Combustion of waste solids in a fluidized bed to generate sustainable energy

Milica R. Mladenović, Biljana S. Vučićević, Ana D. Marinković and Jovana Z. Buha Marković

University of Belgrade, Vinča Institute of Nuclear Sciences – National Institute of the Republic of Serbia, Laboratory for Thermal Engineering and Energy, Belgrade, Serbia

Abstract

Exploring alternative options to address the impending global energy crisis while taking into account environmental concerns and climate change mitigation and addressing the sky-rocketing energy demand has become urgently essential. This need is further highlighted by the significant reliance of the Republic of Serbia on imported energy sources so that the focus of its energy sector strategy is rational use of energy resources, use of renewable energy sources (RES), and waste management with satisfying environmental regulations. The use of low-calorific and waste materials in conjunction with fluidized bed combustion technology is a method to achieve all the above goals synergistically. This paper presents experimental results of combustion of several solid wastes (coal mining waste from the "RB Kolubara" complex, Serbia, paper sludge and hazelnut shells), conducted in an industrial prototype and experimental bubbling FB boiler (capacity up to 500 kW). Burning these wastes has a variety of advantages, including recovering substantial energy remaining in the waste and minimizing the overall waste volumes. The work focused on determination of furnace temperature profiles, composition of the flue gas at the furnace outlet as well as fluidization air and fuel flowrates, the minimum fluidization rate, fluidization number, maximum heat output and the transferred heat of the tested fuels. Based on the obtained results, potentials of FBC of waste fuels and the possibility of utilization of their energy potential are evaluated.

Keywords: Low-grade fuels, biomass; paper sludge; coal, hazelnut shells; bubbling fluidized bed combustor.

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1. INTRODUCTION

Rational use of limited energy resources is becoming increasingly essential, and the use of waste, low-value and non-conventional fuels holds a special place. Transition to "cleaner" combustion technologies while maintaining economic profitability is the most difficult task in the use of such fuels. In these contexts, the fluidized bed combustion (FBC) technology is highly recommended. This technology enables combustion of materials with high ballast contents and very uneven compositions while emitting less pollution [1,2]. These benefits over other conventional combustion technologies are derived from FBC properties. Namely, high thermal inertness of the fluidized bed (FB) material enables fuel to combust at temperatures of 760-900 °C with minimal NOx generation and without ash melting to contaminate the heating surfaces [1]. By injecting limestone in the FB, a direct desulphurization (up to 90 %) in the furnace can be carried out [2]. Intensive mixing of gases in the layer prevents formation of CO and unburned hydrocarbons, leading to high combustion efficiency. As drying, devolatilization and combustion processes take place simultaneously, it is not required to prepare the solid fuel in any special manner except for reduction to granulation of up to 35 mm in size. The design of these boilers does not require any movable elements or fireproof materials in the furnace. This fact and the possibility of utilizing low-grade, low-priced fuels, ensure low operational costs.

The Laboratory of Thermal Engineering and Energy of the "Vinča" Institute has decades of experience in the field of FBC and the development of furnaces and boilers of this type [2,3]. As a result of that research, a methodology for

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Corresponding authors: Milica R. Mladenović, University of Belgrade, Vinča Institute of Nuclear Sciences – National Institute of the Republic of Serbia, Laboratory for Thermal Engineering and Energy, Belgrade, Serbia

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E-mail: mica@vinca.rs

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evaluating suitability of burning a particular fuel in an FB is created. The foundation of the methodology is a combustion test of the subject fuel on a semi-industrial water-heating boiler, with the power of up to 500 kW, in steady-state modes of operation. This paper presents the results of FBC of the following solid waste fuels: coal mining waste from the "RB Kolubara" complex, Serbia, paper sludge and hazelnut shells in order to assess the possibility for combustion of these fuels in industrial-scale FB plants. The text that follows explains why these specific fuels were tested.

Exploitation and mining-geological characteristics of domestic lignite and brown lignite basins inevitably cause fluctuations in coal characteristics. Using out-of-balance coal reserves, such as fine-grained coal with high levels of ballast and low heating value, highlights the need for technology, such as FB boilers, that is less sensitive to uneven and inferior fuel composition while meeting environmental standards.

For the production and processing of paper, there are several domestic factories, including the paper factories in Belgrade, Avala Ada and Umka. One of the by-products of paper processing in these factories is paper sludge of high humidity and uneven composition, which is not suitable for recycling, but can therefore be burned in a FB with the support of a higher calorific fuel.

Finally, the Serbian Ministry of Agriculture estimates that there are 44.9 km^2 (4,479 ha) of hazel tree plantations with an annual output of about 5,000 tons of hazelnuts in shell [4]. Due to the rising demand from the confectionery industry and subsidies from the relevant Ministry of Agriculture for new, intensive hazelnut plantations with modern cultivation technology, there are ambitious plans for a multiple increase in this production. Furthermore, hazelnut shell was characterized as a solid biomass fuel with the best biomass quality index (BQI) [5]. Low moisture content due to dry processing in hazelnut production, low trace elements and ash contents as well as high carbon content and high calorific value are responsible for the best BQI of this biomass. Therefore, this paper encourages the use of this waste biomass as an exceptional fuel, as it is a natural pellet that is clean, easily stored, and doses into a furnace similarly to wood pellets.

2. EXPERIMENTAL SECTION

2. 1. Description of the experimental facility

Combustion experiments were performed in a FBC facility shown in a simplified scheme in Figure 1, along with locations of the measurement-regulation points. More about the shown bubbling fluidized bed combustor (BFBC) can be also found in [6,7].

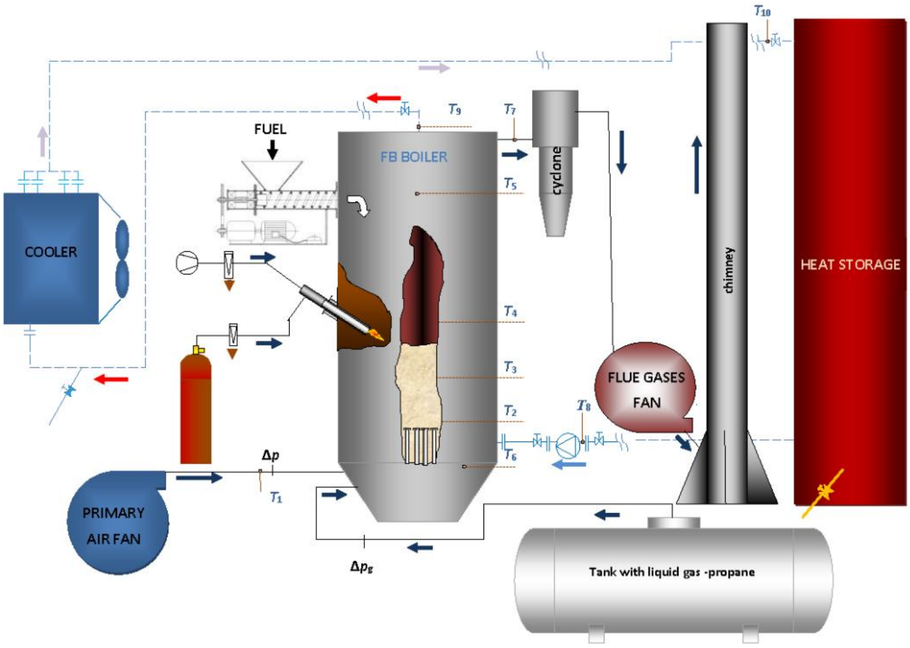


Figure 1. Scheme of the semi-industrial experimental FB facility

Vertical construction of the boiler has been adopted to stop the precipitation of flying solids [7]. Flying solids could originate from the ash or worn-out inert material flown away from the FB furnace. The experiment was conducted with fuel feeding onto the FB by a screw feeder with variable speed. The start-up burner, cooled by water, uses the piezo effect to spark a mixture of liquid gas and air. Flue gases are burned up in the vertical cylindrical space above the FB and then introduced into the vertical tubes of the 1st and 2nd set of flue pipes, which are immersed in the flue gases cooler. During the transfer from the 1st set of the tubes, a part of the flying ash is removed from the flue gas stream due to inertia. After leaving the 2nd set of tubes, flying ash removal is finished in the particle separator - cyclone. To enable experiments in long-term steady state regimes in the FB facility a heat storage unit has been added. Four ports (2 - 5) are used for thermocouples to measure temperature along the furnace height. The thermocouple positions along the gas tract (Fig. 1) are:

- T_1- air temperature on the air distributor inlet,
- T_2 - 5 cm above the air distributor nozzles (in the bed),
- T_3 - 20.5 cm above T_2 (in the bed),
- T_4 - 40 cm above T_3 (above the bed),
- T_5 - 97 cm above T_4 (above the bed),
- T_6 - flue gas temperature in the transition from the first to the second draft, and
- T_7 – flue gas temperature at the combustion chamber exit.

In addition to the temperatures mentioned, the temperatures T_8 - water entering the pump, T_9 - water leaving the boiler and T_{10} - entering the heat storage are also measured (see Fig. 1). The continuous temperature measurement system consists of the thermocouples mentioned above and the KEITHLEY recording device (a Tektronix company, USA). The flue gas composition (CO, NO_x, SO_2, O_2) was measured at the boiler outlet using the MRU Airfare Varioplus industrial gas analyzer (MRU Instruments, Germany) with associated equipment.

2. 2. Fuel characterization

The solid waste fuels tested for their suitability for combustion in a fluidized bed came from: Coal waste (KCW) from the Kolubara Basin, paper sludge (PS) from the Umka factory and hazelnut shells (HSh) from a 0.14 km^2 (14 ha) plantation in Ašanje, AP Vojvodina. Prior to the experimental investigation proximate and ultimate analyses of the subjected fuel have been performed (Table 1) to calculate the adiabatic combustion temperature (T_{adiab}), as the foundation for facility adjustment (defining the fuel and air flow to obtain a steady state on the designed combustion temperature).

Moisture and ash contents of tested fuels were determined by a thermogravimetric analyzer LECO TGA 701 (LECO, USA). The proximate analysis was done according to the standard methods [8-10]. All measurements were done in triplicate. The instrument LECO CHN 628 Series (LECO, USA) was applied to determine the total N, C, and H content in fuels the standard methods [11-13], while O content was calculated [14].

Due to the high ballast content and thus low calorific value (NCV) of the Kolubara waste coal and paper sludge, their combustion was assisted by liquid petroleum (LG) gas (propane or a mixture of propane and butane). Therefore, the composition of the equivalent fuel is also given in Table 1, calculated based on the mass fractions of primary fuel and LG, *i.e.* on the basis of their measured mass flow rates during the combustion test itself in FB.

In addition, finely granulated coal was used in combination with LG right at the beginning of the experiment with paper sludge (PS) in order to stabilize the heating process and achieve stationary parameters for the introduction of the PS into the fluidized bed (constant air flow for fluidization and reaching the bed temperature of 800 °C). After reaching the steady state, the coal was no longer used, and the measurements were performed with continuous dosing of PS and LP to support combustion.

On the other hand, hazelnut shells have a heat value that does not require the support of additional fuel; what's more, 2 kg of these shells is almost energetically equivalent to 1 m^3 of natural gas.

Ash melting temperatures (Table 2) were also determined according to standard methods [15, 16] as a part of fuel characterization in order to prevent the tested fuel's ash from sintering with the bed's inert material, which would eventually cause the fluidized bed to "fall". The only issue in this regard is the combustion of hazelnut shells. The low sintering temperature of ash from hazelnut shells [5,17] is due to their high alkali content [18]. The process of periodically refreshing the sand (replacement or cleaning, *etc.*) overcomes the problem. At temperatures of combustion around the sintering point, however, problems related to "falling" of a bed should not be expected, especially if the procedure of sand refresh is foreseen.

Table 1. Characterization of fuel - partial proximate and ultimate analyses of subject fuels and calculated adiabatic combustion temperature as a function of excess air (λ)

	Content (as received), wt.%				
	Kolubara coal waste		Paper sludge		Hazelnut shells
	Primary fuel composition	Equivalent fuel[1]	Primary fuel composition	Equivalent fuel[2]	Primary fuel composition
Moisture	36.74	35.62	46.09	35.56	12.84
Ash	39.13	37.94	13.94	10.76	1.89
Volatile matter	14.28	16.89	39.35	53.6	66.65
Char	48.98	47.49	14.56	10.9	20.51
C	15.69	17.71	15.99	31.16	45.09
H	1.78	2.28	2.68	6.08	6.53
O	6.28	6.09	20.46	15.79	33.32
N	0.22	0.21	0.73	0.56	0.22
S	0.16	0.16	0.12	0.09	0.11
NCV[3], MJ kg^{-1}	5.21	6.46	4.8	14.26	16.13
λ			T_{adiab} / °C		
1.00	1274	1386	1211	1750	1764
1.15	1186	1285	1135	1602	1605
1.30	1110	1198	1068	1479	1473
1.45	1042	1122	1008	1374	1363
1.60	984	1055	955	1284	1268
1.75	931	996	908	1205	1188
1.90	883	944	865	1135	1116
2.05	841	897	826	1074	1053
2.20	802	855	791	1019	996
2.35	767	816	758	970	947
2.50	735	781	728	925	902

[1]Calculated based on the mass fraction of liquid gas (LG) and Kolubara's coal (on the basis of their measured flows during the combustion test in FB, 0.03 : 0.97) and their elemental compositions; [2]Calculated based on the mass fraction of LG and paper sludge (0.23 : 0.77) and their elemental compositions; [3]Net calorific value

Table 2. Ash melting temperatures in an oxidizing atmosphere

	T / °C		
	Kolubara coal waste	Paper sludge	Hazelnut shells
Sintering point	960	950	845
Softening point	1130	1060	990
Semi sphere point	1280	1280	1250
Melting point	1340	1420	1270

Granulometric analysis of Kolubara waste coal small fractions (Table 3) was also performed according to standard methods [19].

Table 3. Sieve analysis of the Kolubara coal waste used in the study

Particle size, µm		Tare	Gross	Net	*M* / %	*M* / % ↓[1]	*M* / % ↑[2]
	3150	289.07	300.68	11.61	11.58	88.42	11.58
- 3150	+2000	270.02	274.97	4.95	4.94	83.48	16.52
-2000	+1000	418.14	431.23	13.09	13.06	70.42	29.58
- 1000	+ 710	213.82	218.65	4.83	4.82	65.60	34.40
- 710	+ 500	215.01	220.43	5.42	5.41	60.19	39.81
- 500	+200	255.16	303.27	48.11	48.01	12.18	87.82
-200	0	175.56	187.77	12.21	12.18	0.00	100.00
Σ					100		
Average size 940							

[1]The portion of the granulate that has passed through the sieve; [2]The portion of the granulate remaining on the sieve

2. 3. Experimental procedure

After starting the installation by combustion of liquid gas and reaching temperatures of FB required for the beginning of combustion of the examined fuel, it is gradually dosed. Empirically, based on numerous in-house tests on a semi-industrial installation with FB (Fig. 1), the temperature for the start of dosing the subjected fuel depends on the fuel quality. Thus, high-calorific value fuels such as hazelnut shells or dry wood chips can start with gradual dosing already at temperatures of approx. 600 °C, while low-calorific ones, such as PS and KCW, generally require a bed temperature of ≈ 800 °C. Once the combustion is self-sustaining, the liquid gas supply is gradually reduced and if it is possible to independently burn the primary fuel, it is shut off. By adjusting the flows of fuel and air (by frequency regulators), stationary operation of installation with pre-defined performance parameters is achieved. Temperatures along the combustor are monitored and recorded continuously.

Experiments on the BFB installation in long-term operation were performed in several operating regimes, for each of the tested fuels. The paper presents representative regimes for each of the fuels in the aforementioned range of combustion temperatures.

Quartz sand was used as the inert bed material for all fuels and regimes, with the fixed bed parameters given in Table 4.

Table 4. Summary overview of fixed bed properties (without fluidization)

Fuel	d_p / mm	ρ_{b} / kg/m^3	*Ho* / mm	Liquid gas	
				For start-up	For flame support
KCW	0.79	1475	290	propane	
PS	0.96	1380	325	propane/butane mixture	
HSh	0.76	1548	254	propane	-

d_p - average send diameter calculated on the basis of granulometric analysis of quartz sand; ρ_b - bulk density of fixed bed; *Ho* - fixed bed height.

The expressed volatility and the ballast content of the paper sludge determined the choice of the highest *Ho*, while on the other hand the low ballast content and the high calorific value of HSh determined the choice of the lowest *Ho*. The particle diameter and bulk density of the fixed bed are values determined according to standard methods [19,20] on quartz sand supplied for each test.

3. RESULTS OF MEASUREMENTS IN STEADY REGIMES OF OPERATION

After achieving steady-state conditions in the experimental FBC, measurements of flue gas composition and flow rates of fuel and air are taken (Table 5). Figures 2, 4, and 6 in the following text show temperature profiles of the flue gases in the BFB combustion chamber, while Figures 3, 5 and 7 show the measured gas concentrations during the combustion of the tested fuels. All tests were conducted at fluidized bed temperatures of 850-861 °C, which corresponds to the average operating temperature range of industrial-scale facilities [21]. These are optimal temperatures both from the aspect of reduced concentrations of NOx compounds and from the aspect of efficiency of desulfurization with limestone if it turns out that its use is necessary. During the test, a sufficient heat sink was achieved through the heat exchanger and heat storage, so that the experiment was not time-limited.

Table 5 shows the fluidization parameters and flue gas compositions for all three tested fuels, which are as follows:

- $T_{\mathrm{avr}} = T_{2\ \mathrm{avr}} + T_{3\ \mathrm{avr}}$ - measured fluidized bed average temperature (see Fig. 2, 4 and 6),
- $\dot{m}_{\mathrm{air}}$ and $\dot{m}_{\mathrm{fuel}}$ - measured fluidization air and fuel flows
- v_{mf} - minimum fluidization velocity calculated accordingly to [22],
- $N = v_{\mathrm{f}} / v_{\mathrm{mf}}$ - fluidization number, where v_{f} is measured fluidization velocity (calculated from the measured air flow for fluidization ($\dot{m}_{\mathrm{air}}$) divided by the cross-section of the FB combustion chamber),
- $P_{\max} = \dot{m}_{\mathrm{fuel}}$ NCV- maximum power output and
- $Q_{\mathrm{w}} = \dot{m}_{\mathrm{w}}\, C_{\mathrm{w}}\, \Delta T_{\mathrm{w}}$, the heat transferred to the boiler working fluid (water), where are:
    - $\Delta T_{\mathrm{w}} = T_8 - T_9$ = 16.72, 11.11 and 17.00 K, for KCW, PS and HSh, respectively
    - specific heat capacity of water C_{w} = 4.18 kJ/kg K and measured flow of working fluid-water - $\dot{m}_{\mathrm{w}}$ = 12000, 10000 and 12000 kg/h for KCW, PS and HSh, respectively

- H_{exp} - expanded bed height, *i.e.* expanded splash zone calculated according to the equations from the paper [22].

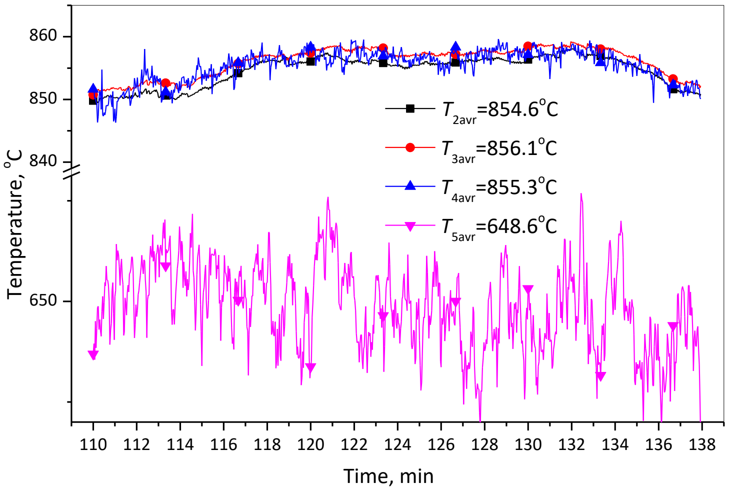


Figure 2. The temperature profile in the furnace in the KCW combustion regime

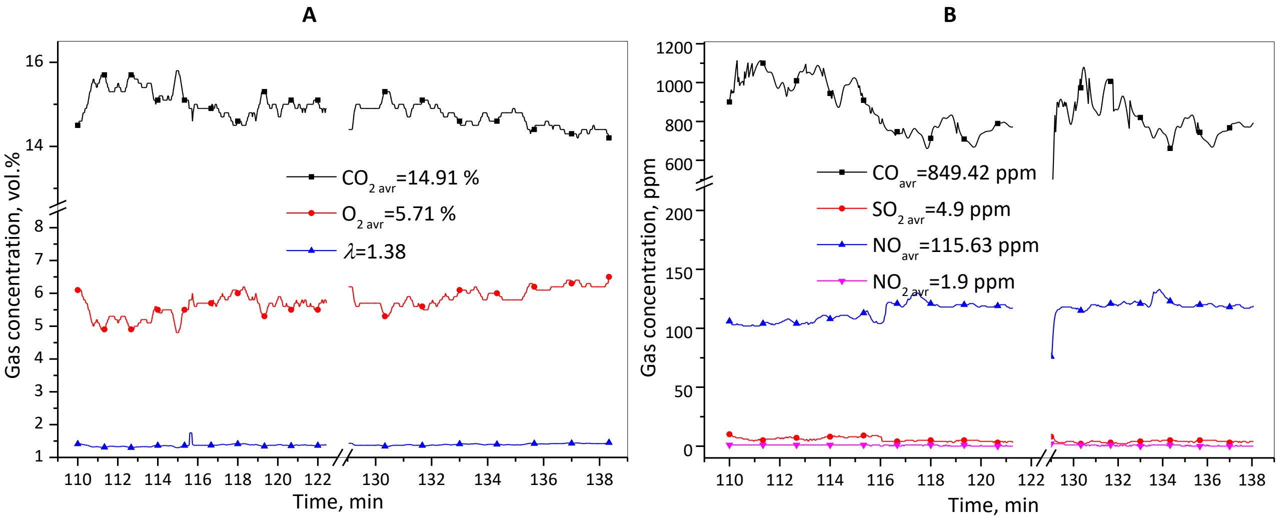


Figure 3. Gas composition in the flue gas during the KCW combustion regime expressed in A - vol.% and B - ppm

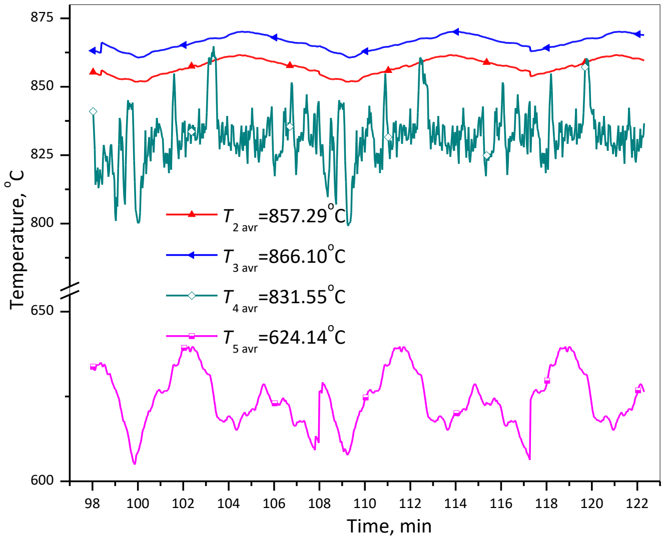


Figure 4. The temperature profile in the PS combustion regime

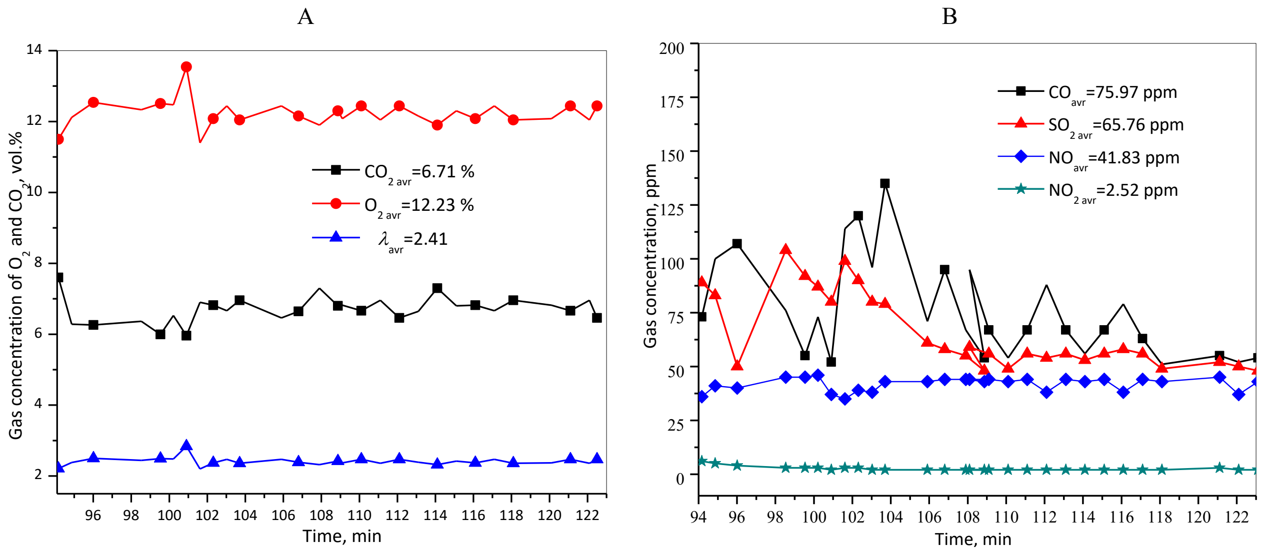


Figure 5. Gas concentration in the flue gas during the PS combustion regime

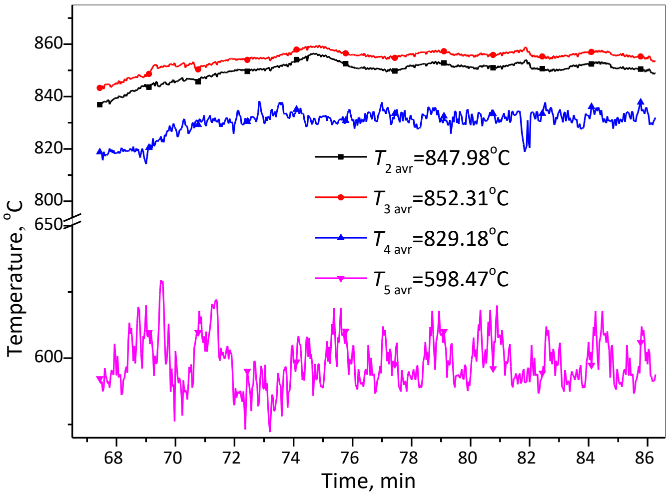


Figure 6. The temperature profile in the furnace in the HSh combustion regime

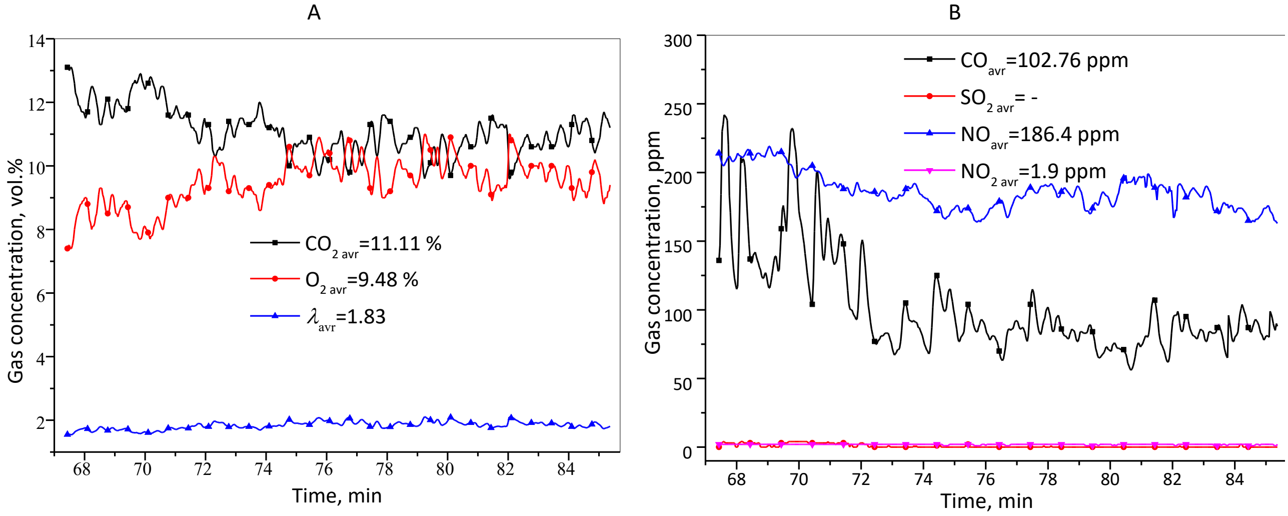


Figure 7. Gas concentration expressed in A - vol.% and B - ppm in the flue gas in the HSh combustion regime

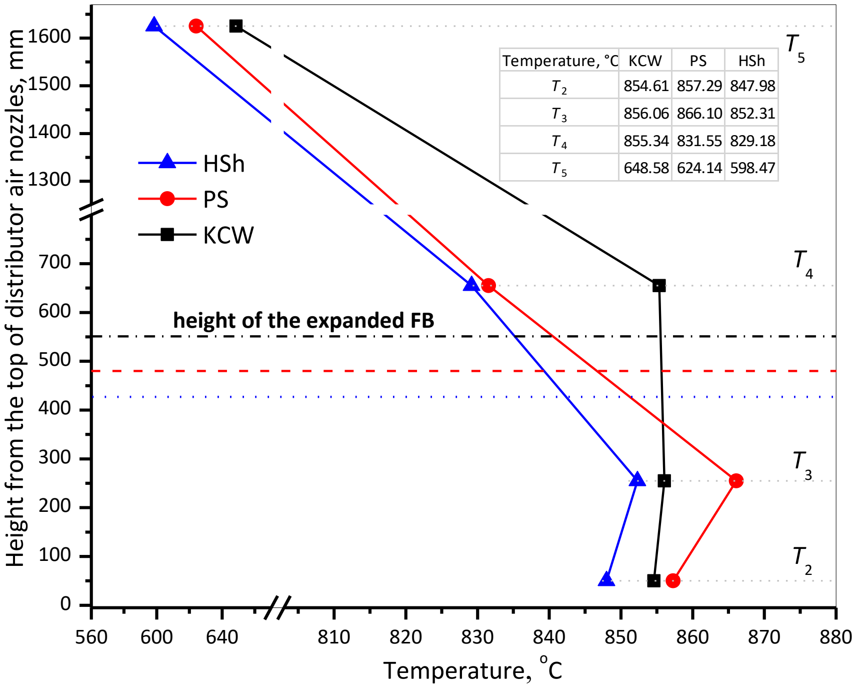
According to the Regulations in the Republic of Serbia [23], CO_{ref}, $SO_{2\ ref}$ and $NO_{x\ ref}$ are the contents of flue gas components calculated on the reference value of oxygen - $O_{2\ ref}$, for small combustion plants. Namely, the volume share of oxygen in the waste gas for existing small combustion plants that use coal, briquettes and coke from coal is 8 %, and when using other solid fuels the $O_{2\ ref}$ is 13 %. In Table 5, the measured values of CO, SO_2 and NO_x (Figs. 3, 5 and 7 right) for the reference value O_2 are converted into CO_{ref}, $SO_{2\ ref}$ and $NO_{x\ ref}$ in accordance with the Regulations [23]. The fluidization parameters were obtained at uniform combustion (bed) temperatures for each of the tested fuels.

Table 5. Fluidization parameters and flue gas composition for all three tested fuels

Fuel	FB operating parameters							
	T_{avr} / °C	$\dot{m}_{air}$ / kg h^{-1}	v_{mf} / m s^{-1}	N	H_{exp} / mm	$\dot{m}_{fuel}$ / kg h^{-1}	P_{max} / kW	Q_w / kW
KCW	855	699	0.31	7.1	551	144.40	258	233
PS	861	632	0.46	4.4	480	75.17	297	129
HSh	850	582	0.30	6.0	471	54.60	245	237

	$O_{2\ ref}$ content, %	Content, mg m^{-3}					
		CO	CO_{ref}	SO_2	$SO_{2\ ref}$	NO_x	$NO_{x\ ref}$
KCW	8	1059.79	900.84	13.99	11.89	238.36	202.61
PS	13	94.78	86.47	187.66	172.63	90.87	77.24
HSh	13	128.21	89.04	-	-	385.87	328.00

To illustrate the zone of intensive combustion, Figure 8 shows the change of average measured temperatures along the furnace height for all tested fuels.



Temperature, °C	KCW	PS	HSh
T_2	854.61	857.29	847.98
T_3	856.06	866.10	852.31
T_4	855.34	831.55	829.18
T_5	648.58	624.14	598.47

Figure 8. Measured temperature gradients along the furnace height

4. DISCUSSION

Due to the pronounced content of ballast in the fuel composition and consequently low heating values (NCV), the KCW and PS combustion experiments took place with the support of supplementary fuel (Table 1). The energy share of propane during the combustion of KCW was 22 %, and the propane-butane mixture during the combustion of PS was 74 %, so the latter process effectively was the incineration of paper sludge in a fluidized bed. The combustion process in all regimes was encompassed by the heat exchange with the water-cooled furnace surface (Q_w, Table 5), so the measured combustion temperatures in the fluidized bed ($T_2 + T_3 = T_{avr}$) are considerably lower than the theoretical adiabatic combustion temperatures for the measured excess air and the composition of the tested fuel. The adiabatic combustion temperatures calculated based on the ultimate analysis (Table 1) of the equivalent fuel for KCW and PS and the measured excess air were 1157 °C (λ = 1.38) and 953 °C (λ = 2.41), respectively. For HSh, this value was 1150 °C (λ = 1.83).

The consequence of that is also a temperature drop from the layer surface to the top of the furnace of 207 °C for KCW and PS, and 231°C, for HSh, (Fig. 8). The highest measured temperatures in the combustion chamber are the temperatures in the bed: T_2 and T_3 (Fig. 8), which indicates that the process was carried out in a way that the zone of intensive combustion was in the bed itself, at temperatures which avoid sintering of the bed inert material. The literature [24, 25] has shown that this indicates a good organization of combustion in the fluidized bed. From the same diagram it can be noticed that the difference between the temperature in the bed and above it ($\Delta T_{34} = T_3 - T_4$) increases directly with decreasing the degree of fluidization - N (Table 5), as a direct consequence of reducing the height of the expanded bed. Furthermore, a very low ΔT_{34} = 0.72 °C was recorded during KCW combustion also as a result of the removal and combustion of the predominant finer coal particles (Table 3) above the fluidized bed.

The FBC facility where the combustion experiments were performed belongs to small combustion facilities [23]. According to [23], section 29, for small combustion plants that use solid fuels in a fluidized bed, the highest prescribed limit values for solid fuels from Annex 3 of this regulation are applied, when they alternately or simultaneously use two or more types of fuel, which is practically presented in Table 6.

Table 6. Emission limit values (ELV) for small combustion facilities (150-500 kW of thermal power) [23]

Polluting matter	Type of fuel	ELV, mg m^{-3}	
		existing[1]	new[2]
CO	coal, wood, briquettes or wood pellets	2000	1000
	all gaseous fuels	100	100
NO_x	liquefied petroleum gas	200	150

[1]article 3 no. 13 of regulation [23]: an **existing** small combustion plant is a combustion plant which has a use permit issued before the entry into force of this regulation and, in the absence of a use permit, a building permit or which was put into operation before the entry into force of this regulation.
[2]article 3 no. 14 of regulation [23]: a **new** small combustion plant is a combustion plant which has a use permit issued after the entry into force of this regulation and, in the absence of a use permit, a building permit or which has been put into operation after the entry into force of this regulation.

Tables 5 and 6, as well as the fact that the limit value of SO_2 is not prescribed for small combustion plants, indicate that the emission limits have not been exceeded in any of the tests performed.

When KCW is combusted, high CO emissions must be observed regardless of whether they are within the permitted limits. This is due to a combination of factors, including high concentrations of small particles that partially burned in the space above the bed, where the temperature drops to 650 °C - insufficient for complete oxidation to CO_2, insufficient height, and a lack of insulation in the space above the bed. Following the same fuel combustion experiments, only 19.5 % of the expected amount of ash (based on the material balance) was captured in the particle separator (cyclone, Fig. 1). About 70 % of the captured ash had granulation greater than 200 µm, with a combustible content of 4.6 %. Given that the sand level was not increased due to the ash remaining in the layer, this means that 80 % of the finest ash particles were brought out of the bed, confirming the previous assertion that their after-burning and combustion occurred under unfavorable conditions above the fluidized bed. At the same time, the SO_2 emission is very low, which is logical considering the KCW composition. Given the mass participation of propane of only 3 % (energy-wise 22 %), it is a matter of burning solid fuel, so the value of $NO_{x\ ref}$ is not subject to restrictions even though it is also relatively low.

Combustion of paper sludge resulted in very low CO and NOx emissions, but an unexpectedly high SO_2 emission, considering the composition of the used PS. This is because, for this experiment, coal with a significantly higher sulfur content than PS was used to stabilize the flame during the boiler startup, so residual sulfur in the bed was included in the overall average SO_2 emission value. This is visible in Figure 5 (B). Considering the high N content in both the primary fuel (PS) and the equivalent (Tab. 1), low NOx emissions have to be noted. This suggests that the lowest degree of fluidization (N) and the highest initial bed height (Ho) in all three experiments, provided sufficient mixing in the bed to achieve the catalytic effects of ash, char and water [6,26] on reduction of nitrogen oxides.

HSh, superior to the other two used fuels in terms of its fuel characteristics (Table 1), is the only fuel that burned without the support of another fuel. At the same time, the measured emissions were below the legal limits, even though the concentration of SO_2 was at the detection limit of the gas analyzer, so this emission value is not listed in Table 5. Although the N content in the fuel is identical to that in KCW, a higher NOx emission was recorded, which is justified by the lower content of ash and char, as NOx reduction catalysts, compared to KCW.

Based on the tests carried out and the analysis of the test results, it can be concluded that combustion of both PS and HSh can be successfully carried out in an industrial plant with a similar concept to the FBC facility where the tests were performed, while a modified concept is proposed for the combustion of KCW. Namely, due to possible large variations in the quality of KCW and the effort to avoid the use of higher quality supplementary fuel, a FB boiler with an adiabatic two-part combustion chamber could be proposed. The adiabatic combustor enables the combustion of fuel whose NCV is even below 5 MJ kg^{-1}, while the two-part combustor enables a greater range of boiler powers. Adiabatic furnaces are also very important from the aspect of reducing the output concentration of CO because combustion above FB would take place at temperatures of 800 to 850 °C, which is significantly higher than the temperature obtained in our boiler during the experiments. Another solution could be the combustion of KCW in a circulating fluidized bed (CFB) [28]. In the CFB, the majority of solids leaving the furnace are captured by the gas-solid separator and recirculated back to the FB at a sufficient rate to cause a minimum degree of solids refluxing in the furnace. In this way, it is possible to completely burn particles and gases in the return loop, but with more complex fluidization dynamics and higher fluidization velocities .

The question also arises as to whether it is economically justified to dry KCW or PS first and then combust these fuels later with a lower moisture content. To answer that question, a simple analysis has been performed, defining the power of the furnace when the moisture content in the used samples decreases by 20 % (Table 7 and Fig. 9).

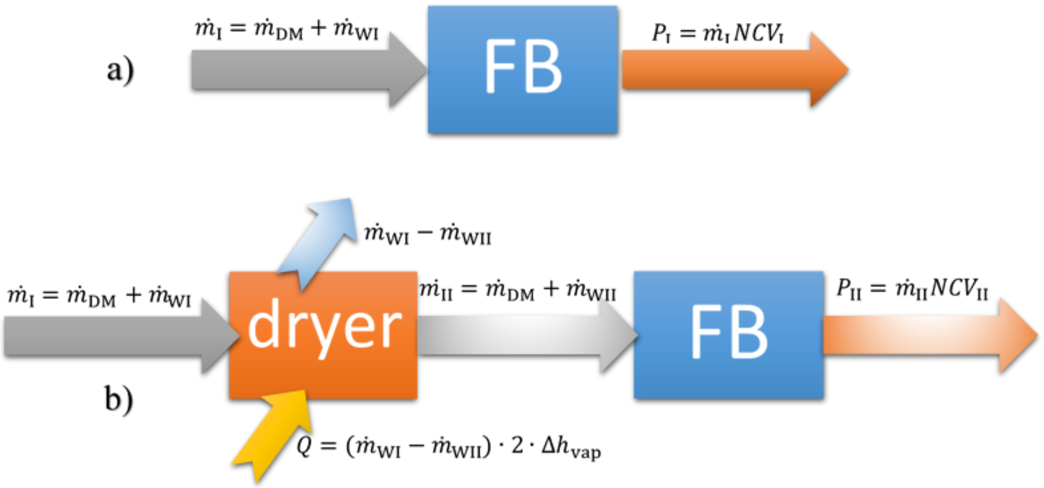


Figure 9. Scheme of the simplified analysis: a) the fuel enters the FB directly without drying; b) the fuel is first dried by removing 20 % of the original moisture (W) and then enters the FB after drying

For simplicity's sake, it is assumed that the fuel can be burned without the support of the auxiliary fuel, and that the flows of the undried fuel directly dosed into the FB and the fuel inserted first into the dryer, are the same (see Fig. 9). It is also assumed that the energy of drying is at least twice as high as the latent heat of water vaporization, Δh_{vap} =2,500 kJ kg^{-1}.

The example shows that combustion of the undried tested fuel saves 14 and 5 % of the required energy (for PS and KCW, respectively). However, in the literature it could be found that the drying energy is 3 to 20 MJ kg^{-1} of the evaporated water [27], thus the drying energy consumption could be significantly higher. The higher the moisture content in the fuel, the greater the energy savings during its direct combustion in the fluidized bed compared to the drying pre-treatment. It is crucial to note that the dryer investment and operating costs have not been considered in this straightforward analysis.

Table 7. Comparative overview of the calculated maximum power of the furnace, with non-dried and pre-dried (20 % reduced moisture content) test fuel without the auxiliary fuel use

Calculation parameters		PS		KCW	
		Non-dried (I)	Pre-dried (II)	Non-dried (I)	Pre-dried (II)
W / %		46.09	26.09	36.74	16.74
Content of dry matter, %		53.91	73.91	63.26	83.26
NCV, kJ/kg		4825	7547[1]	5217	8137[1]
Fuel flow at the FB inlet, kg h^{-1}	$\dot{m}_{I}$	58		140	
	$\dot{m}_{II}$		42.31		106.37
Flow of dry matter ($\dot{m}_{DM}$), kg h^{-1}		31.27	31.27	88.56	88.56
Amount of water removed from the pre-dried fuel ($\dot{m}_{WI}$ - $\dot{m}_{WII}$), kg h^{-1}		15.69		33.63	
Maximum power of furnace obtained from non-dried fuel (P_I), kW		77.74		202.98	
maximum power of furnace obtained from pre-dried fuel minus drying energy (P_{II} - Q), kW		66.89		193.72	
Savings[2], $\left(1-\frac{P_{II}-Q}{P_{I}}\right)100$, %		14		5	

[1]Calculated based on the fuel composition; [2]Achieved by direct combustion in FB

6. CONCLUSION

The investigation of the suitability of the tested waste solid fuels (coal mining waste from the “RB Kolubara” complex, paper sludge and hazelnut shells) for fluidized bed combustion was focused on the combustion quality, *i.e.* combustion efficiency, and the combustion stability, as well as on the fulfilment of the environmental protection criteria.

From the point of view of combustion organization, PS and HSh are burned with an intensive combustion zone in the bed, while combustion of the finest KCW fractions took place above the bed. As far as compliance with environmental norms is concerned, they were not exceeded in any test. However, high CO emissions were also detected during the combustion of KCW, although these were within the permissible limits. It can therefore be concluded that the combustion of both PS and HSh can be successfully carried out in an industrial plant with a comparable concept to the FBC facility in which the tests were carried out, while a modified concept is recommended for the combustion of KCW.

Aside from successfully combusting fuel with a high ballast content with the support of more calorific fuel, a simple analysis revealed that combusting wet fuel directly in a fluidized bed is more cost-effective than drying it first and then combusting it.

The paper demonstrated that by burning the investigated and similar waste materials in a fluidized bed, the principles of sustainability are realized - the waste issue is solved through their energy utilization (economic benefits), while meeting environmental standards.

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Sagorevanje čvrstih otpadnih materija u fluidizovanom sloju za generisanje održive energije

Milica R. Mladenović, Biljana S. Vučićević, Ana D. Marinković i Jovana Z. Buha Marković

Univerzitet u Beogradu, Institut za nuklearne nauke "Vinča"-Institut od nacionalnog značaja za Republiku Srbiju, Laboratorija za termotehniku i energetiku, Beograd, Srbija

(Naučni rad)

Izvod

Istraživanje alternativnih opcija za rešavanje aktuelne globalne energetske krize uzimajući u obzir zabrinutost za životnu sredinu i klimatske promene, kao i rešavanje naglo rastuće potražnje za energijom postaje suštinska neophodnost. Ova potreba je dodatno naglašena značajnim oslanjanjem Republike Srbije na uvozne energente i strateškim fokusom njenog energetskog sektora, koji podrazumeva racionalno korišćenje energetskih resursa, korišćenje obnovljivih izvora energije i upravljanje otpadom uz zadovoljavanje ekoloških propisa. Upotreba niskokaloričnih i otpadnih materijala u kombinaciji sa tehnologijom sagorevanja u fluidizovanom sloju je metod za sinergijsko postizanje svih gore navedenih ciljeva. U radu su prikazani eksperimentalni rezultati sagorevanja više vrsta čvrstog otpada (kolubarski otpadni ugalj, papirni mulj i ljuske lešnika), sprovedeni u industrijsko-demonstracionom i eksperimentalnom kotlu sa fluidizovanim slojem (kapaciteta do 500 kW). Spaljivanje ovog otpada ima niz prednosti, uključujući iskorišćenje značajne preostale energije u otpadu i minimiziranje ukupne količine otpada. U radu su određeni temperaturni profili u fluidizovanom sloju u ložištu, sastav dimnih gasova na izlazu iz ložišta, kao i protoci vazduha za fluidizaciju i goriva, minimalna brzina fluidizacije, stepen fluidizacije, maksimalna snaga ložišta i predata toplota, za ispitivana goriva. Na osnovu ovih rezultata data je procena kvaliteta sagorevanja otpadnih goriva u fluidizovanom sloju i mogućnosti iskorišćenja njihovog energetskog potencijala.

Ključne reči: goriva lošeg kvaliteta, biomasa; papirni mulj; ugalj; ljuske lešnika; ložište sa mehurastim fluidizovanim slojem