established. The optimal solution is the one which demands minimal investment, with maximal potential gain. Analysis showed that average annual active power in the heating season is 45% of the installed power for the hospital, 38% for the school, 35% for the office building and 55% for the greenhouses.

5. Conclusions

Energy potential of renewable energy sources in the Republic of Serbia equals approximately 4.3 Mtoe/year. Biomass is deemed to be the main source of renewable energy, with estimated 2.7 Mtoe/year of energy potential, with 60% being the potential of agricultural biomass and the remaining 40% being attributed to the forest biomass. Combustion of agricultural biomass was analyzed with respect to the cigar burner combustion technology, suitable for the whole-bale combustion. Technology developed was tested in the 75 kWth hot water boiler, 1 MWth demonstration furnace and 1.5 MW industrial hot water boiler, where combustion of soybean and rapeseed straw samples was investigated. Results obtained indicated that combustion technology developed was very convenient for combustion of biomass varieties characterized by high ash melting temperatures. A cigar firing combustion system is expected to exhibit the following advantageous features: a) combustion of whole bales and whole energy crops; b) compact combustor design; c) short start up period, good load-following performance; d) profitable operation of smaller facilities (down to 1 MWth); e) division of combustion from the heat recovery system, usable not only for the provision of steam (for heat generation or CHP), but also as a hot gas generator in industrial drying applications.

Cigar burner combustion system promises a more competitive use of renewable for “green” heat and power generation as well as their use in various industrial applications. In the same time, biomass combustion in cigar burners was modeled by appropriately developed numerical model. The model developed enabled the effect of fuel moisture content on the temperature distribution in the furnace to be analyzed, as well as related emissions of harmful combustion products into the environment. Research investigation conducted has demonstrated that high combustion temperatures can be achieved in furnaces used for the combustion of agricultural biomass and that achieved CO and NOx emission levels are lower than the regulatory emission limit values defined by Serbian legislation.

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