COMBUSTION OF REFINED RENEWABLE BIOMASS FUEL (RRBF) IN A FLUIDIZED BED

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ABSTRACT: Within the framework of EU-Life+ research project MARSS (Material Advanced Recovery Sustainable Systems), the outlet stream of a mechanical-biological treatment plant for the processing of mixed municipal solid waste is further processed to produce RRBF (Refined Renewable Biomass Fuel). The material is dry and has (very) small particle sizes below 40 mm, which makes it impossible to be burnt in standard grate firing systems. The main purpose was to examine whether RRBF is a suitable fuel for bubbling fluidized bed combustion for the decentralised production of combined heat and power. RRBF was fed into a bubbling fluidized bed combustion plant with a nominal fuel input of 100 kW in 3 combustion test runs. Proximate and ultimate analyses were performed for original RRBF and fly ash. Fuel analyses showed high ash contents between 25 and 37 weight-%, while the lower heating value lay in the range of 10.5 – 12.9 MJ/kg. The ash softening temperature was above 1,150 °C and therefore no bed agglomeration was observed. Combustion at around 900 °C could be maintained even without preheating of the combustion air. The carbon content of the fly ash was about 1 %, which indicates complete combustion in the bubbling fluidized bed with sufficient residence time. The content of phosphorous in the fly ash was above 1 % and therefore this is an interesting material for prospective phosphorous recovery, potentially together with sewage sludge or ash from sewage sludge combustion. RRBF is a suitable solid fuel for fluidized bed combustion.

KEYWORDS: fluidized bed, solid fuel, waste recovery, ash characterization

1. INTRODUCTION

Since 1999 the EC directive 1999/31/EC, called the “Landfill Directive”, is in force (European Council, 1999). It defines BMW as biodegradable municipal waste and sets out targets for the reduction of such waste being deposited on landfill. Compared to 1995 the amount of BMW

Proceedings Venice2016, Sixth International Symposium on Energy from Biomass and Waste, 14 - 17 November 2016
Great School of St. John the Evangelist, Venice, Italy

deposited on landfill must be reduced to 75 % by the end of 2000, to 50 % by the end of 2003 and to 35 % by the end of 2010. For countries with a very high share of landfilled municipal waste compared to other disposal options, exemptions of 4 additional years were granted by the EU to these countries to provide extra time to fulfil the set goals. However, in 2013 the European Environment Agency stated in their report (European Environment Agency, 2013) that several European countries still do not meet the requirements of the Landfill Directive. As waste incineration, which is one possible and technologically highly sophisticated option for disposal of BMW, is quite expensive, alternative waste treatment processes including mechanical biological treatment (MBT) have been developed. Such MBT processes can either treat mixed municipal solid waste (MMSW) to such an extent that the remaining part is considered suitable for landfill disposal (European Council, 1999). This means that the biological degradation of the majority of the BMW contained in the MMSW has taken place to an adequate level. Alternatively, the MMSW is only dried and stabilized by the MBT process leaving the majority of the biomass contained in MMSW in the product. With such a MMSW pre-treatment it is possible to produce a solid fuel for energy recovery and replacement of fossil fuels in power stations and other applications (Clausen et al., 2013).

The EU-Life+ project Material Advanced Recovery Sustainable System “MARSS” was coordinated by I.A.R. Department of Processing and Recycling, RWTH Aachen University, and carried out together with the partners Regionale Entsorgungsgesellschaft mbH (RegEnt), pbo Ingenieurgesellschaft mbh, Parthenope University of Naples and Universitat Autonoma de Barcelona. The aim was to develop an innovative process for the production of Refined Renewable Biomass Fuel (RRBF) from the output of an existing MBT-plant based on the Herhof Stabilat® process operated by RegEnt at Mertesdorf in Germany (Clausen et al., 2013; Giani et al., 2014).

It was first discovered from screening analyses that the majority of the biogenic part is contained in the fraction with particle size below 40 mm. In order to further increase the calorific value and to reduce and recover the minerals and metals, a process of sieving and density sorting (air sifting) was developed. After this processing the streams containing mainly biogenic material were mixed to form the final RRBF fuel product.

As solid fuels with such small particle sizes below 40 mm containing a high amount of fines cannot be combusted in classical grate stoker furnaces, its combustion should be tested in a bubbling fluidized bed reactor. The solid fuel had to be characterized regarding heating value and ash melting behaviour as well as an assessment of its suitability for use in power stations based on fluidized bed combustion testing campaigns had to be made.

2. METHODS AND MATERIALS

2.1 Origin of stabilized MMSW

The MMSW is collected in the city of Trier, Germany, and 4 surrounding counties with 523.000 inhabitants. As there is no separate collection of biogenic waste in place, the collected MMSW contains a high amount of organic matter and high moisture content of about 40 %. The MMSW is stabilized (biologically dried) using a Herhof Stabilat® process with a capacity of 225.000 metric tonnes per year to produce high calorific refuse derived fuels (RDF). The process is designed to reduce the water content in the material by about 30 % points. The stabilized material is marketed as RDF to different customers, e.g. industrial co-generation power station Andernach. The whole process is described in detail elsewhere (Monzel et al., 2015).

2.2 Production of RRBF in MARSS demo-plant

A side stream of the product coming from the MBT plant is fed to the MARSS demo.plant with a capacity of 6 to 10 tonnes per hour. The biogenic material is enriched and cleaned by a cascade of mechanical screening and separation steps. The first screening takes place in a drum sieve with mesh size of 40 mm. Only the screen underflow is processed further, as this stream contains the majority of biogenic material. This material is further screened in two consecutive flip-flow screens to fractions with particle sizes between 12 and 40 mm, 3.5 and 12 mm and below 3.5 mm. The first fraction is then air-sifted, the heavy fraction composed of mainly mineral matter and metals is removed and the light fraction of this separation is processed in a second air-sifting. Here, the light fraction is mainly composed of fossil based plastic foils and is therefore discarded. The second fraction with the smaller particle sizes is also air-sifted and the heavy fraction containing the inerts is removed. In the end, the stream with the smallest particles is taken as is and mixed with the light fraction from the medium-sized material and the remaining part of the larger material (heavy fraction of the firstly produced light fraction). The process is described in detail elsewhere (Giani et al., 2016).

2.3 Test rig for RRBF combustion campaigns

The combustion of RRBF was tested in a small-scale bubbling fluidized bed gasification/ combustion test rig at Fraunhofer UMSICHT. The reactor has an inner diameter of 400 mm in the lower part (bubbling fluidized bed) and 600 mm in the upper part (freeboard). The height of the lower part is 1.4 m and that of the upper part 1.7 m. The vessel is thermally insulated by a refractory lining, which comprises of three layers of different materials with an overall thickness of 300 mm. On the outside of the reactor vessel, additional 100 mm of rock wool are installed for better thermal insulation. The maximum allowed temperature of the refractory lining is 1050 °C, which limits the combustion temperature to about 950 °C (to ensure sufficient long-lasting protection of the lining). The reactor is equipped with 8 temperature sensors over the reactor height and 7 differential pressure measurements against reactor exit pressure. The latter allows the detection of fluidized bed height by the axial pressure profile. In addition, the pressure at the reactor exit relative to ambient pressure is measured. As depicted in Figure 1, heat exchanger modules can be installed in the fluidized bed and in the freeboard to withdraw combustion heat. For the experiments conducted with RRBF, these modules were not installed.

The nominal capacity of the test rig is 100 kW fuel input. The dosing of the feedstock is performed by a screw feeder from the dosing hopper which is controlled by a frequency converter. After calibration, the input mass flow rate can be calculated from the set-point of the frequency converter. Below the dosing screw feeder, the RRBF passes through a rotary valve which constitutes the pressure lock between fluidized bed and atmosphere. A screw feeder (wall and shaft cooled), which is located below the rotary valve, injects the RRBF into to the lower third of the bubbling fluidized bed. The flue gas from combustion leaves the reactor through a cyclone, where most of the fly ash is separated and collected in a small bin which must be emptied repeatedly depending on the amount of ash. To secure full combustion, the gases pass through a combustor equipped with a natural gas burner.

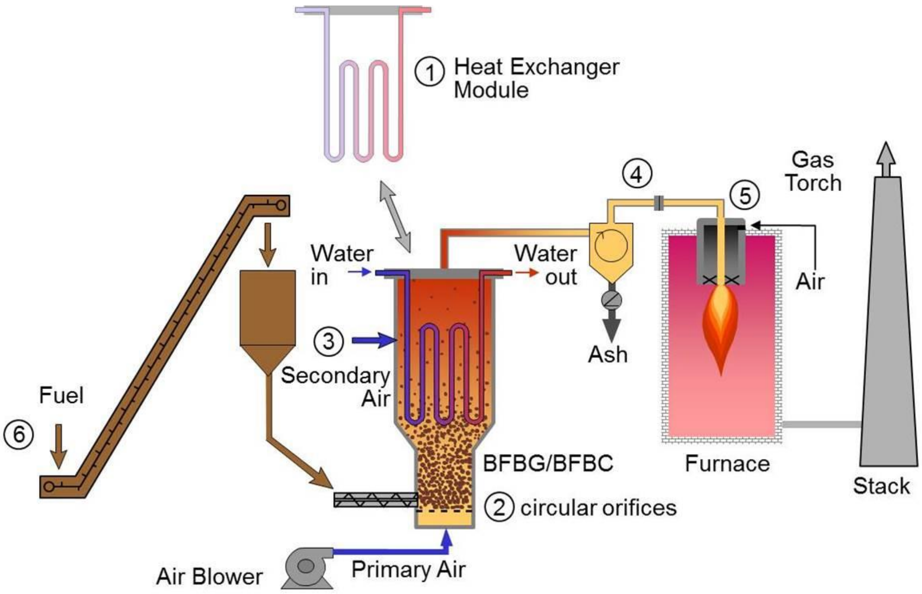


Figure 1. Schematic drawing of combustion plant.

2.4 Secondary treatment of RRBF to fit to combustion test rig feeding system

The RRBF testing samples were delivered by RegEnt in 3 batches in January, May and September 2015 to cover varying composition of originally collected mixed solid municipal waste and different ambient conditions (temperature and moisture content of ambient air used for drying) over the year. The delivered material was contained in FIBCs (Flexible Intermediate Bulk Container - BigBag) with a weight of approximately 300 kg each. Samples were taken directly after delivery and proximate and ultimate analyses were performed.

In order to prepare for the combustion tests, calibration runs with the dosing screw feeder were executed. Dosing tests with RRBF as originally received in the 1st batch were not successful in the fuel handling system of the small scale fluidized bed combustion plant. Due to bad flowing behaviour of the material, the fuel flow was neither constant over time with a fixed rotation speed of the dosing screw nor reproducible. Additionally, the original material contained several unwanted items that would block the rotary feeder in real operation due to oversize. Some of these items were handpicked from one of the delivered FIBCs during dosing tests and are shown in Figure 2. Due to the presence of these foreign bodies, and with the aim to improve the quality of the RRBF, the material was transported to RWTH (Department of Processing and Recycling) for secondary milling by means of a single shaft shredder with an installed screen of 30 mm. After this secondary treatment, the dosing tests and calibration runs were successful, and the fraction of biogenic material in the large particle stream (12 – 40 mm) of 2nd and 3rd batch were then shredded to 30 mm by RegEnt directly at MARSS demonstration plant in Mertesdorf before final mixing of the 3 RRBF streams.

Figure 2. Picture of oversize items handpicked from originally delivered RRBF.

2.5 Experimental procedure for combustion test campaigns

For the combustion test runs an original filling of 130 ltrs. silica sand (particle size from 400 – 800 µm) was used as bed material. After each combustion test, the bed material was removed from the reactor, sieved with a screen of 1 mm mesh size and 130 ltrs. of screen underflow was used for the next combustion test.

A complete test run for RRBF combustion comprises of 4 phases. In phase I the fluidized bed reactor is heated up with electrical heaters for the fluidization air. Once the maximum temperature with electrical air heating is reached, phase II commences with the addition of propane to the inlet air (in a burner), which further increases the temperature. When the temperature in the fluidized bed exceeds 400 °C, further heating up is achieved by the addition of and combustion of industrial wood pellets in phase III (where the addition of propane has been stopped). After reaching the desired bed temperature of around 900 °C, the solid fuel is changed from industrial wood pellets to RRBF in phase IV. Figure 3 shows the development of the 8 temperatures measured with thermocouples installed in the reactor exemplary for the 1st combustion test run performed in February 2015. The points of measurement are from bottom (TIR 4.0) to top (TIR 4.40), while the lower 4 ones are installed in the bed area and the upper 4 ones in the freeboard. It can be clearly seen that the 4 thermocouples installed in the bed area show the same temperature over the whole experiment (TIR 4.0 to TIR 4.22 are the apparently two highest lines; 3 of them are superposed), while there is a clear temperature drop in the freeboard, which becomes even more pronounced after the ignition of combustible gas components in the lower part of the freeboard (when the bed temperature reaches approximately 600 °C, around 123 h). TIR 4.30 and TIR 4.33 are the two lines in the middle of the temperature range and represent the temperatures in the lower part of the freeboard, while TIR 4.35 and TIR 4.40 are the lowest to lines in the diagram and represent the temperatures in the top part of the freeboard.

The fly ash from the cyclone was collected over the complete combustion test and samples were taken afterwards. Again, proximate and ultimate analyses were performed. In addition, samples from the originally delivered RRBF were ashed at 550 °C and the ash melting behaviour was analysed in comparison to the melting behaviour of fly ash.

After the combustion tests the screen overflow (mesh size 1 mm) of the bed marterial was separated manually into metals and non metals and a rough mass balance for ash-forming components was prepared.

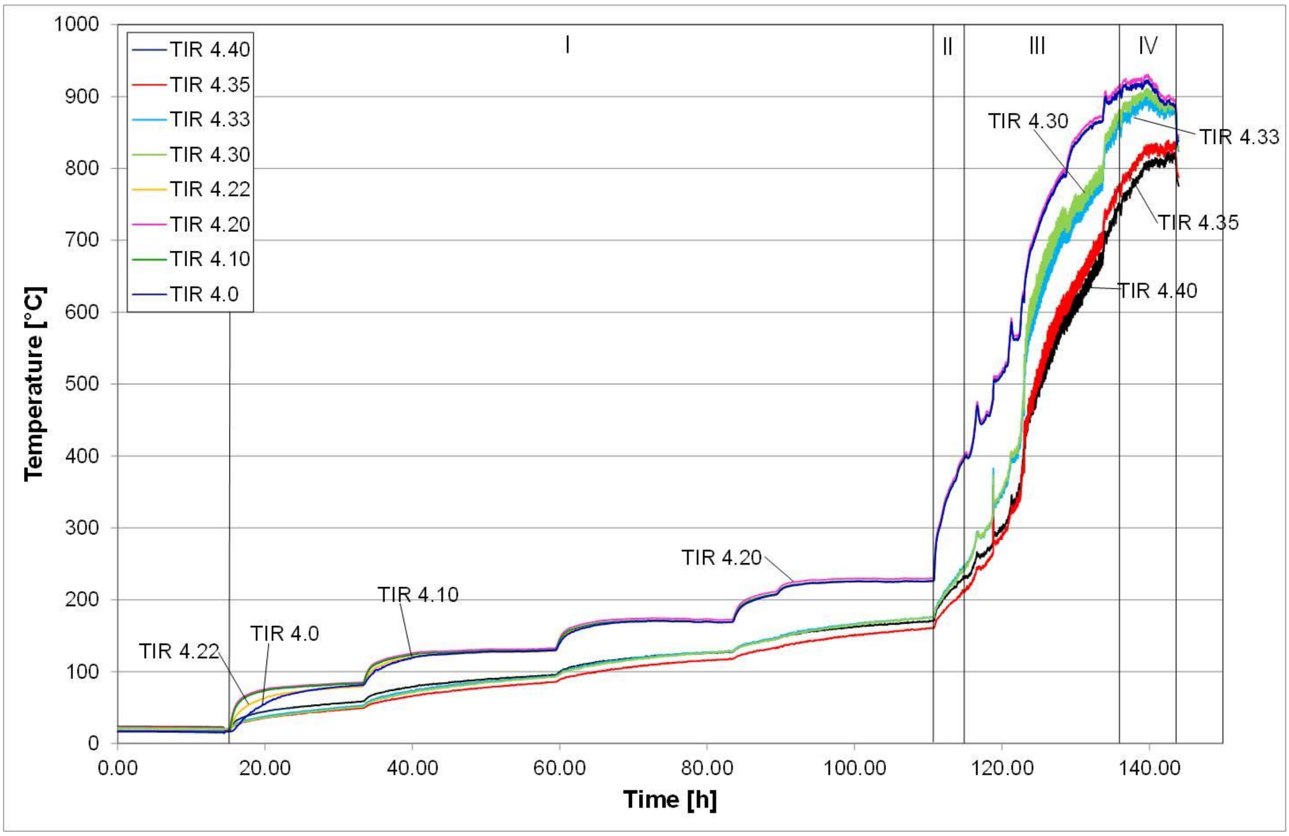


Figure 3. Development of temperatures in fluidized bed over complete experiment time, 1st combustion test run.

3. RESULTS AND DISCUSSION

3.1 Fuel Analyses

Proximate and ultimate analysis were performed for the three batches of RRBF and results are summarized in Table 1. For the utilization of RRBF as fuel in combustion processes the high ash amount between 22 and 32 % and the low lower heating value of 10.5 to 12.9 MJ/kg, both values with regard to original substance, are the most critical values. The high ash content requires frequent bed ash remocal from the combustion reactor and the low heating value might give rise to the need of hich caloric additional fuel. The variation in the lower heating value based on dry and ash-free matter is only 4.7 %, although water and ash content, which directly influence original matter heating value, vary widely.

The average composition of woody biomass can be represented by the following values: 50 % carbon, 6 % hydrogen and 44 % oxygen based on dry ash-free mass (Perry et al., 1984). As can be seen from Table 1 the carbon and hydrogen content of all batches of RRBF are higher and the oxygen content is lower than the average values for biomass. This is an indication for some remaing plastics based on fossil resources in the preparation of RRBF. Analyses showed that the fossil based content is in the range of 6 to 9 % (Giani et al., 2016).

Table 1. Proximate and ultimate analysis of RRBF.

	Original matter			Dry matter			Dry ash-free matter		
Batch	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Water [%]	13.2	14.99	24.5						
Ash [%]	23.3	31.88	21.74	26.84	37.5	28.8			
C [%]	33.18	29.58	29.07	38.23	34.8	38.5	52.26	55.68	54.07
H [%]	5.55	5.58	5.89	4.7	4.6	4.2	6.42	7.36	5.9
N [%]	1.56	1.19	1.43	1.8	1.4	1.9	2.46	2.24	2.67
O [%]	35.23	29.39	41.86	27.08	18.9	26.6	37.01	30.24	37.36
S [%]	0.38	0.48	0.3	0.43	0.56	0.4	0.59	0.90	0.56
Cl [%]	0.8	0.71	0.91	0.92	0.84	1.2	1.26	1.34	1.69
Na [ppm]	6,290	5,326	5,616	7,250	6,265	7,439			
K [ppm]	864	5,728	4,938	996	6,738	6,541			
P [ppm]	2,150	1,471	2,103	2,480	1,730	2,786			
LHV [MJ/kg]	12.88	10.45	11.1	15.21	12.7	15.5	20.79	20.32	21.77

3.2 Combustion tests

When the combustion/gasification test rig was designed at Fraunhofer UMSICHT it was only intended to use woody biomass with a low ash content (below 1 %) as fuel. For plant operation with such materials no bed inventory withdrawl is necessary during operation. Therefore, the screw conveyor installed at the bottom of the reactor to remove the bed inventory was operated only after experiments, when the bed material already was at or near ambient temperature. As mentioned in section 3.1 the high ash amount in RRBF requires frequent bed inventory withdrawl, as inert material accumulates in the reactor. The bed height increases during combustion of RRBF, which can be seen by an increasing bed pressure drop. Design specifications limit this bed pressure drop to 100 mbarg. This value was reached in the first combustion test run after the combustion of 260 kg of RRBF after 9.8 h. The attempt to start the screw conveyor to remove bed material at high temperature to continue combustion operation failed: due to the expansion of the bed material in the screw the friction increased so much, that the electrical engine was not able to turn the screw. Therefore the combustion test of the first RRBF batch ahd to be terminated at that time.

Prior to the 2nd combustion test run a colling jacket was installed ath the ash removal screw. Unfortunately this measure did not solve the problem, as the ash removal screw could not be started during operation when required. After 10.4 h of RRBF combustion the design limit of 100 mbarg bed pressure drop was reached. To find the operation limit of the test plant the combustion test run was continued until the backflow of combustion flue gas through the injection screw due to the high pressure difference became too high, as the fines from the RRBF were separated above the rotary valve and blown together with the sealing air and the reverse flowing flue gas to the environment (see section 2.3). This real operation limit was reached after 15.1 h and the test was stopped. The bed pressure drop at that time could not be measured, as it exceeded the upper range value of the differential pressure transducer which was 118.5 mbarg.

The second measure to overcome operation problems with the ash removal screw conveyor was the installation of a butterfly vlave between the combustion reactor and the screw inlet. With this butterfly valve installed the ash removal screw could be switched on before the heating-up of the bed material and kept running all the time without the necessitiy to cool the screw jacket. To remove bed material from the combustion reactor during operation the butterfly valve was opened for approximately 2 min and then closed again to stop the sand flow. With this modification the 3rd combustion test run could be conducted with the bed pressure drop kept within the design limits until other difficulties occurred, which caused termination.

Figure 4 shows the development of reactor temperatures during the combustion period of RRBF for the 3rd batch (temperatures are the same as in Figure 3; the highest "two" lines represent the bed temperatures TIR 4.0 to TIR 4.22; the temperatures in the lower part of the freeboard are shown by the two lines in the middle TIR 4.30 and TIR 4.33 while the two lowest lines represent the temperatures in the upper part of the freeboard TIR 4.35 and TIR 4.40). Although the temperature in the fluidized bed and in the lower part of the freeboard is quite constant just under 950 °C over the whole time, the upper part of the freeboard only reached steady state temperature conditions during the last 5 to 8 hours of the experiment, which can be seen by the steady increase in temperature before 127 h of total experiment time.

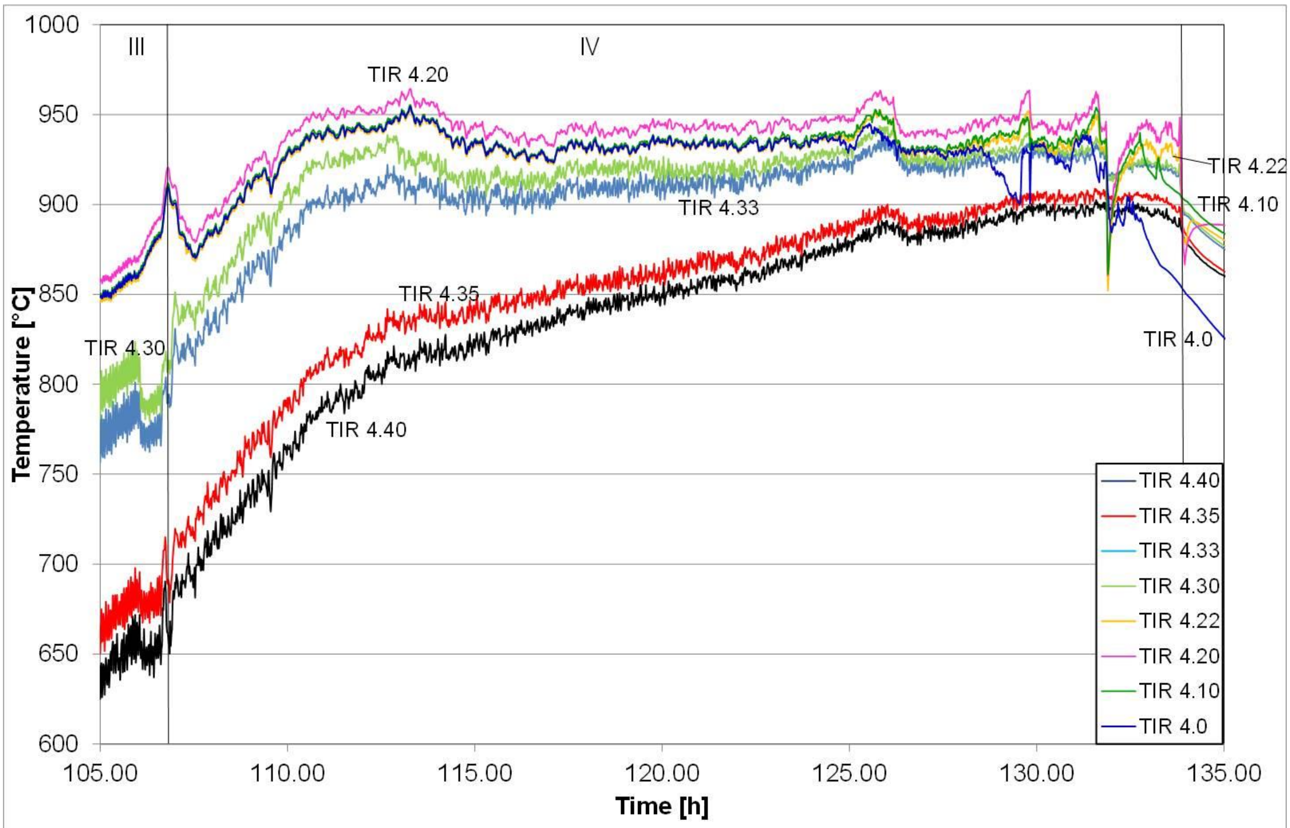
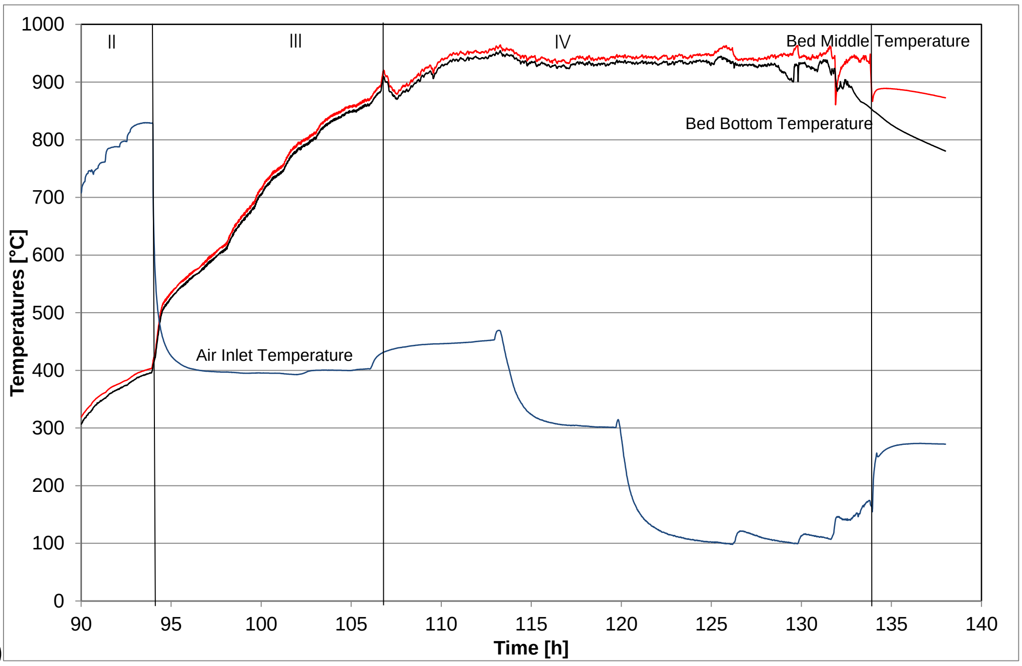


Figure 4. Development of temperatures in fluidized bed for combustion period, 3rd test run

To further discuss results from 3rd combustion test run Figure 5 gives–in addition to bed bottom temperature TIR 4.0 and bed middle temperature TIR 4.20–the air inlet temperature (Figure 5a), fuel input, bed pressure drop and reactor head pressure (Figure 5b) for the combustion of industrial wood pellets (III) and RRBF (IV).

a) 

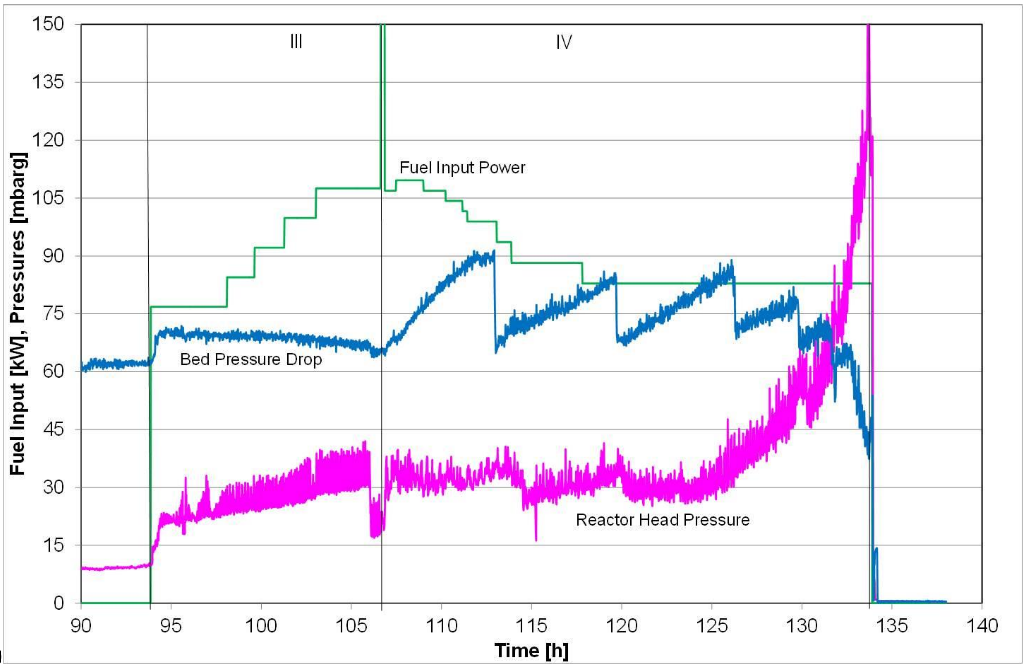
b) 

Figure 5. Development of characteristic parameters during combustion period, 3rd test run
a) bed bottom temperature, bed middle temperature and air inlet temperature;
b) fuel input, bed pressure drop and reactor head pressure.

After changing from propane combustion in phase II to combustion of industrial wood pellets (phase III) with electrically preheated air after 94 h of total experiment time the air inlet temperature dropped from 825 °C to 400 °C. The fuel feed rate in phase III was increased stepwise from 76 kW to 106 kW to evenly increase the bed temperature until the desired temperature for RRBF combustion near 900 °C. After fuel switch to RRBF in phase IV, the fuel feed rate had to be reduced stepwise from 107 kW to 83 kW to keep the bed temperature below 950 °C. Later the electrical air preheating was first reduced and finally, after 120 h of total experiment duration, completely switched off in order to keep the bed temperature within the operation limits. The thermocouple is installed directly in the air box underneath the air nozzles, which explains the remaining elevated temperature above 100 °C.

From figure 5b it can be seen that during wood pellet combustion the bed inventory is slightly decreasing as wood pellets nearly contain no ash and the originally fed sand is slowly attrited and the fines are then carried out of the reactor together with the flue gas. This can be concluded from the slight decrease in bed pressure drop during phase III. After the fuel switch from industrial wood pellets to RRBF a large amount of minerals and ash was fed to the reactor, which did not leave it at the top together with the flue gas, as can be deduced from the steep bed pressure drop increase after about 107 h of total experiment time. To restrict the bed inventory build-up the newly installed butterfly valve was operated repeatedly after 113 h, 119.7 h, 126.4 h, 129.9 h, 131.7 h and 133.1 h of total experiment time to remove parts of the bed.

After about 128.5 h of total experiment time a partial breakdown of fluidization inb the lower part of the bed was noticed, because the bed bottom temperature started to deviate more and more from the bed middle temperature. This could be attributed to two reasons: firstly, the RRBF contained a considerable amount of larger mineral particles (e.g. glass fragments), which could not be fluidized by the air flow and accumulated in the bottom part of the reactor. The amount of bed inventory removal was not enough to completely discharge these large particles from the reactor. Secondly, the reactor head pressure started to increase exponentially after about 125 h of total experiment time. As a consequence the outlet pressure at the side channel blower supplying the combustion air to the reactor increased and thus reduced the volumetric air flowrate, which in turn further contributed to the observed breakdown of fluidization. Finally, the repeated bed material removal at 131.8 h and 133.1 h was not enough to reduce the level of stationary particles below the feeding screw; therefore the combustion experiment had to be aborted at this point after 133.8 h of total experiment time.

A later inspection of the plant revealed that the increase in reactor head pressure was caused by fly ash deposits in the flue gas piping downstream of the cyclone. Evidently the installed cyclone was inadequate for the separation of the whole fly ash and the unusual long piping to the combustion chamber was steadily filled with fly ash from all consecutive combustion experiments. The free cross section of the flue gas pipe became so small that it affected the flow through the pipe and as a consequence led to increased head pressure in the reactor only in the last experiment.

3.3 Ash balance

Figure 6 shows pictures of residual material after the 1st combustion test run. Figure 6a depicts the fly ash from the cyclone, which had a mean diameter of 60 µm. The bed inventory completely removed from the reactor after the combustion test run was sieved with a screen of 1 mm mesh size. The mesh minus consisted of the original bed material silica sand mixed with the fine ash particles larger than the fly ash. The mesh plus completely consisted of ash, minerals and metals. A considerable number of metal pieces were found in this fraction (Figure 6d). The largest pieces contained in the mesh plus fraction (Figure 6b) were broken glass covered with a thin layer of sand and ash particles (Figure 6c). Bed agglomerates could not be discovered in the bed inventory after all three combustion test runs. The occurrence of bed agglomarates would have rendered RRBF unfeasible for fluidized bed combustion, because this would inevitably lead to a sudden breakdown of fluidization instead of gradual breakdown which occurred due to the high amount of large inert particles in the fuel. Even a high amount of coarse inert particles can be removed from the reactor in large scale application, if the fine particles serving as bed material are reinserted to the reactor after sieving, while for sticky particles with the tendency to form agglomerates this is not possible.

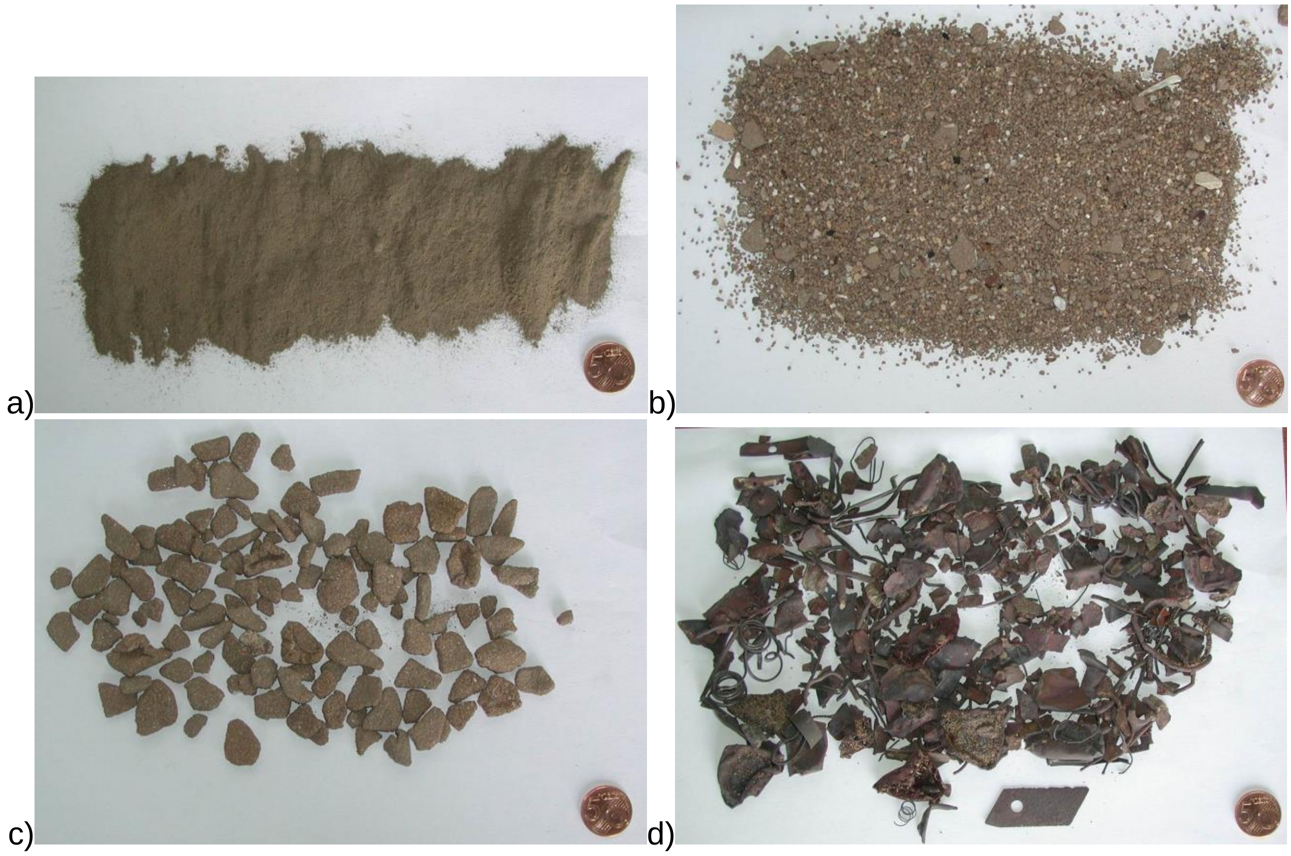


Figure 6. Ash from combustion test run – a: fly ash, b: sieve retention from 1mm screenc: glass particles handpicked from b, d: metal particles handpicked from b.

Table 2 gives the mass balance of the ash fraction fed to the combustion reactor for test runs 1 and 3, as the 2nd combustion test run was not evaluable with respect to ash mass balance. The values are in good agreement taking into account the achievable accuracy of the measurement.

Table 2. Ash mass balance

Batch	1st	3rd
RRBF fed to combustion reactor [kg]	260	860.5
Total ash content in RRBF [kg]	61	187
Fly ash from cyclone (Figure 6a) [kg]	16	49.39
Fly ash from cyclone (Figure 6a) [% of total ash]	26	24:8
Metal pieces from bed withdrawl [kg]	-	0.499
Metal pieces from bed withdrawl [% of total ash]	-	0.27
Metal pieces from bed inventory [kg]	0.4	0.185
Metal pieces from bed inventory [% of total ash]	0.7	0.1
1 mm mesh plus from bed withdrawl (Figure 6b) [kg]	-	27.733
1 mm mesh plus from bed withdrawl (Figure 6b) [% of total ash]	-	14.8
1 mm mesh plus from bed inventory (Figure 6b) [kg]	22	34.237
1 mm mesh plus from bed inventory (Figure 6b) [% of total ash]	36	18.3
1 mm mesh minus (by balance) [kg]	22.6	77.96
1 mm mesh minus (by balance) [% of total ash]	37	41.7

In addition to the estimated overall ash balance ultimate analysis of the fly ash for all 3 batches were performed. The bed ash is dominated by the initial bed material silica sand, so it was not analysed. The results of fly ash analysis are given in Table 3. The first remarkable result is represented by the very low carbon and hydrogen contents, which indicate a good burnout of the RRBF in fluidized bed combustion. Only the fly ash from the 3rd test run reveals a slightly increased carbon content, which is caused by the lower airflow towards the end of the experiment due to a reduced oxygen overspill in the combustion zone induced by the lower airflow towards the end of the experiment (see section 3.2). Additionally, the high amount of phosphorus above 1 % of weight in all 3 samples of fly ash is remarkable. This turns the fly ash into a potential source for this crucial element for the future.

Table 3. Ultimate analysis of fly ash (n.a. not analysed, n.d. not detected).

Batch	1st	2nd	3rd
Ash [%]	95.1	97.3	n.a.
C [%]	0.77	0.6	1.9
H [%]	0.05	0.1	<0.1
N [%]	0.52	n.d.	0.1
S [%]	0.41	1.08	0.75
Cl [%]	2.03	3.23	2.0
Na [ppm]	21,600	24,600	22,300
K [ppm]	36,400	39,700	16,400
P [ppm]	11,100	14,500	10,900

3.4 Ash melting behaviour

Although no bed agglomeration was observed in the combustion test runs, the ash melting behavior of the original matter as received (after secondary milling for the 1st batch) and the fly ash was analysed to determine the risk of bed agglomeration for later industrial implementation. The results are summarized in Table 4. Despite an even temperature distribution in the combustion reactor, as fluidized beds are quite well mixed, the risk exists that low melting eutectic mixtures from ash components and bed material (especially in the case of silica bed material) soften and lead to agglomeration. Therefore it is important to know, how far the starting point of such effects is from the medium operating temperature. There seems to be no real difference in ash melting behavior between original material and the mixture of attrited silica sand and fuel ash, which makes up the fly ash. The addition of silica sand as bed material gives no rise to the formation of lower melting eutectics compared to the original matter, which justifies the use of cheap silica sand as starting bed material. The first relevant temperature assessed is the Shrinkage Start Temperature SST, which in all cases lies around 1,150 °C. This is more than 200 °C above the medium operating temperature of the combustor and therefore no sintering or agglomeration of bed material must be feared in industrial implementation.

Table 4. Ash melting behaviour of original RRBF and fly ash after combustion

	Ash of RRBF			Fly ash		
Batch	1st	2nd	3rd	1st	2nd	3rd
Shrinkage Start Temperature (SST) [°C]	1,151	1,150	1,148	1,168	1,159	1,152
Deformation Temperature (DT) [°C]	1,180	1,172	1,172	1,180	1,170	1,196
Hemisphere Temperature (HT) [°C]	1,187	1,175	1,175	1,183	1,177	1,197
Flow Temperature (FT) [°C]	1,214	1,190	1,190	1,192	1,186	1,215

4. CONCLUSIONS

After solving first difficulties with the transport behaviourof the delivered RRBF samples in the feeding system of the combustion test rig by additional milling to smaller particle sizes, the material could be reproducibly handled by the feeding system. The fuel analysis of the 3 different batches revealed a broad variation especially in ash and moisture content of the material, but the combustion behaviour showed no significant difference. Fluidized bed combustion of RRBF was not only able to fully combust material with small particle sizes that would fall between classical grate furnaces, but also enables the combustion of material with a lower heating value between 10.5 and 12.9 MJ/kg without the necessity for additional high calorific fuel or air preheating due to the high heat capacity of the bed inventory. Furthermore, for an industrial implementation of RRBF fluidized bed combustion it is possible to produce steam from the flue gases leaving the combustor. This steam can either be used to supply process heat or via turbine produce electricity. The operability of such an installation will not be threatened by the risk of bed agglomeration, as proven by the combustion tests. The fly ash collected with a cyclone contains considerable amounts of phosphorus (above 1 %), which make this material interesting for later phosphorus recycling maybe together with sewage sludge.

The RRBF produced with the MARSS pilot plant was proven to be a suitable fuel for fluidized bed combustion in industrial scale. Although small combustion test installations like the one used in these trails have adversely large surface-to-volume ratio and thus lose high amount of heat to the surroundings, combustion at temperatures above 900 °C could be maintained even without preheating of combustion air and without high calorific supplemental fuel. Special care must be taken with respect to the content of large particles in the fuel material. Due to their presence a higher amount of bed ash removal needs to be performed with subsequent sieving and re-injection of the fine particles below 1 mm to the fluidized bed combustion reactor to insure continuous operation. Also fly ash removal from the flue gas needs some attention, although the unfortunate blocking of the flue gas pipe at the end of the 3rd combustion test run was a peculiarity of the pilot plant (long flue gas pipe with several 90° bends) and would not occur to this extent in industrial plants.

AKNOWLEDGEMENTS

The work presented in this paper was financed by a subcontract from the EU Project LIFE11ENV/DE/343 MARSS “Material Advanced Recovery Sustainable Systems”.

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