COMBUSTION OF RRBF IN A BUBBLING FLUIDIZED BED

T. SCHULZKE[1,*], J. WESTERMEYER[1,2] and K. HORNSBY[3]
[1] Fraunhofer UMSICHT, Department Biorefinery & Biofuels, Oberhausen, Germany.
[2] now at: Kofler Energies Ingenieurgesellschaft mbH, Heidelberg, Germany
[3] RWTH Aachen, Department of Processing and Recycling, Aachen, Germany.
*Corresponding author: tim.schulzke@umsicht.fraunhofer.de, +49 208 8598-1155

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

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.

The fuel analysis 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 below 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.

1- INTRODUCTION

Since 1999 the EC directive 1999/31/EC, called the "landfill directive", is in force [1]. 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 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 to fulfil the goals. However, in 2013 European Environment Agency stated in their report [2] 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) were developed. Such MBT processes can either treat the mixed municipal solid waste (MMSW) to such an extent that the remaining part is suitable for landfill disposal [a]. This would mean biological degradation of the majority of the BMW contained in the MMSW. Alternatively, the MMSW only is dried and stabilized by the MBT process leaving the majority of the biomass contained in MMSW in the product. With such a MMSW pretreatment it is possible to produce a solid fuel for energy recovery and replacement of fossil fuels in power stations and other applications [3].

The EU-Life$^+$ project Material Advanced Recovery Sustainable System "MARSS" was performed by I.A.R. Department of processing and recycling of solid waste material of RWTH Aachen University, Regionale Entsorgungsgesellschaft mbH RegEnt, pbo Ingenieurgesellschaft mbh, Parthenope University of Naples and Universitat Autonoma de Barcelona with the aim to develop a process for the production of Refined Renewable Biomass Fuel (RRBF) from the output of an existing MBT-plant according to the Herhof Stabilat® process operated by RegEnt at Mertesdorf in Germany [3, 4]. It was first discovered from screening analysis that the majority of the biogenic part is contained in the fraction with particle size below 40 mm. To further increase the calorific value and to reduce the minerals and metals a process of sieving and density sorting (air sifting) was developed. The fraction 0 – 40 mm, coming from the MBT process, is further sieved and separated to 3 fractions: 0 – 4 mm, 4 – 11.5 mm and 11.5 – 40 mm. The 2nd and 3rd size fractions were air sifted. The 1st fraction with very small particles was then joined with the light fractions from sifting of the two other size fractions to give the RRBF [4].

As solid fuel with such small particle size with a high amount of fines cannot be combusted in classical grate stoker furnaces, its combustion should be tested in bubbling fluidized bed reactor. The solid fuel had to be characterized regarding heating value and ash melting behaviour and the suitability for power stations based on fluidized bed combustion tested.

2- MATERIALS AND METHODS

The combustion of RRBF was tested in a small scale bubbling fluidized bed gasification/ combustion test rig. 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 (for 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. 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.

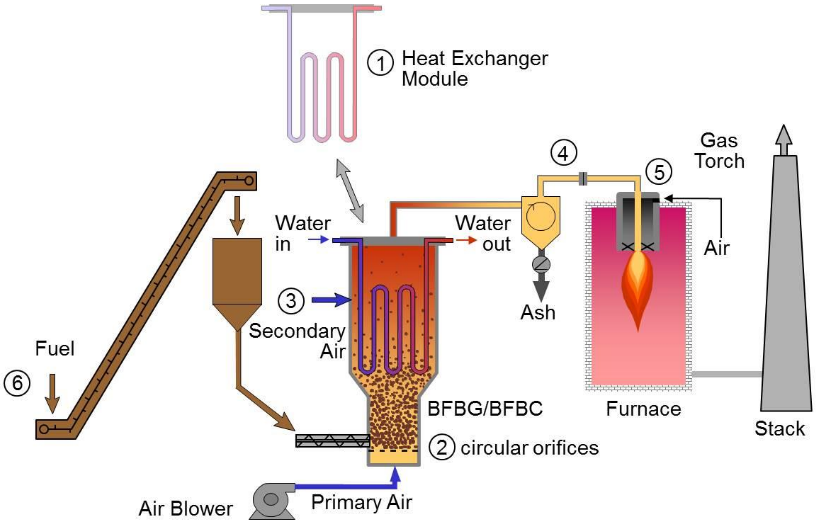

Figure 1: Schematic drawing of combustion plant.

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 setpoint 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.

The RRBF was 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. Directly after delivery samples were taken and proximate and ultimate analyses were performed.

To prepare 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 (no straight lines in Figure 2) nor reproducible (see deviation between lines 100%A and 100%B in Figure 2). Additionally, the original material contained several 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 shown in Figure 3. Therefore, 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.

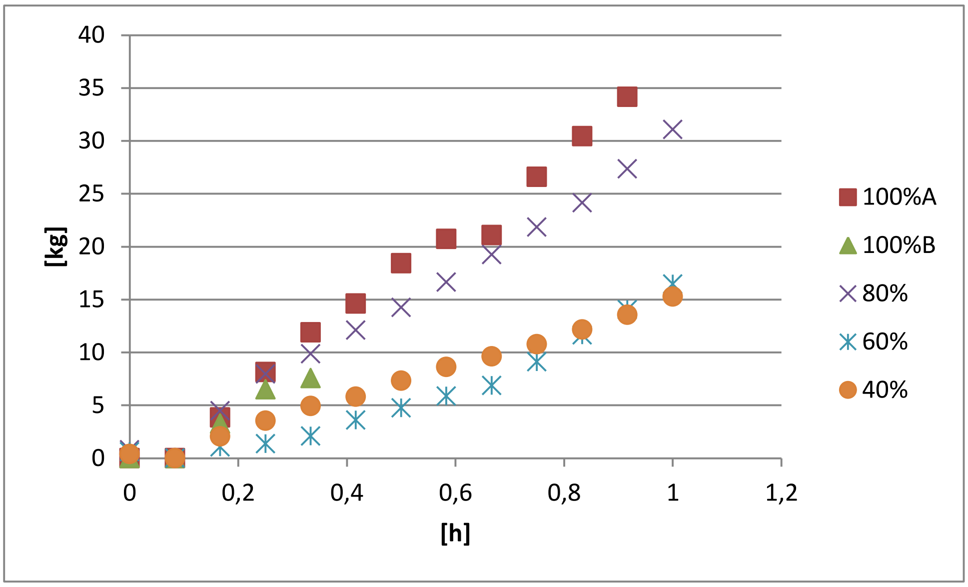

Figure 2: Calibration test of dosing screw with 1st batch as delivered.

Figure 3: Picture of oversize items handpicked from originally delivered RRBF.

After this secondary treatment the dosing test and calibration runs were successful and the 2nd and 3rd batch were already shredded by RegEnt at MARSS demonstration plant in Mertesdorf.

For the combustion test runs an original filling with 130 ltrs. of 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 sections. In section 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, in section II propane addition to the inlet air (in a burner) further increases the temperature. When the temperature in the fluidized bed exceeds 400 °C, the further heating up is done by the combustion of industrial wood pellets in section III (the propane addition is stopped). After reaching the desired bed temperature of around 900 °C, the solid fuel is changed from industrial wood pellets to RRBF in section IV. Figure 4 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 seen clearly 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 in the freeboard there is a clear temperature drop, 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.

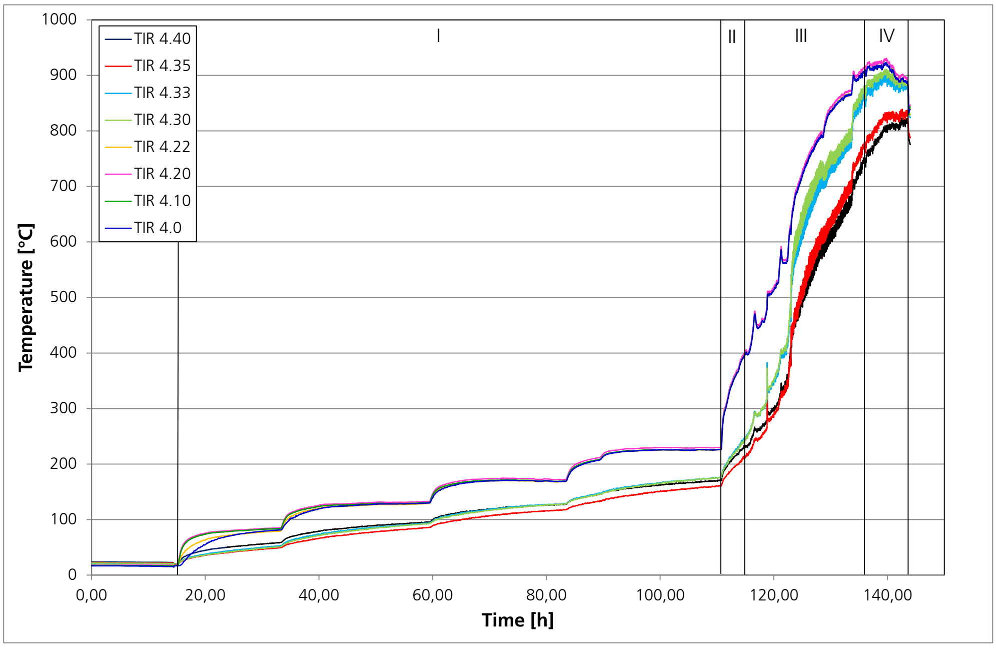

Figure 4: Development of temperatures in fluidized bed over complete experiment time, 1st combustion test run.

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. Additionally, 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 was separated manually into metals and non metals and a rough mass balance for ash-forming components was prepared.

3- RESULTS AND DISCUSSION

Table 1 gives the results of proximate and ultimate analyses for the three batches of RRBF as delivered by RegEnt. The most relevant values for assessing the suitability of such fuel for fluidized bed combustion systems are the high ash content of 22 to 32 % and the lower heating value of 10.5 to 12.9 MJ/kg, both values with regard to original substance. Although water and ash content vary widely, the lower heating value of the fuel varies only 4.7 % based on the remaining dry ash-free matter.

Woody biomass has an overall composition of 50 % carbon, 6 % hydrogen and 44 % oxygen based on dry ash-free mass [5]. Higher carbon and hydrogen content as well as lower oxygen content on dry ash-free basis in the RRBF analysis indicate that the removal of plastics during the preparation of RRBF was not complete and part of it remained in the delivered fuel.

	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

Table 1: Proximate and ultimate analysis of RRBF.

After secondary milling of the RRBF delivered as 1st batch the calibration tests in the dosing screw always showed straight lines for all tested setpoints on the frequency controller as shown in Figure 5. The slope of each line gives the mass feed rate in kg/h for a certain setpoint for the frequency controller of the dosing screw. Figure 6 depicts these mass feed rates as a function of setpoint for frequency controller. Again, the points show a straight line with acceptable accuracy. So the mass feed rate can be calculated with a linear relationship from the setpoint for the frequency controller of the dosing screw. As 0 to 100 % for the setpoint correspond to 0 to 50 Hz on the frequency controller, the mass feed rate can be correlated to be 1.2588 kg h^{-1}/Hz for the 1st batch of RRBF.

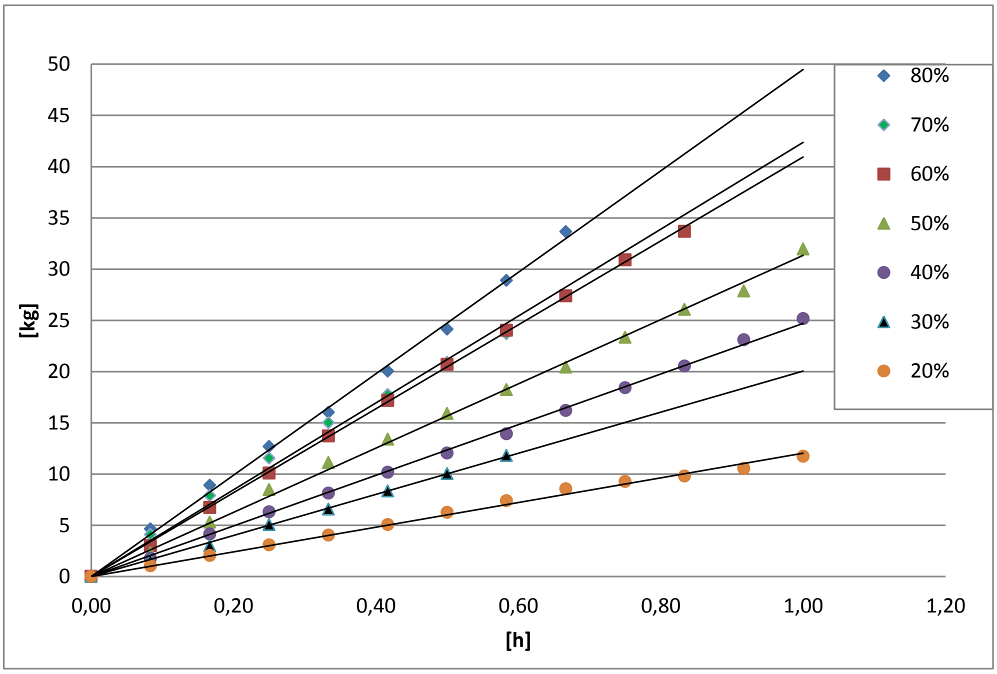

Figure 5: Calibration test of dosing screw with 1st batch after secondary milling and sieving – transported mass as a function of time.

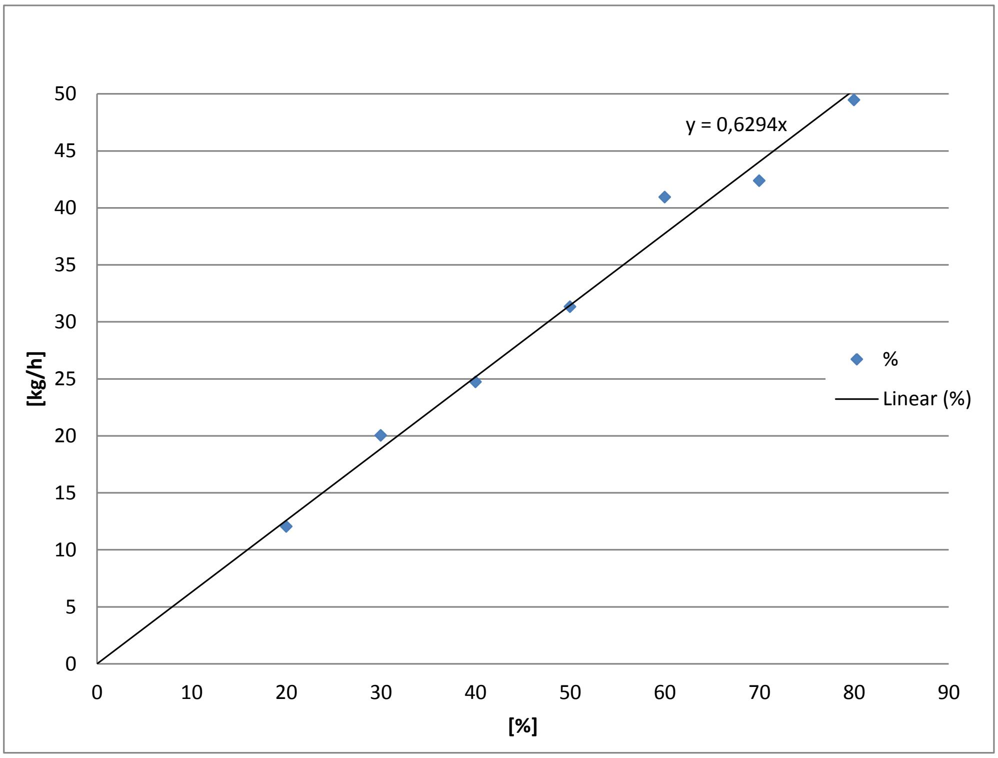

Figure 6: Calibration test of dosing screw with 1st batch after secondary milling and sieving – mass feed rate as a function of setpoint for frequency controller.

This calibration procedure was repeated with RRBF delivered as 2nd and 3rd batch and the general behaviour could well be reproduced. Due to the different water and ash content the absolute value for the mass feed rate differed. It amounted to 1.876 kg h^{-1}/Hz for the 2nd batch and 1.734 kg h^{-1}/Hz for the 3rd batch.

Due to the high ash content in the RRBF the bed inventory increases continuously over time in combustion section IV (see Figure 4) during the combustion test runs. The test rig was originally designed for the gasification or combustion of wood with very low ash content compared to RRBF used in this test runs. Therefore the bed removal screw installed at the test rig was tested in former experiments only after the experiments, when the bed already was cooled down to approximately ambient temperature. During the first combustion test the bed removal screw could not be switched on due to thermal expansion of the bed material in the entrance of the screw. This increased the friction so far, that the engine was not able to turn the screw. The bed pressure drop in the combustion reactor, which is directly coupled to the bed height, should not exceed 100 mbarg. This value was reached after the combustion of 260 kg of RRBF and therefore the combustion test run was terminated after 9.8 h RRBF combustion.

To overcome the problem with ash removal during the combustion period a cooling jacket was installed at the ash removal screw prior to the 2nd combustion test run, which then took its course similar to the 1st one. Despite the addition of the cooling jacket, the ash removal screw could not be started in section IV, as still the starting torque of the electric engine was too high. The combustion test was continued for 15.1 h, although the bed pressure drop rose above 100 mbarg after 10.4 h. The test run had to be stopped at the point where 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 released to the surrounding (bed pressure above 118.5 mbarg; which is the upper range value the used of differential pressure transducer).

Prior to the 3rd combustion test, a butterfly valve was installed between the ash pipe of the combustion reactor and the ash removal screw. The ash removal screw was switched on already in cold condition (before the heating up of the bed was initiated) and kept running all the time. The butterfly valve was used to release bed material together with coarse particles to the ash removal screw and to stop the sand flow again. This change in plant construction served the purpose and bed material could be repeatedly removed from the fluidized bed combustion reactor in order to keep the bed pressure drop within the target range. With this modification the plant operation in RRBF combustion could be extended until other difficulties occurred.

Figure 7 shows the development of reactor temperatures during the combustion period of RRBF (temperatures are the same as in Figure 4; 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 still increasing temperature before 127 h of total experiment time.

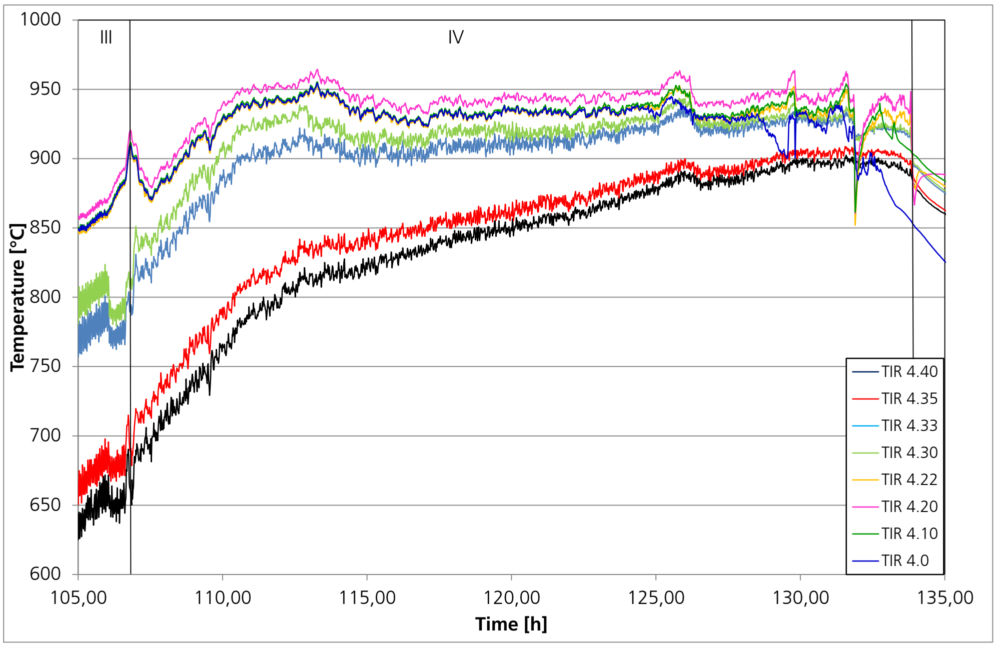

Figure 7: Development of temperatures in fluidized bed for combustion period, 3rd test run.

Figure 8 depicts in addition to bed bottom temperature TIR 4.0 and bed middle temperature TIR 4.20 the air inlet temperature, fuel input, bed pressure drop and reactor head pressure for the combustion of industrial wood pellets (III) and RRBF (IV). After switching off the propane addition for reactor heating after 94 h of total experiment duration, the air was still preheated electrically. Therefore the air inlet temperature drops from 825 °C to 400 °C during wood pellet combustion. During RRBF combustion, the electrical air heaters were reduced and after 120 h of total experiment duration switched of totally. The remaining slightly elevated temperature of the combustion air in the reactor inlet compared to ambient temperatures is due to heat transfer from the fluidized bed, as the thermocouple is installed in the air box directly underneath the air nozzles. The feed rate of the wood pellets was increased stepwise from 76 kW to 106 kW to evenly increase the bed temperature. After fuel switch to RRBF the fuel feed rate had to be reduced stepwise from 107 kW to 83 kW to keep the bed temperature below 950 °C. During wood pellet combustion with nearly no ash occurrence the bed pressure drop is slightly decreasing due to bed attrition. The attrited bed material left the rector as dust with the flue gas, thus reducing the bed inventory and subsequently bed pressure drop. After fuel switch to RRBF, which contains high amount of ash, a steep increase in bed pressure drop could be noticed as consequence of bed inventory build-up. This bed material increase must be withdrawn by opening the butterfly valve at the reactor bottom for about 2 min after 113 h, 119.7 h, 126.4 h, 129.9 h, 131.7 h and 133.1 h of total experiment time.

The operation of the combustion test rig continued quite well until approximately 125 h of total experiment time. At that time the reactor head pressure started to increase exponentially, which was not noticed by plant operators. As a consequence the outlet pressure at the side channel blower supplying the combustion air to the reactor increased and thus reducing the volumetric air flow rate. This is one reason, why a partial breakdown of bed fluidisation could be noticed after 128.5 h of total experiment time. With increasing reactor head pressure and decreasing volumetric air flow rate the bed pressure drop decreased with increasing rate towards the end of the experiment.

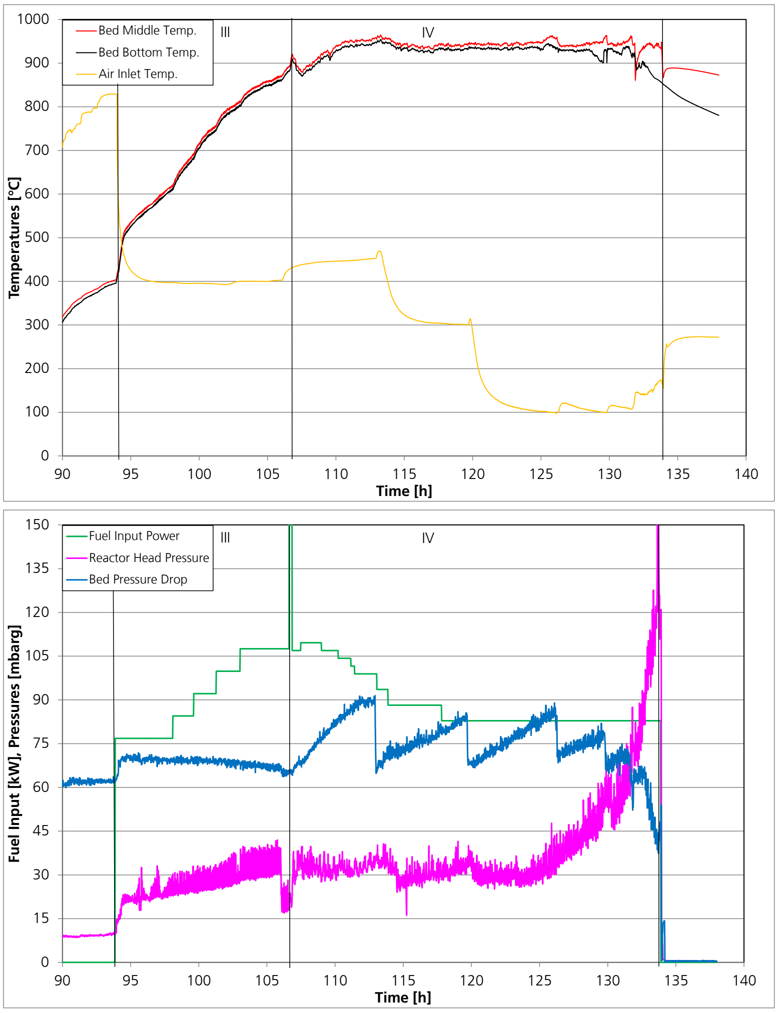

Figure 8: Development of characteristic parameters during combustion period, 3rd test run
a) bed bottom temperature, bed middle temperature and air inlet temperature;
b) fuel input, bed pressure drop and reactor head pressure.

The partial breakdown of fluidisation became obvious to the plant operators, when the bed bottom temperature, which was always approximately 10 °C below the bed middle temperature, increasingly deviated from the bed middle temperature after 128.5 h. In addition to the above mentioned reduction in air flow large inert particles introduced to the reactor with the fuel accumulated in the bottom part of the bed. They were too large to be fluidized by the (decreasing) air flow and too many to be completely withdrawn with the bed material. After 131.7 h of total experiment time the breakdown of fluidisation reached the thermocouple TIR 4.10, which is installed directly opposite the fuel feeding screw. The repeated bed material removal at 131.8 h and 133.1 h was not enough to reduce the level of not moving particles below the feeding screw; therefore the combustion experiment had to be aborted at this point after 133.8 h of total experiment time.

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 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 combustion experiments. Only in the last experiment 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.

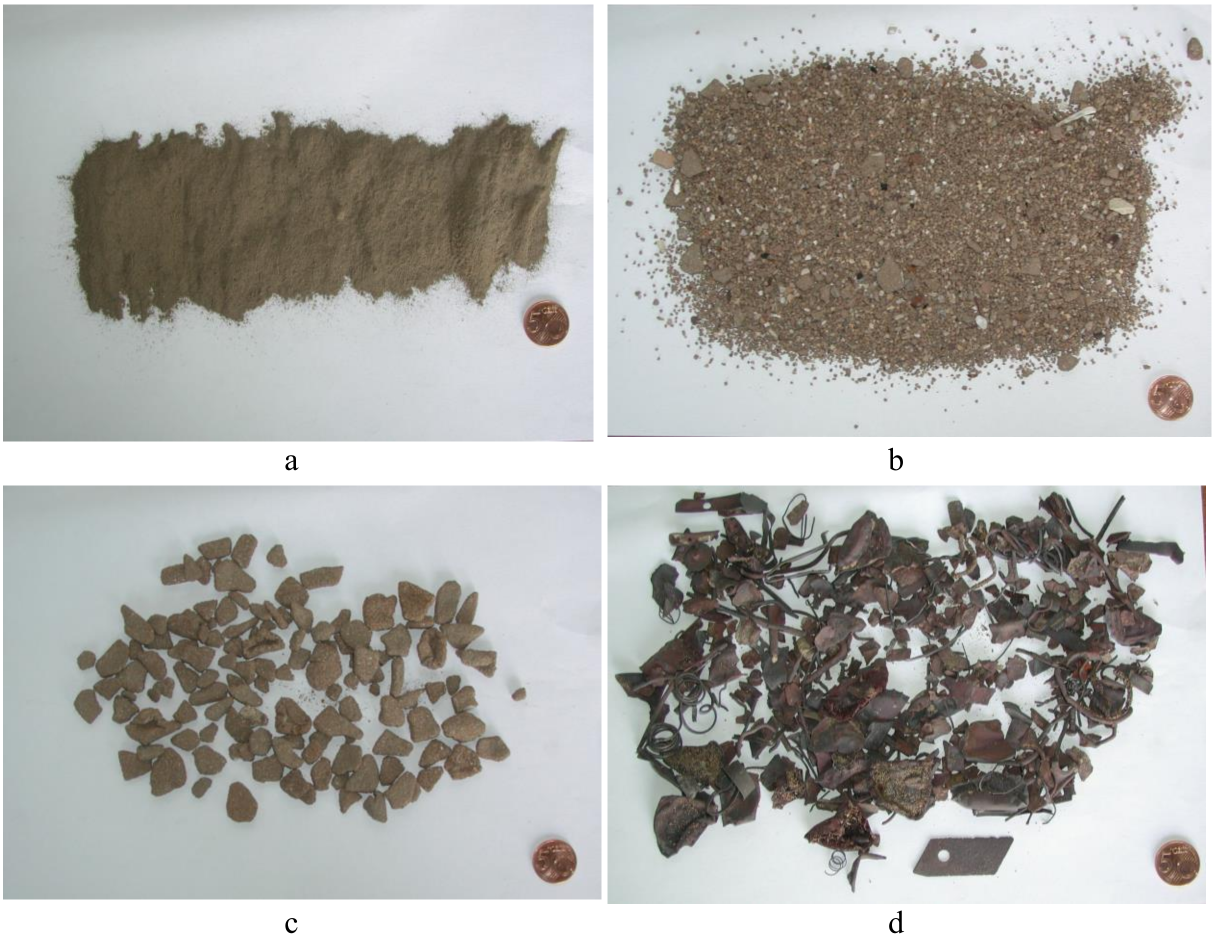

Figure 9: Ash from combustion test run – a: fly ash, b: sieve retention from 1mm screen c: glass particles handpicked from b, d: metal particles handpicked from b.

Figure 9 shows pictures of residual material after the 1st combustion test run. Fig. 9a depicts the fly ash from the cyclone, which had a mean diameter of 60 µm. The bed material was sieved with a screen of 1 mm mesh size. The screen underflow consisted of the original bed material silica sand mixed with the fine ash particles larger than the fly ash. The screen retention completely consisted of ash, minerals and metals. Although during RRBF preparation several ferrous and non-ferrous separators were passed, a considerable amount of metal pieces were found in the screen retention (Fig. 9d). The largest pieces contained in the screen retention (Fig. 9b) were broken glass covered with a thin layer of sand and ash particles (Fig. 9c). At first sight they looked like bed agglomerates, which could have been expected from the combination of silica sand and ash with a high sodium and potassium content. Fortunately, bed agglomerates did not occur, because they would inevitably lead to a sudden breakdown of fluidisation. Even a high amount of coarse 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, but bed agglomeration would have been detrimental.

An approximate mass balance for the ash can be compiled as following: during the 1st combustion test run 1 FIBC with roughly 260 kg EBS was fed to the fluidized bed. This material contained 61 kg of ash (23.3 % ash in OS, see Table 1). The cyclone ash (Fig. 9a) weighed 16 kg (26 % of total ash), the metal parts in the oversize bed ash (Fig. 9d) 0.4 kg (0.7 %), the oversize bed ash without metals (glass included, Fig. 9b) 22 kg (36 %) and the bed ash below 1 mm 22.6 kg by balance (37 % of total ash).

For the 3rd combustion test run, a similar mass balance could be made: 860.5 kg of OS were combusted, containing 187 kg of ash. The fly ash from the cyclone weighed 46.39 kg (24.8 % of total ash), the metal pieces in the withdrawn bed material 499 g, the metal pieces in the residual bed material 185 g (overall metal pieces in bed 684 g, equivalent to 0.37 % of total ash), oversize particles from withdrawn bed material 27.733 kg (14.8 %), oversize particles in residual bed material 34.237 kg (18.3 %), all oversize particles together 61.97 kg (33.1 %). By balance, the remaining ash in the particle size range of the bed material accounts for 77.956 kg (41.7 %). These values are in good agreement with the first combustion campaign taking into account the achievable accuracy of the measurement.

Table 2 gives the ultimate analysis of the fly ash from all 3 combustion test runs. The very low carbon and hydrogen content indicate a good burnout. Only the fly ash from the 3rd test run reveals a slightly increased carbon content. This is caused by the lower air flow towards the end of the experiment due to higher reactor head pressure and subsequently reduced oxygen overspill in the combustion zone. 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.

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

Table 2: Ultimate analysis of fly ash (n.a. not analysed, n.d. not detected).

The ash melting behaviour of original material (after secondary milling) and fly ash was analysed. Values for characteristic temperatures describing ash melting behaviour are compile din Table 3. Although the temperature is nearly equal throughout the reactor due to good mixing, in fluidized bed combustion 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. The ash melting behaviour of the original fuel and the cyclone ash (which is a mixture of "pure" ash and attrited silica sand) is approximately identical. The shrinkage start temperature (SST) is around 1,150 °C for all analysed material, which is more than 200 °C above operation temperature of the combustor. Therefore it can be assumed that ash sintering or agglomeration will not occur during normal operation of fluidized bed combustion of the material. The small deviation between characteristic temperatures of original RRBF ash and fly ash indicates, that there is already silica containing material in RRBF. Otherwise the characteristic temperatures of the fly ash would be significantly lower compared to RRBF ash.

	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

Table 3: Ash melting behaviour of original RRBF and fly ash after combustion.

4- CONCLUSIONS

The original material received for the 1st combustion test run could not be transported within the installed screw feeders and rotary valve. After secondary milling in a shredder, the transport characteristic was compatible with the feeding system, which resembles industrial equipment. The RRBF for the 2nd and 3rd test run were directly processed to meet these identified requirements. Although the three different batches of RRBF showed larger variations primarily in moisture and ash content the combustion behaviour did **not** show significant differences. The lower heating value of between 10.5 and 12.9 MJ/kg allowed combustion without supplemental high calorific fuel in a fluidized bed combustor and proved the possible production of steam from the flue gas to supply either process heat or electricity in future industrial scale applications. The ash forming minerals did not form low melting eutectic mixtures with the bed material silica sand during the performed combustion tests within the test period, so bed agglomeration is not to be expected. The fly ash collected with a cyclone contains considerable amount of phosphorus (above 1 %), which make this material interesting for later phosphorus recycling.

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 used one have adversely large surface-to-volume ratio and thus lose high amount of heat to the surrounding, combustion at temperatures above 900 °C could be maintained even without preheating of combustion air. 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 specialty of the pilot plant (long flue gas pipe with several 90° bends) and would not occur to this extend in industrial plants.

REFERENCES

[1] European Council: Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste. Official Journal of the European Communities, L 182/1-19, July 16th, 1999

[2] European Environment Agency: Managing Municipal Solid Waste – a Review of Achievements in 32 European Countries. EEA Report No. 2/2013, ISSN 1725-9177

[3] Clausen, A., Giani, H., Pretz, T.: Production of Biomass Fuel from Mixed Municipal Solid Waste by MBT. Proceedings of 14th International Waste Management and Landfill Symposium (Sardinia 2013), Forte Village, S. Margherita di Pula, Italy, September 30th – October 4th, 2013

[4] Giani, H., Borchers, B., Kaufeld, S., Feil, A., Pretz. T.: Fine Grain Separation for the Production of Biomass Fuel from Mixed Municipal Solid Waste. Proceedings of 5th International Symposium on Energy from Biomass and Waste (Venice 2014), San Servolo, Venice, Italy, November 17th- 20th, 2014

[5] Perry, R. H., Green, D. W. und Mloney, J. O.: Perry's chemical engineers' handbook. 6th Edition. New York, McGraw-Hill Book Company, 1984