

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Combustion requirements to conversion of ash rich novel energy crops in a 250 kW_{th} multifuel grate fired system

Maryori Díaz-Ramírez^{1,2}, Fernando Sebastián², Javier Royo¹ and Adeline Rezeau²*

¹ Department of Mechanical Engineering - University of Zaragoza, María de Luna, 3

E-50018 Zaragoza, Spain

² Centre of Research for Energy Resources and Consumption, CIRCE Foundation,

E-50018 Zaragoza, Spain

* Corresponding author: e-mail: mdiaz@unizar.es Phone number: +34-976-76-25-82

ABSTRACT:

Dedicated energy crops production is seen as a path to develop local biomass sources for heating consumer needs. It also offers new possibilities to improve the current state of grate firing systems based on traditionally used stemwood assortments. Novel energy crops are generally described as “problematic” fuels due to having a more complex composition than stemwood sources. Consequently, conversion technology should be adapted to their combustion requirements. The main objective of this work was to assess the suitability of a 250 kW_{th} multifuel grate fired system technology to the novel fuel properties. Thermal conversion of two pelletised novel energy crops currently assessed in Spain, an herbaceous biomass, Brassica, and a short rotation coppice, Poplar

1 were assessed in terms of required adjustments on three combustion parameters, i.e.,
2 lambda factor, air distribution and residence time on the grate leading to the best
3
4 combustion performance of the system. CO emissions and efficiency were under the
5
6 European requirements. Nevertheless, Brassica, depicted the worst condition. It was
7
8 mainly attributed to the ash composition and high ash content in fuels. Results have also
9
10 emphasized that further improvements and optimization of the current conversion unit
11
12 are still possible to manage the energy crops requirements.
13
14
15

16
17 Keywords: energy crops, heating, combustion, ash problems, air staging, emissions
18
19

20 1 INTRODUCTION 21

22 Biofuels from stemwood based assortments have been traditionally used as a fuel for
23
24 heating application in the northern part of Europe. For the past few decades, rather new
25
26 technologies based on wood pellet heating systems have been developed in order to
27
28 increase the conversion system thermal efficiency and also to fulfil established limiting
29
30 values regarding gaseous and particulate matter emissions. Nevertheless, local biomass
31
32 availability and growing concerns about established greenhouse gases emissions
33
34 reduction goals and also those related to rising petroleum prices and future supply
35
36 uncertainties are the main driving forces for seeking novel non-petroleum-based
37
38 alternative fuels [1, 2].
39
40
41
42
43

44 Currently, dedicated energy crops production is seen as a path not only to satisfy local
45
46 heating demand but also to address environmental and also economic aspects related to
47
48 fossil fuels. The novel fuels evolve a great miscellany of biomass sources, which are
49
50 generally described as “problematic” fuels due to having a more complex fuel
51
52 composition than biofuels traditionally used such as stemwood based assortments [3-6].
53
54 Substantial differences may occur in the chemical and physical composition from fuel
55
56 to fuel, both with respect to proximate, ultimate and ash matter compositions.
57
58
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Consequently, in order to develop a sustainable worldwide energy crops market, knowledge related to the understanding of the environmental and thermal conversion behaviour of these novel fuels is relevant for the sustainable development of this sector.

Dedicated grated fired plants have been traditionally used for heterogeneous fuels due to their adaptability to these resources particle size and water and ash contents. They are basically characterized by rather low investments and costs, which constitutes an advantage if they are distributed to a commercial scale. Nevertheless, current drawbacks of this technology are its rather bad adjustability and sensibility to fuel quality variations. Moreover, combustion is not as homogeneous as in fluidized bed systems. In order to achieve complete combustion, they require higher excess of air ratio (i.e., total lambda factor, λ_T , at the exit of the conversion system should be kept between 1.5 and 2 for small heating applications [7]), and consequently, they have a lower conversion unit thermal efficiency. In order to satisfy local heat and excess air ratio requirements during combustion, air staging technologies should be implemented and adapted to size limitations of the conversion unit [7-11]. This means that air should be supplied to specific requirements in each combustion zone of the combustion chamber. According to primary measures for emissions reduction, during heating up, drying and devolatilization phases, the excess air ratio requirements correspond to conditions that resemble pyrolysis process (i.e., $\lambda_1 < 1$), while requirements corresponding to devolatilization and char oxidation phases are closer to gasification conditions (i.e., λ_2 close to 1). Based on all these considerations, the primary lambda factor in the grate area (i.e., primary combustion zone), λ_p , is suggested to be remained around 0.7 [7]. In order to increase turbulence and consequently, air and flue gases mixing, a considerably higher excess of air tends to be supplied above the grate (i.e., $\lambda_s \gg 1$ in the secondary combustion zone). This means that at the same total lambda factor (i.e., λ_T), higher

1 amounts of secondary combustion air are applied inside the combustion chamber to
2 almost complete oxidation of gaseous components released from the fuel bed (e.g.,
3 carbon monoxide, CO and organic compounds, OGC).
4
5

6
7 Air staging also contributes to a slight and homogeneous fuel bed movement over the
8 grate. Controlled bed movements within the fuel bed can also be achieved by means of
9 moving grates or by using an ash removal system. They may contribute to ensure a
10 more uniform air combustion distribution over the whole fuel bed and also to avoid air
11 channelling effects in the fuel bed due to the ash occurrence. These controlled
12 movements also allow to the ash rich fuel bed to reach the completion of each
13 combustion step without disturbances of the combustion process, elutriation of fly ash
14 particles and unburned matter towards the heat exchanger tubes leading to ash deposit
15 formation, worsening emissions and lowering thermal efficiency of the system by huge
16 excess air. Nevertheless, ash occurrence as slag or sinter formation on the grate may
17 difficult the air to fuel contact. Consequently, more residence time and primary air
18 supply may be required in comparison to ash lean fuels [11-15].
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35

36 In Spain, research efforts have been mainly addressed to some dedicated crops not
37 only to identify the most suitable fuels to local conditions but also to learn how to
38 handle and how to use these materials for heating purposes. This goal has entailed the
39 assessment of the energy crop properties influence, i.e., physical and ash chemical
40 aspects, as well as the development of the most suitable thermal conversion technology.
41 In order to evaluate the applicability for heating purposes of the energy crops assessed
42 to the Spanish conditions, a medium biomass grate fired boiler has been developed
43 based on both previous knowledge from stemwood combustion and on some specific
44 experimental research carried out with these energy crops. Furthermore, the conversion
45 technology implemented in this system has been adapted to the specific combustion
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 properties and ash chemical characteristics of the most promising fuel alternatives that
2 are currently being assessed in Spain. Taking into account the acquired knowledge from
3 this research, the work presented here is a part of the development of a 250 kW_{th} grate
4 fired thermal conversion system adapted to pelletized ash rich fuel properties.
5
6
7

8
9 The main objective of the work described in this paper was to assess the suitability of
10 the current conversion system development state based on the comparison of the results
11 from thermal conversion of two pelletised novel energy crops currently assessed in
12 Spain; an herbaceous biomass, i.e., *Brassica carinata*, Brassica and a short rotation
13 coppice, i.e., *Populus ssp.*, Poplar energy crops. Influence of fuel characteristics such as
14 ash content and composition on the specific combustion behaviour of the novel crops is
15 assessed by means of required adjustments on three combustion parameters, i.e., lambda
16 factor, air distribution and residence time on the grate by means of the ash removal
17 system leading to the best performance in terms of CO emissions, thermal efficiency
18 and bottom ash sintering occurrence. Therefore, research from this work may lead to
19 identify key factors related to design considerations, modification requirements or
20 operation conditions to be considered to burn novel biofuels or to develop multi-fuel
21 thermal conversion systems.
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42

43 2 MATERIALS AND METHODS

44 2.1 Fuels

45
46 Two varieties of energy crops, which are currently assessed in the Mediterranean area
47 as some of the most promising energy crops, were tested in this study. An herbaceous
48 energy crop, Brassica (Br), and a short rotation coppice, Poplar (Pop), both cultivated
49 and pelletized in Spain. Biomass raw materials used in the pelletizing process consisted
50 of brassica straw and grains and poplar stem. Poplar's branches, leaves and bark as well
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 as possible sources of biomass contamination (roots, sand and rocks) were separated
2 and removed from both crops before being pelletized. Brassica and Poplar pellets were
3 produced as part of the PSE “On Cultivos” Project at the same pelletization plant
4 located at CEDER-CIEMAT in Spain (Soria), and had a diameter of 6 mm and a length
5 of 15–20 mm. Characteristics of the tested pellets regarding the main fuel properties are
6 provided in Table 1. The ash chemical composition of both fuels is listed in Figure 1
7 and given on a mole per GJ fuel dry basis (d.b.). As it can be seen from Table 1, fuels
8 samples are characterised by combustible fractions in a comparable range. Although
9 both fuels are rich in ash, ash content in Brassica is rather high. Regarding the inorganic
10 composition, it is shown in Figure 1 that K, Ca, Si, S, P, Mg and Cl are their main
11 inorganic constituents.
12
13
14
15
16
17
18
19
20
21
22
23
24
25

26 2.2 Conversion system characteristics

27 The current 250 kW_{th} grate fired thermal conversion system has been developed based
28 on design modifications and experimental research performed on an equipment initially
29 composed by a biomass burner consisting of six horizontally positioned and separated
30 cast iron grates connected to an horizontal and modular cast iron heat exchanger, which
31 was designed and normally used for gaseous and liquid fuels. Main characteristics of
32 this previous design as well as the further improvements carried out on the system
33 conducting to the current state of development of the 250 kW_{th} grate fired thermal
34 conversion unit can be found elsewhere [16-20]. Combustion behaviour of the
35 pelletized ash rich energy crops regarding the thermal efficiency of the conversion unit,
36 gaseous emissions and ash sintering behaviour have been considered as inputs for all the
37 improvements which have led to the current system design presented in this work.
38 Therefore, the current state of the conversion technology implies some design
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

modifications basically aimed to manage the specific combustion properties and ash chemical characteristics of the novel ash rich opportunity fuels.

As ~~it is~~ presented in Figure 2, the grate fired thermal conversion system is mainly divided into four zones: burner (I), combustion chamber (II) and two heat exchanger sections (III and IV). The burner zone is constructed according to the main principles for combustion of pellets. In this system, fuel feeding (see Figure 2, 1) is carried out by using a screw with rotation speed control to provide an optimum adjustment of the fuel flow to the required load condition. The burner consists of two stationary main grates (see Figure 2, 5). The first one is divided into four horizontally positioning small steps resembling a ladder (with nozzles in the riser part to primary air injection), while the second one is also flat but longer to ensure the complete char burnout. Primary air (see Figure 2, 2) is provided as underfeed air through each grate by using a frequency meter. Air injection nozzles arrangement and their number differ in each grate step to supply as much air as possible according to requirements for each thermal transformation process in which fuel particle undergoes during combustion over the grate (i.e., heating up, drying, devolatilization and char oxidation phases).

This burner is also designed with an automatic ash removal system (see Figure 2, 3), which scrapes ashes and other combustion residues away from the second grate and moves them into the ash pit located at the bottom zone inside the boiler combustion chamber (see Figure 2, 7). The ash pusher on/off working period is automatically controlled and can be modified according to fuel properties requirements in order to guarantee the required time for char combustion and so as to avoid ash accumulation and severe slag and sintering occurrence over the grate. By means of the pusher speed controller system, adjustments can be done to the residence time required to ensure as maximum as possible fuel and air mixing. A higher air-fuel contact on the grate is also

1 provided due to the periodical ash removal. Therefore, bed movement conditions on the
2 grate, under a continuous operation mode, are controlled by adjustments on both the air
3 distribution and the ash removal system.
4
5

6
7 In order to facilitate as complete mixing as possible between air and volatilized matter
8 released, secondary air is distributed into the combustion chamber through several
9 nozzles located in a surrounding channel (see Figure 2, 6), where secondary air is
10 partially preheated by radiation and convection heat transferred to the boiler walls.
11
12
13
14
15

16 Besides the boiler walls in the combustion chamber, the integrated heat exchanger
17 (see Figure 2, III and IV) is also water jacketed. Cleaning heat exchanger warm
18 turbulators (see Figure 2, 8) are located in the second heat exchanger zone and
19 contribute to increase the flue gases turbulence and therefore, the heat transfer rate into
20 the system. Shedding of fly ash deposited on heat exchanging surfaces is also possible
21 by the automatically controlled up/down turbulators movement. Finally, in order to
22 control the amount of air supply and flue gases residence time during their path into the
23 system, force draught is automatically regulated by using a fan provided with a
24 frequency meter (see Figure 2, 9).
25
26
27
28
29
30
31
32
33
34
35
36
37
38

39 2.3 Experimental design 40

41 Firstly, five preliminary experiments were carried out for each fuel in order to identify
42 operation conditions leading to the best performance of the system in terms of CO
43 emissions, thermal efficiency and bottom ash sintering occurrence. In these tests, the
44 screw feeding frequency, the ash pusher on/off working period, the excess air flow and
45 the primary/secondary air distribution were considered as the main parameters to
46 control and consequently, they were adjusted to attain the maximum load as it was
47 possible to each fuel. Secondly, an additional experimental combustion test was carried
48 out at the previously identified maximum load operation conditions, in order to verify
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 results reproducibility. Data was collected for further calculation of combustion
2 performance parameters, after a steady-state regime was reached at fixed operation
3 conditions by the preliminary experiments and results from these tests are presented in
4 this work.
5
6
7

8
9 During the tests, combustion temperatures were continuously measured at different
10 locations in the system: in the vicinity of the burner grates, in the flue gases channel and
11 in the water steps. Two type K thermocouples were located at the top (T_1 and T_2), other
12 two at the bottom (T_3 , T_4) of the secondary grate zone and three more (T_5 , T_6 and T_7) at
13 different positions in the flue gases path through the heat exchanger (see Figure 2).
14 Three PT 100 were located at one position in the water-in step (T_8) and at two positions
15 in the water-out step (T_9 and T_{10}), respectively (see Figure 2). The concentrations of the
16 gaseous flue gas components O_2 , CO and NO within the exhaust gas were continuously
17 measured with electrochemical sensors (Flue gas analyzer Testo 350XL), just after the
18 second heat exchanger exit, during all the tests. Primary and secondary air were
19 measured using an annubar tube and were adjusted to the appropriate flow rate by
20 means of the flow controllers. Unburnt content in solid combustion residues was
21 determined as the difference between 100 % and the ash content obtained from a sample
22 of the gathered bottom ash heated at 550 °C.
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42

43 2.4 Sampling of residual ash and assessment of the sintering degree 44 45

46 After each experiment, the residual ash from the burner grates and the residues below
47 the burner zone inside the combustion chamber were assessed by visual inspection in
48 terms of colour and hardness. Sintering degree in collected bottom ash samples was
49 assessed both through visual inspection and by means of a simple strength test, and
50 weight measurements of each fraction were carried out. Samples were classified in five
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

ash fractions based on a revised classification of sintering degree defined by Öhman et al [21, 22]:

- Category 1 (S_1): Non sintered ash residue, i.e., non fused ash (clear grain structure).
- Category 2a (S_{2a}): Partly sintered ash, i.e., particles contained clearly fused ash that breaks at a light touch (distinguishable grain structure).
- Category 2b (S_{2b}): Partly sintered ash, i.e., particles contained clearly fused ash that holds together at a light touch but is easily broken apart by hand (distinguishable grain structure).
- Category 3 (S_3): Totally sintered ash, i.e., the deposited ash was fused to smaller blocks that still are breakable by hand (slightly distinguishable grain structure).
- Category 4 (S_4): Totally sintered ash, i.e., the deposited ash was totally fused to larger blocks that are not possible to break by hand (no distinguishable grain structure).

2.5 Ash mass balance

An ash mass balance was carried out for each combustion test to estimate the deposits and fly ash formation. The closure of the mass balance was calculated taking into account the total in-going ash in fuel as the input stream. The measured outputs were collected bottom ash fractions namely according to their sintering degree (i.e., slagging and/or sintering occurrence in both burner ash and ash scraped by the pusher into the boiler combustion chamber). Particles deposited on the heat exchanging surfaces and those ones in flue gases were considered and counted as unquantified matter, namely ID, the rest ash fraction. It was calculated by difference between the total amount of in-going ash and the measured outputs to finally determine the closure of the ash mass

balance.

In order to quantitatively estimate the sintering tendency in bottom ash corresponding to each fuel, bottom ash fractions were also estimated as weight percentage of the total amount of collected bottom ash. It was defined as total amount of each fraction gathered according to their sintering degree as S_1 , S_{2a} , S_{2b} , S_3 and S_4 fractions divided by the total amount of collected bottom ashes.

2.6 Chemical characterisation

The chemical composition of formed bottom ash fraction, deposits and particulate matter was semi-quantitatively analysed by means of scanning electron microscopy (SEM, JEOL JSM-6400) equipped with energy dispersive spectroscopy (EDS), and qualitatively assessed with powder X-ray diffraction (P-XRD, RIGAKU D/max system instrument). Diffraction data for the XRD analysis was obtained from JCPDS-International Centre for Diffraction Database-2000. The P-XRD measurements were performed on ground samples, which subsequently were analysed by SEM-EDS spot and area mapping methods. Three areas $1\text{ mm} \times 1\text{ mm}$ on each sample were examined to obtain good reproducibility. Thus, P-XRD and SEM-EDS analysis were carried out on identical samples, allowing direct comparison of the two complementary methods.

2.7 Combustion performance parameters

In addition to measurements of gaseous emissions and determination of slagging and sintering occurrence in bottom ashes, energy distribution into the system regarding total energy input, combustion thermal efficiency, useful heat output and lambda factor were the main combustion parameters calculated to assess the system combustion thermal performance for each fuel. A statistical analysis was considered to determine the mean and standard deviation for each parameter.

1 Combustion thermal efficiency, η , was calculated by indirect methodologies
2 considering losses related to the energy output in flue gases at the exit of the conversion
3 system and unburnt solids and gases. Heat losses from the system walls have been
4 excluded and considered as negligible due to the insulation available in the system. To
5 carry out the comparison of energy distribution and combustion efficiency results
6 among fuels, a temperature of 120 °C was considered at the conversion system flue
7 gases exit. Two lambda factors have been defined in this study, namely lambda factor at
8 the burner or primary lambda factor, λ_p , and lambda factor at the exit of the conversion
9 system or total lambda factor, λ_T .
10
11
12
13
14
15
16
17
18
19
20
21
22
23

24 3 RESULTS

25 3.1 Gaseous emissions from the boiler

26 Generally, combustion conditions were controlled and relatively stable with an
27 average O₂ concentration in the range of 10-12 % dry gas (d.g.) as it is presented in
28 Table 2. Values reported in Table 2 correspond to the best performance attainable in the
29 system for each fuel. CO emissions were under the European EN 303-5 requirements
30 [23] set at 1200 mg/Nm³ at 10 % O₂ for boilers of nominal output < 300 kW_{th} class 3 for
31 woody pellets combustion. Nevertheless, CO emissions results do not satisfy the
32 Austrian requirements (UZ-37-Austria) set at 135 mg/MJ at 10 % O₂ in the dry flue gas
33 at low load for boilers ≤ 400 kW_{th} [24].
34
35
36
37
38
39
40
41
42
43
44
45
46
47

48 3.2 Thermal performance of the system

49 As is shown in Table 2, Poplar exhibited the maximum energy input, H_{fuel}^i . In
50 addition, the thermal performance of the system showed a high overall efficiency,
51 approximately over 90 % in both Brassica and Poplar tests. Although the global thermal
52 efficiency was similar for both fuels, there were some differences regarding the total
53
54
55
56
57
58
59
60
61
62
63
64
65

1 energy input distribution into the system (see Figure 3). Useful energy in the
2 combustion chamber was higher in Poplar than in Brassica test. Moreover, losses from
3
4 unburnout carbon matter were slightly higher in Brassica while the heat losses from
5
6 exhaust gases were the lowest ones in Poplar test. This condition corresponded to a total
7
8 lambda factor close to 2 and more than 50 % was distributed as primary air and was
9
10 relatively higher in Br test (see Table 2 and Figure 3).
11
12

13 3.3 Ash fractionation 14

15 Measured and estimated ash fractions are presented in Figure 4-a for each energy
16
17 crop. As it can be seen, there were clear differences on the ash fractionation between
18
19 fuels. For Brassica, bottom ash (i.e., fractions S₁-S₄) was found as the main ash fraction
20
21 while for Poplar was the opposite (see Figure 4-a). As it is shown in Figure 4-b, slightly
22
23 sintered ash (i.e., S₁ and S₂ ash sintering fractions) was identified in both fuels and
24
25 corresponded to the main bottom ash fraction in Poplar. Further, a significant amount of
26
27 slag formation (S₃ and S₄ ash fractions) resulted in Brassica.
28
29
30
31
32

33 3.4 Chemical characterisation 34

35 The results from SEM-EDS analyses of collected bottom ash fractions (i.e., S₁, S_{2a},
36
37 S_{2b}, S₃ and S₄) are given in Figure 4. As it can be seen, major ash-forming elements
38
39 identified by SEM-analysis in bottom ashes were Ca, K, Si, S, P and Mg. As it is shown
40
41 in Figure 4, Si content in bottom ash increased progressively when the sintering degree
42
43 was higher. Based on P-XRD analysis, it has been identified that bottom ash fractions
44
45 were dominated by relatively refractory silicates. The presence of refractory phosphates
46
47 and K-sulphates was also recognized as the major crystalline phases.
48
49
50
51
52
53
54

55 4 DISCUSSIONS 56

57 4.1 General remarks 58 59 60 61 62 63 64 65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Limitations regarding local biomass availability may imply the use of a great miscellany of sources and consequently, the occurrence of a broad range of chemical and physical properties. It entails gaining a more detailed knowledge of both the novel opportunity biofuel physical and chemical characteristics and the technological requirements that should be considered to their optimal conversion at maximum benefit, less time-consuming and satisfactory results. On the other hand, these limitations offer new possibilities to develop local biomass sources to supply heating consumer needs as well as to improve the state of the art of bioenergy chain steps, from fuel production to its transformation in the energy conversion system. In Spain, current state of grate firing conversion systems is adapted to thermochemical conversion requirements of different commercial sources available for the heating sector. However, some limitations can appear regarding conversion of more troublesome fuels not only due to the total amount of ashes but also by the complex ash composition leading to severe occurrence of ash related problems. The conversion system presented in this work is commercially available in the current Spanish heating market and it has been satisfactorily tested with different fuels type generally supplied in the sector. Nevertheless, specific research has been needed to evaluate its suitability to the novel energy crops combustion requirements and hence, results from conversion of the two energy crops selected to this study are compared and assessed to identify current limitations of the system and also to remark possible improvements possibilities for their conversion.

4.2 Combustion performance of the system with novel energy crops

According to results presented in Table 2, the current state of development of the 250 kW_{th} grate fired thermal conversion unit have demonstrated that the novel ash rich energy crops can be combusted according to the European gaseous emissions and efficiency requirements established by EN-303-5 European standard based on

1 stemwood pellets. This condition was attained to a maximum load higher than 160
2 kW_{th}, which corresponded to an useful output more than 60 % of the nominal one.
3
4 Although severe slag and sinter formation on the grate was observed in both fuels, the
5
6 worst condition was obtained for Brassica (see Figure 4). Same tendency was observed
7
8 concerning CO emissions and useful output (see Table 2 and Figure 3). As it can be
9
10 seen in Table 2, total lambda factor, λ_T , was similar among fuels and also to the one
11
12 proposed by literature to achieve complete combustion for this heating applications size,
13
14 i.e., around 2. Nevertheless, the primary air ratio was equal to almost twice the one
15
16 proposed for emissions reduction by primary measures [7] and it was considerably high
17
18 in Brassica tests (see Figure 5).
19
20
21
22
23

24 Based on the experimental results, it is suggested that there is a dependent tendency
25
26 among the ash content and operation conditions studied here leading to the maximum
27
28 useful output attained in the system. CO emissions are typically attributed to imperfect
29
30 combustion conditions due to deficiencies related to the well known “3T” criterion:
31
32 long enough residence time at sufficiently high temperature with adequate mixing of air
33
34 and combustible gases. As it is shown in Table 2, thermal profile reached in the primary
35
36 combustion zone, i.e., 802-1119 °C, was according to expected values for grate firing
37
38 technologies. Furthermore, in spite of CO emissions were in a comparable range
39
40 between fuels, the residence time in the grate area for Poplar was almost twice the one
41
42 for Brassica, which was based on adjustments on bed movements within the fuel bed by
43
44 means of using the pusher on/off working period (see Table 2). Consequently, it seems
45
46 that CO oxidation was not restricted by temperature and fuel residence time in the grate
47
48 area. In addition, oxygen was not the limiting parameter for CO oxidation due to high
49
50 O₂ values obtained for both fuels (see Table 2). Instead, physical ash properties as well
51
52 as the total amount of ash may evolve negative influence on the achievement of an
53
54
55
56
57
58
59
60
61
62
63
64
65

1 optimum air-fuel contact on the grate. According to Figure 4-a, a high proportion of in-
2 going ash in fuels was retained as residual bottom ash. It was more significant for
3 Brassica with more than 60 % (see Figure 4-a), which mainly corresponded to sintering
4 category 3 and 4 (see Figure 4-b). According to previous research studies, residual
5 bottom ash from these fuels tends to form low melting temperature compounds.
6
7 Nevertheless, a higher sintering tendency is expected for Brassica at temperatures
8 higher than 800 °C due to its ash composition in comparison to Poplar [25]. It is mainly
9 attributed to the relative content of main ash forming elements presented in Figure 1, as
10 it has been discussed in previous research [25]. As it is shown in Table 2, the burner
11 temperature was rather high in the fuel bed (> 900°C) leading to the melting of ashes.
12
13 The slag and sinter occurrence in bottom ashes was confirmed by chemical composition
14 (see Figure 5) and SEM pictures from SEM-EDX analysis. Furthermore, XRD results
15 showed the typical trace of amorphous phases, i.e., a halo on the base line. Hence, the
16 occurrence of slag and sinter formation on the grate leading to air channeling effects in
17 the fuel bed due to air injection nozzles were blocked. This means that an efficient
18 mixing of the reactants in the combustor was not possible, and consequently, the
19 combustion quality turned to be poorer. In order to minimize this negative effect and
20 also to avoid ash melting as much as possible, a higher ash removal frequency and also
21 more primary air proportion (λ_p) is needed when fuels with high ash content are
22 combusted in this type of technology. Due to this fact, a lower residence time of
23 reactants on the grate took place in Brassica tests leading to the higher unburnout matter
24 heat losses found in this test. Hence, results obtained for the energy crops tested confirm
25 the significant effect of ash content and fuel composition on the combustion
26 performance of the system under operating conditions for this size grate firing
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 technologies and consequently, they also substantiate the expected behaviour from the
2 literature data.
3

4 Furthermore, limitations to reach the nominal values in the system has suggested that
5 available design features might be improved and some drawbacks related to operation
6 conditions have to be overcome before achieving the final introduction of this
7 technology evaluation for thermal conversion of ash-rich fuels with critical
8 composition. Main efforts have to be addressed to the air supply system by means of
9 advanced tools such as using computational fluid dynamics codes.
10
11
12
13
14
15
16
17
18
19
20

21 5 CONCLUSIONS 22

23 This paper has discussed the combustion performance of pelletized energy crops
24 currently assessed to the Mediterranean conditions, when they are burnt in a 250 kW_{th}
25 grate fired thermal conversion system adapted to the ash rich fuel properties. Thermal
26 conversion of one herbaceous, Brassica, and one short rotation coppice, Poplar, was
27 assessed in terms of required adjustments on combustion parameters, i.e., lambda factor,
28 air distribution and residence time on the grate by means of the ash removal system
29 leading to the best performance concerning CO emissions, thermal efficiency and
30 bottom ash sintering occurrence.
31
32
33
34
35
36
37
38
39
40
41
42

43 Results with this technology have demonstrated that the novel ash rich energy crops
44 can be fired according to the gaseous emissions and efficiency requirements established
45 by the European standard EN-303-5 based on stemwood pellets. For all the tested fuels,
46 the best performance regarding gaseous emissions, thermal efficiency and bottom ash
47 sintering behaviour was attained to a useful output higher than the 60 % of the nominal
48 one. Limitations to reach the nominal value were mainly attributed to the high ash
49 content and the occurrence of slag and sinter formation in bottom ashes.
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 Melting and sintering behaviour of their ashes were influenced not only by ash
2 chemical composition in fuels but also by design and operation parameters. Changes in
3
4 the combustion conditions due to factors like bed movement on the grate done by the
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Melting and sintering behaviour of their ashes were influenced not only by ash chemical composition in fuels but also by design and operation parameters. Changes in the combustion conditions due to factors like bed movement on the grate done by the pusher, bed temperature and air distribution are suggested to be the main controlling parameters. Consequently, adjustments between the ash pusher on/off working period and the primary/secondary air distribution lead to guarantee the required time for char combustion, the avoidance of severe ash accumulation and slag formation and finally, the achievement of an appropriate air-fuel contact on the grate. Considering all these issues, a balance between the required residence time for the char burnout and the ash removal on the high temperature grate is a key factor to avoid severe slagging formation as well as to attain a complete burnout during combustion of ash-rich fuels with critical composition. Nevertheless, available design features, e.g., the current state of air distribution system, can also be possible factors of influence.

31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Based on research from this work, some drawbacks that have to be overcome before achieving the final introduction of this technology to the ash rich energy crops thermal conversion have been identified. Therefore, further improvements and optimization of the current conversion unit are still also possible. Main modification requirements should include both design features and operation conditions. The optimization of the burner and combustion chamber geometries and also of the air supply system might be achieved by means of using computational fluid dynamics (CFD). A more detailed study on the air distribution system, regarding the total number of air injection nozzles, their dimensions and their arrangement, might also contribute to adapt this system according to requirements for each thermal transformation process, which energy crops fuel particle undergoes during its path in the combustion unit.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Although further improvements should be required to offer optimal thermal conversion of the novel ash rich opportunity fuels, results from this research are another step on the road to sustainable energy crops pellets final penetration in the market.

Acknowledgements

The authors would also like to express their gratitude to the Spanish Education and Science Ministry for the financing the PSE “On Cultivos” project, PS-120000-2005-6 reference. Within the framework of this project the development of the grate fired thermal conversion system has been economically supported and Mediterranean pellet fuels have been provided. Acknowledgements are also given for the financing of the ‘Small-Scale Trigeneration based on Mediterranean Energy Crops and Residual Biomass Combustion’ project, ENE2008-03194/ALT reference. Within the framework of this project some of the work presented in this paper has been developed. The authors would like to extend special thanks to the company LASIAN Tecnología del Calor, S.L., especially to all the employees involved in this work.

REFERENCES

- [1] Berndes G., Hansson J. Bioenergy expansion in the EU: Cost-effective climate change mitigation, employment creation and reduced dependency on imported fuels. *Energy Policy* 2007; 35 (12): 5965-5979.
- [2] McManus M.C. Life cycle impacts of waste wood biomass heating systems: A case study of three UK based systems. *Energy*; 35 (10): 4064-4070.
- [3] Monti A., Di Virgilio N., Venturi G. Mineral composition and ash content of six major energy crops. *Biomass & Bioenergy* 2008; 32 (3): 216-223.
- [4] Vassilev S.V., Baxter D., Andersen L.K., Vassileva C.G. An overview of the chemical composition of biomass. *Fuel* 2010; 89 (5): 913-933.
- [5] Jenkins B.M., Baxter L.L., Miles T.R. Combustion properties of biomass. *Fuel Processing Technology* 1998; 54 (1-3): 17-46.
- [6] Cuiping L., Chuangzhi W., Yanyongjie, Haitao H. Chemical elemental characteristics of biomass fuels in China. *Biomass and Bioenergy* 2004; 27 (2): 119-130.
- [7] Obernberger I., Brunner T., Bärnthaler G. Chemical properties of solid biofuels--significance and impact. *Biomass and Bioenergy* 2006; 30 (11): 973-982.
- [8] Obernberger I. Decentralized biomass combustion: state of the art and future development. *Biomass and Bioenergy* 1998; 14 (1): 33-56.
- [9] Nussbaumer T. Combustion and co-combustion of biomass: fundamentals, technologies, and primary measures for emission reduction. *Energy & Fuels* 2003; 17 (6): 1510-1521.
- [10] Werther J., Saenger M., Hartge E.U., Ogada T., Siagi Z. Combustion of agricultural residues. *Progress in Energy and Combustion Science* 2000; 26 (1): 1-27.
- [11] Frandsen F.J., Pedersen A.J., Hansen J., Madsen O.H., Lundtorp K., Mortensen L. Deposit Formation in the FASAN WtE Boiler as a Function of Feedstock Composition and Boiler Operation *Energy & Fuels* 2009; 23 (7): 3490-3496.
- [12] Rhen C., Ohman M., Gref R., Wasterlund I. Effect of raw material composition in woody biomass pellets on combustion characteristics. *Biomass & Bioenergy* 2007; 31 (1): 66-72.
- [13] Mladenovic R., Dakic D., Eric A., Mladenovic M., Paprika M., Repic B. The boiler concept for combustion of large soya straw bales. *Energy* 2009; 34 (5): 715-723.
- [14] Kuprianov V.I., Kaewklum R., Chakritthakul S. Effects of operating conditions and fuel properties on emission performance and combustion efficiency of a swirling fluidized-bed combustor fired with a biomass fuel. *Energy* 2011; 36 (4): 2038-2048.
- [15] Heschel W., Rweyemamu L., Scheibner T., Meyer B. Abatement of emissions in small-scale combustors through utilisation of blended pellet fuels. *Fuel Processing Technology* 1999; 61 (3): 223-242.
- [16] Rezeau A., Díaz M., Arqué H., Quintero A., Sebastián F., Royo J. Improvement of a biomass burner and its connection to a modular diesel fuel boiler and analysis of the new biomass boiler concept efficiency and emissions, in: 15th European Biomass Conference and Exhibition, Berlin, Germany, 2007, pp. 1678-1683.
- [17] Díaz M., Rezeau A., Sebastián F., Royo J. Environmental performance of a novel small-scale biomass boiler fuelled with native spanish resources, in: 16th European Biomass Conference and Exhibition, Valencia, Spain, 2008, pp. 1447-1450.
- [18] Rezeau A., Díaz M., Sebastián F., Royo J. Operation and efficiencies of a new biomass burner when using pellets from herbaceous energy crops, in: 16th European Biomass Conference and Exhibition, Valencia, Spain, 2008, pp. 1447-1450.

- 1 [19] Díaz M., Boström D., Boman C., Royo J. Effect of fuel composition on ash
2 transformation and emissions during combustion of pellets from herbaceous and woody
3 energy crops, in: 17th European Biomass Conference and Exhibition, Hamburg,
4 Germany, 2009, pp. 1219-1224.
- 5 [20] Díaz M., Sebastián F., Boström D., Boman C. Lignocellulosic energy crops
6 combustion operation conditions impact on their bottom ashes transformation behaviour
7 and fractionation based on pilot-scale and full-scale measurements, in: 18th European
8 Biomass Conference and Exhibition, Lyon, France, 2010, pp. 1316-1320.
- 9 [21] Öhman M., Boman C., Hedman H., Nordin A., Boström D. Slagging tendencies of
10 wood pellet ash during combustion in residential pellet burners. *Biomass and Bioenergy*
11 2004; 27 (6): 585-596.
- 12 [22] Lindstrom E., Sandstrom M., Boström D., Öhman M. Slagging characteristics
13 during combustion of cereal grains rich in phosphorus. *Energy & Fuels* 2007; 21 (2):
14 710-717.
- 15 [23] European Committee for Standardization (CEN), European standard EN 303-5:
16 Heating boilers for solid fuels, hand and automatically stoked, nominal heat output of
17 up to 300 kW. 1999.
- 18 [24] Verma V.K., Bram S., De Ruyck J. Small scale biomass heating systems:
19 Standards, quality labelling and market driving factors - An EU outlook. *Biomass and*
20 *Bioenergy* 2009; 33 (10): 1393-1402.
- 21 [25] Díaz-Ramírez M., Boman C., Sebastián F., Royo J., Xiong S., Boström D. Ash
22 characterisation and transformation behaviour from novel crops fixed bed combustion:
23 Poplar, Brassica and Cassava fuels. Submitted for publication in *Energy and Fuels*.
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 FIGURE CAPTIONS:
2
3

4 Figure 1. Main ash-forming elements in fuel samples. Amount of element is calculated
5
6 based on the LHV of dry solid fuel.
7

8
9 Figure 2. Experimental set-up schematic figure. Scheme presents the main zones in the
10
11 conversion system and the main components in each zone.
12
13

14
15 Figure 3. Energy distribution into the system regarding the total energy input. Mean
16
17 values of the best performance under steady-state regime attained to: a) Pop and b) Br
18
19 are represented as Sankey diagrams.
20
21

22
23 Figure 4. Ash fractions from the mass balance (unburnt matter in the residual ash is not
24
25 considered) concerning a) total ash input and b) total ash collected. In all cases,
26
27 categories 1 and 2a, it means, S_1 and S_{2a} ash fractions, were grouped together as S_1 - S_{2a}
28
29 fraction in Figure 4 due to they could not be separated by sieving. ID corresponds to the
30
31 rest ash fraction, it means, difference among in-going amount of fuel ash and collected
32
33 bottom ash fractions.
34
35
36

37
38 Figure 5. Chemical composition of the collected ash fractions by SEM-EDS analysis.
39
40 Results from SEM-EDS were normalized to 100% for the major ash forming elements
41
42 in the energy crops bottom ash, a) Poplar, b) Brassica.
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

FIGURES:

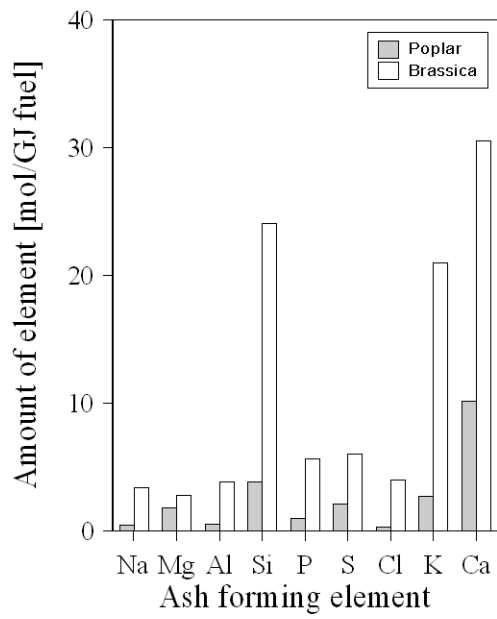


Figure 1. Main ash-forming elements in fuel samples. Amount of element is calculated based on the LHV of dry solid fuel.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Legend:

Main zones in the conversion system:

- I. Burner zone
- II. Combustion chamber
- III. Heat exchanger tubes (first zone)
- IV. Heat exchanger tubes (second zone)

Main components in each zone:

- 1. Fuel feeding system
- 2. Primary air fan and ignitor
- 3. Ash removal system
- 4. Ash container
- 5. Burner flat grates
- 6. Secondary air fan and air distribution
- 7. Ash worms
- 8. Turbulator driving gear
- 9. Draught fan

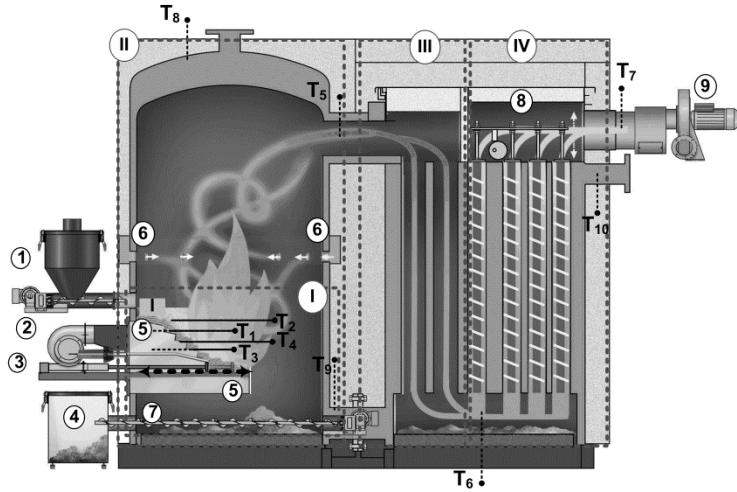


Figure 2. Experimental set-up schematic figure. Scheme presents the main zones in the conversion system and the main components in each zone.

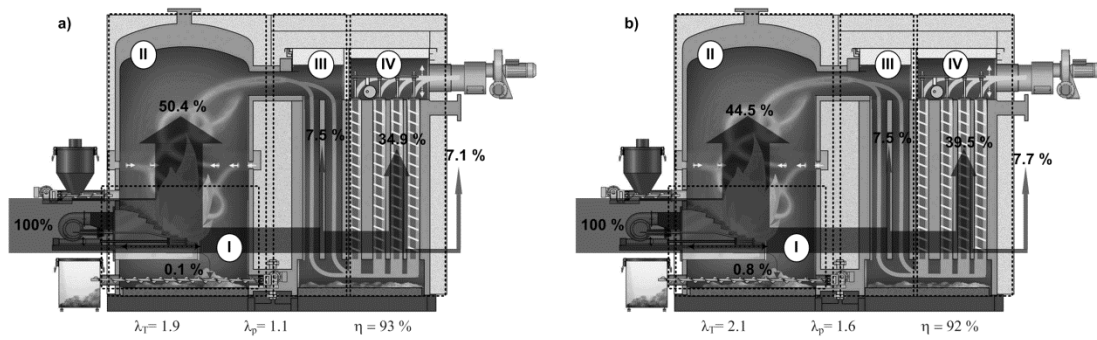


Figure 3. Energy distribution into the system regarding the total energy input. Mean values of the best performance under steady-state regime attained to: a) Pop and b) Br are represented as Sankey diagrams.

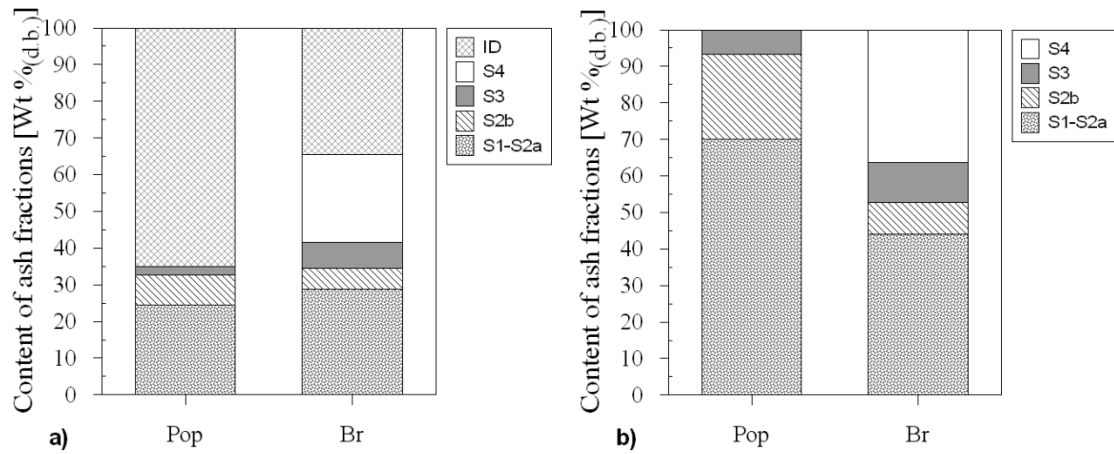


Figure 4. Ash fractions from the mass balance (unburnt matter in the residual ash is not considered) concerning a) total ash input and b) total ash collected. In all cases, categories 1 and 2a, it means, S_1 and S_{2a} ash fractions, were grouped together as S_1 - S_{2a} fraction in Figure 4 due to they could not be separated by sieving. ID corresponds to the rest ash fraction, it means, difference among in-going amount of fuel ash and collected bottom ash fractions.

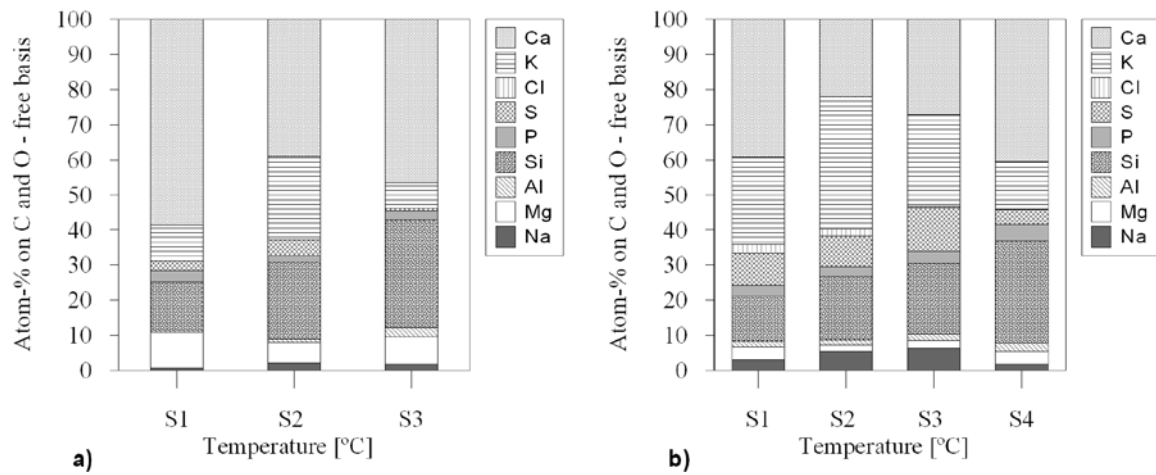


Figure 5. Chemical composition of the collected ash fractions by SEM-EDS analysis. Results from SEM-EDS were normalized to 100% for the major ash forming elements in the energy crops bottom ash, a) Poplar, b) Brassica

TABLE CAPTIONS:

Table 1. Fuel characteristics. Values in Table 1 are given in weight percent dry basis (wt % d.b.) except for moisture and heating value which are given in weight percent and MJ/kg d.b. respectively.

Table 2. Set parameters and characteristics of the stationary combustion phase obtained to each fuel combustion test.

TABLES:

Table 1. Fuel characteristics. Values in Table 1 are given in weight percent dry basis (wt % d.b.) except for moisture and heating value which are given in weight percent and MJ/kg d.b. respectively.

Parameter		Pop	Br
Higher heating value, HHV	MJ/kg d.b.	19.49	17.45
Lower heating value, LHV	MJ/kg d.b.	18.13	16.31
Proximate analysis			
Ash content in pellets	wt % d.b.	2.8	10.7
Fixed carbon ^a	wt % d.b.	15.2	18.8
Volatile matter	wt % d.b.	82.0	70.4
Moisture	wt %	5.0	4.9
Ultimate analysis			
C	wt % d.b.a.f.	50.8	49.7
H	wt % d.b.a.f.	6.1	6.2
N	wt % d.b.a.f.	0.1	1.3
O ^a	wt % d.b.a.f.	42.9	42.2
S	wt % d.b.a.f.	0.16	0.36
Cl	wt % d.b.a.f.	0.02	0.26
Percentage of dry substance in ashes			
SiO ₂	wt % d.b.	15	22
Al ₂ O ₃	wt % d.b.	1.7	3.0
CaO	wt % d.b.	37	26
Fe ₂ O ₃	wt % d.b.	0.6	1.2
K ₂ O	wt % d.b.	8.3	15
MgO	wt % d.b.	4.8	1.7
MnO	wt % d.b.	0.06	0.05
Na ₂ O	wt % d.b.	0.9	1.6
P ₂ O ₅	wt % d.b.	4.5	6.1
SO ₃	wt % d.b.	11	7.3
BaO	wt % d.b.	0.03	0.01
SrO	wt % d.b.	0.05	0.01
TiO ₂	wt % d.b.	<0.2	<0.2
ZnO	wt % d.b.	0.01	0.08
a. Calculated by balance.			

Table 2. Set parameters and characteristics during stationary combustion phase obtained to all test period at conditions leading to the maximum load attainable for each fuel. Average values are given with standards deviations.

Parameter		Pop	Br
Operation conditions			
Energy input in fuel (load)	kW _{th}	207	161
Useful output	kW _{th}	193 ± 1	148 ± 1
Primary/secondary air distribution	%	58/42	75/25
Lambda total, λ _T	Adim.	1.9 ± 0.1	2.1 ± 0.1
Pusher on/off working period	Adim.	4/100	5/50
Draught	mmca	12.0	8.1
Unburnt matter	%	2.84	3.43
Temperature profile			
Burner mean	°C	880 ± 55	1013 ± 153
Burner minimum	°C	765	774
Burner maximum	°C	1039	1232
T ₁ and T ₂ (mean)	°C	847 ± 31	802 ± 12
T ₃ and T ₄ (mean)	°C	913 ± 55	1119 ± 37
Temperature at the exit of the combustion chamber, T ₅	°C	653 ± 8	668 ± 16
Temperature in the exhaust gases, T ₇	°C	165 ± 2	155 ± 1
Flue gas composition during all test period at maximum load			
O ₂	vol % d.g.	10 ± 1	12 ± 1
CO (1200 mg/Nm ³ at 10 % O ₂) ^a	mg/Nm ³ (10 % O ₂)	231 ± 91	908 ± 655
CO (135 mg/MJ at 10 % O ₂) ^b	mg/MJ (10 % O ₂)	103 ± 34	495 ± 377
Flue gas composition during best conditions at max. load			
O ₂	vol % d.g.	10 ± 1	11 ± 1
CO (1200 mg/Nm ³ at 10 % O ₂) ^a	mg/Nm ³ (10 % O ₂)	196 ± 38	286 ± 95
CO (135 mg/MJ at 10 % O ₂) ^b	mg/MJ (10 % O ₂)	91 ± 17	143 ± 50
Thermal efficiency, η	%	93	92

a. Reference values according to the European Standard EN-303-5 [23].

b. Reference values according to the Austrian law art.15a B-VG [24].

Figure 1. Main ash-forming elements in fuel samples. Amount of element is calculated based on the LHV of dry solid fuel.

Figure 1
[Click here to download high resolution image](#)

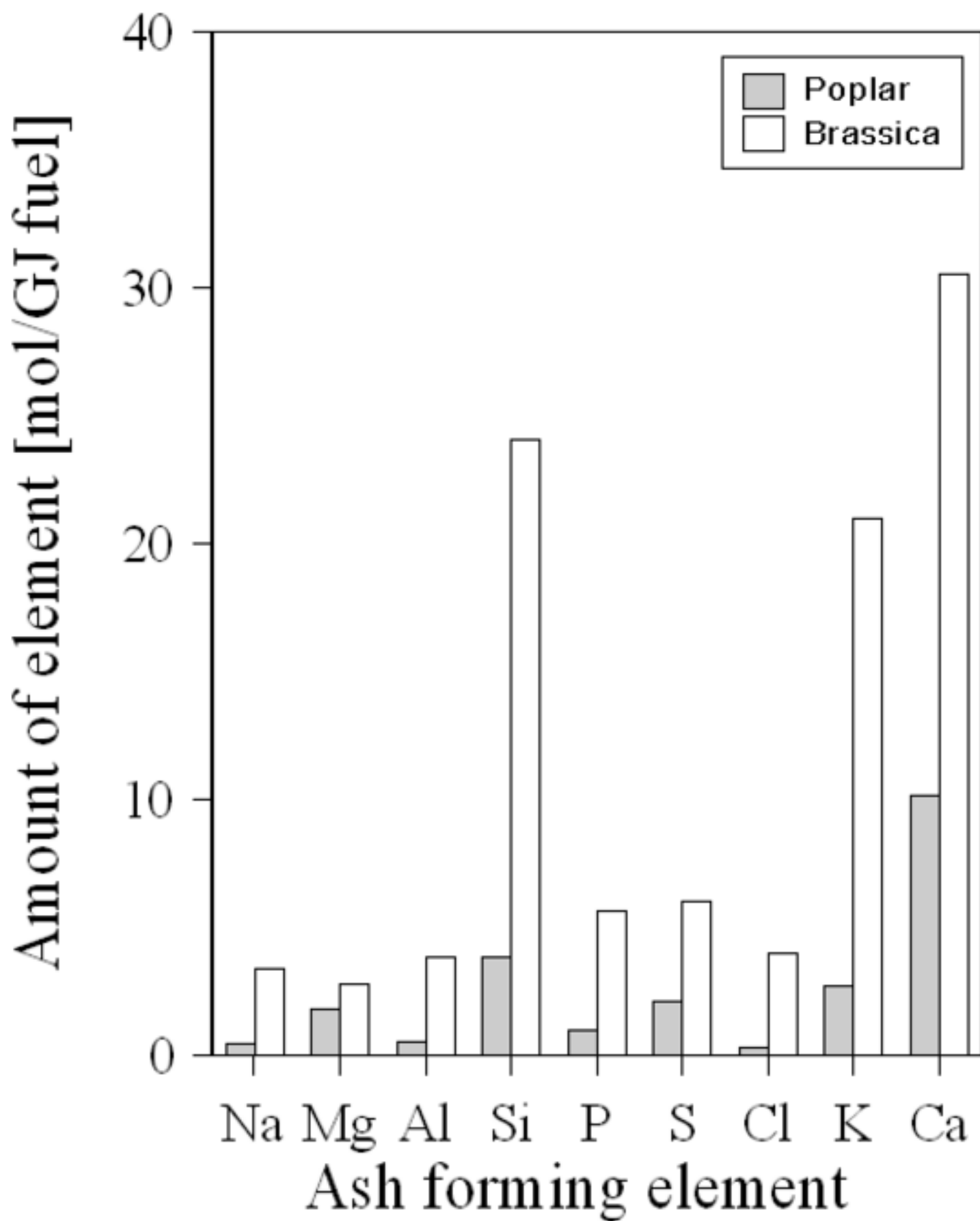


Figure 2. Experimental set-up schematic figure. Scheme presents the main zones in the conversion system and the main components in each zone.

Figure 2

[Click here to download high resolution image](#)

Legend:

Main zones in the conversion system:

- I. Burner zone
- II. Combustion chamber
- III. Heat exchanger tubes (first zone)
- IV. Heat exchanger tubes (second zone)

Main components in each zone:

- 1. Fuel feeding system
- 2. Primary air fan and ignitor
- 3. Ash removal system
- 4. Ash container
- 5. Burner flat grates
- 6. Secondary air fan and air distribution
- 7. Ash worms
- 8. Turbulator driving gear
- 9. Draught fan

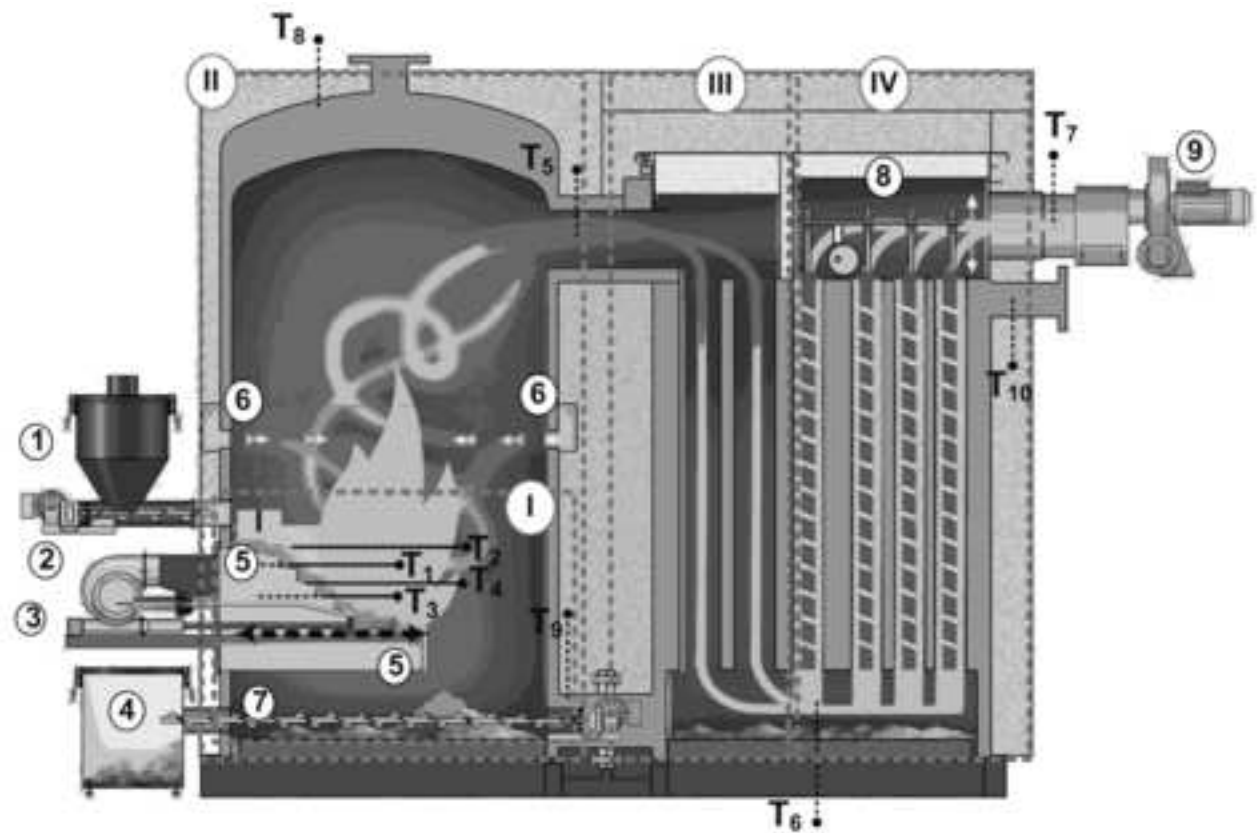


Figure 3. Energy distribution into the system regarding the total energy input. Mean values of the best performance under steady-state regime attained to: a) Pop and b) Br are represented as Sankey diagrams.

Figure 3
[Click here to download high resolution image](#)

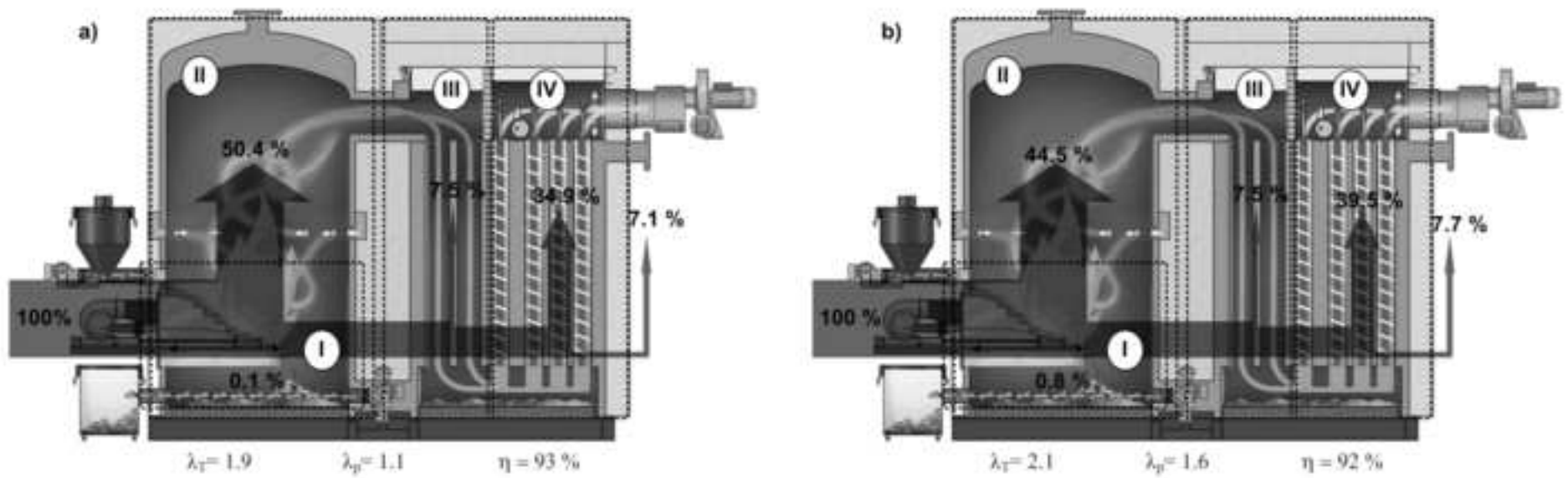


Figure 4. Ash fractions from the mass balance (unburnt matter in the residual ash is not considered) concerning a) total ash input and b) total ash collected. In all cases, categories 1 and 2a, it means, S_1 and S_{2a} ash fractions, were grouped together as S_1-S_{2a} fraction in Figure 4 due to they could not be separated by sieving. ID corresponds to the rest ash fraction, it means, difference among in-going amount of fuel ash and collected bottom ash fractions.

Figure 4
[Click here to download high resolution image](#)

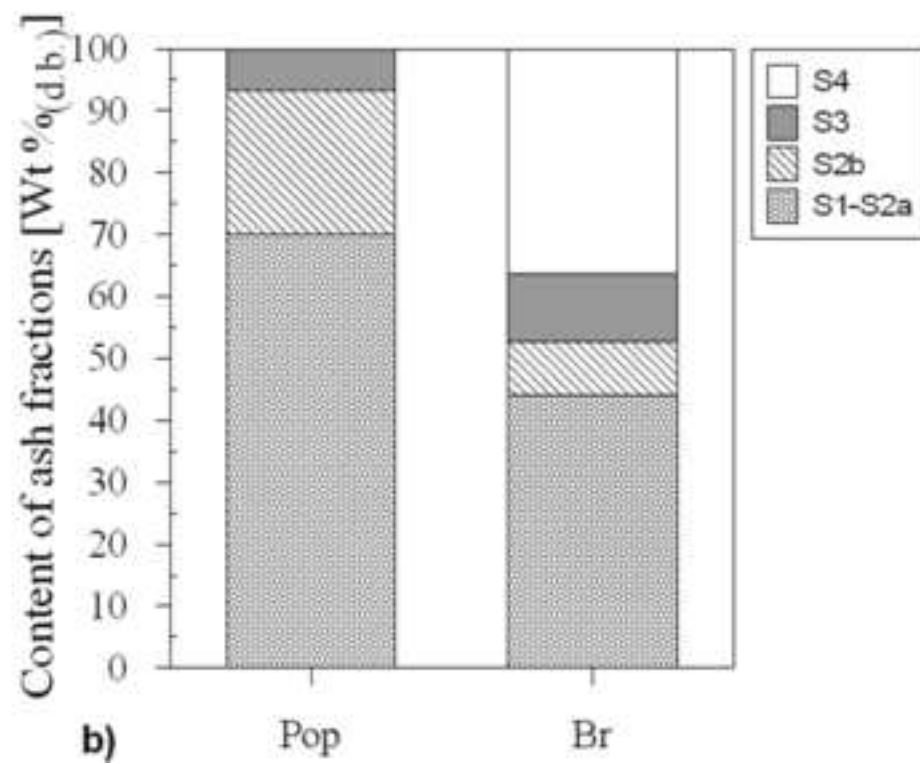
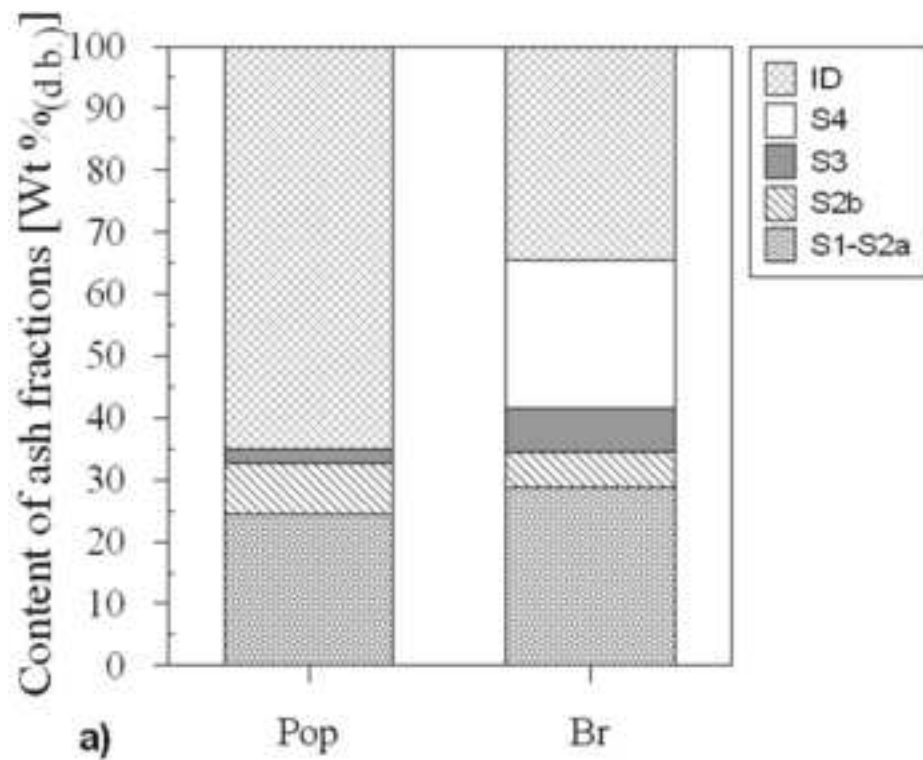


Figure 5. Chemical composition of the collected ash fractions by SEM-EDS analysis. Results from SEM-EDS were normalized to 100% for the major ash forming elements in the energy crops bottom ash, a) Poplar, b) Brassica.

Figure 5
[Click here to download high resolution image](#)

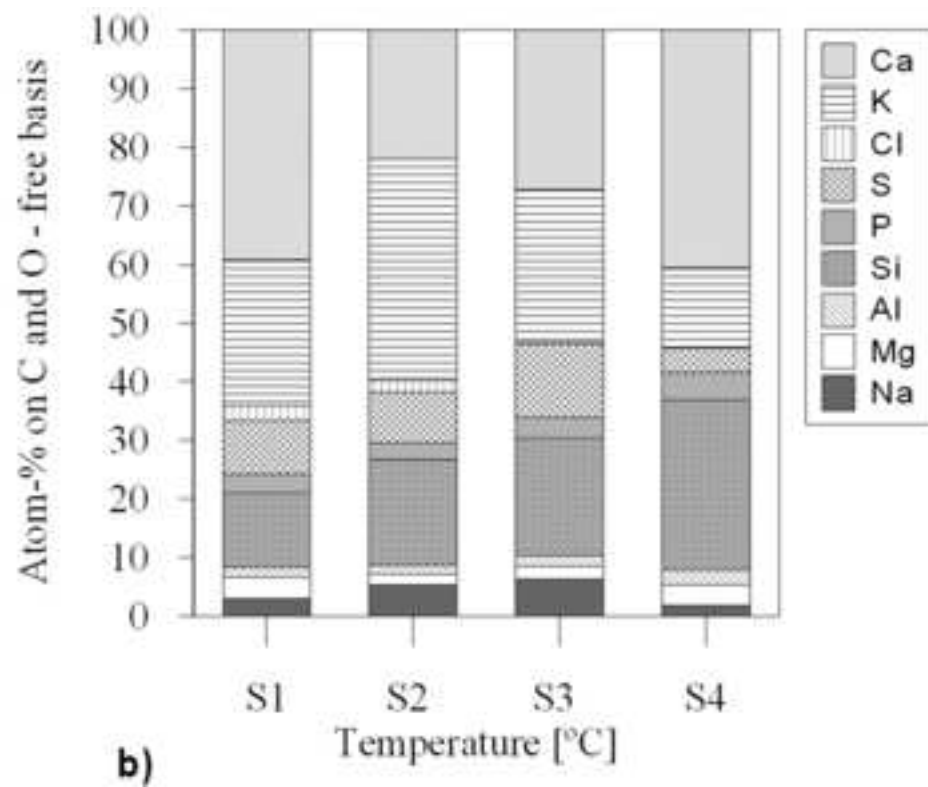
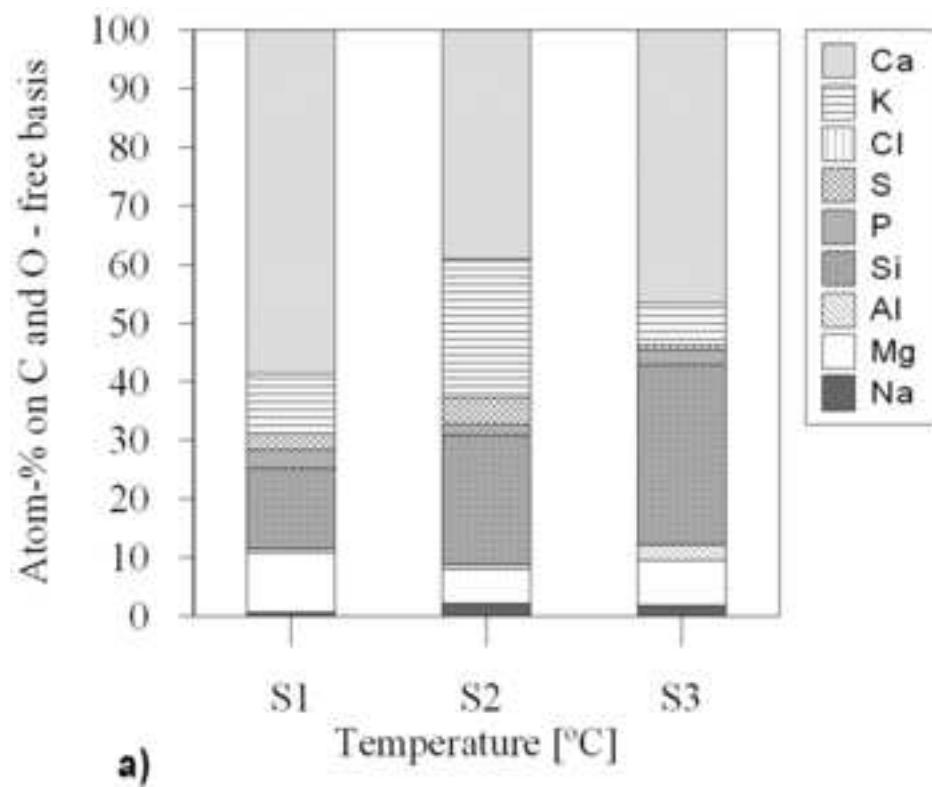


TABLE CAPTIONS:

Table 1. Fuel characteristics. Values in Table 1 are given in weight percent dry basis (wt % d.b.) except for moisture and heating value which are given in weight percent and MJ/kg d.b. respectively.

Table 2. Set parameters and characteristics of the stationary combustion phase obtained to each fuel combustion test.

TABLES:

Table 1. Fuel characteristics. Values in Table 1 are given in weight percent dry basis (wt % d.b.) except for moisture and heating value which are given in weight percent and MJ/kg d.b. respectively.

Parameter		Pop	Br
Higher heating value, HHV	MJ/kg d.b.	19.49	17.45
Lower heating value, LHV	MJ/kg d.b.	18.13	16.31
Proximate analysis			
Ash content in pellets	wt % d.b.	2.8	10.7
Fixed carbon ^a	wt % d.b.	15.2	18.8
Volatile matter	wt % d.b.	82.0	70.4
Moisture	wt %	5.0	4.9
Ultimate analysis			
C	wt % d.b.a.f.	50.8	49.7
H	wt % d.b.a.f.	6.1	6.2
N	wt % d.b.a.f.	0.1	1.3
O ^a	wt % d.b.a.f.	42.9	42.2
S	wt % d.b.a.f.	0.16	0.36
Cl	wt % d.b.a.f.	0.02	0.26
Percentage of dry substance in ashes			
SiO ₂	wt % d.b.	15	22
Al ₂ O ₃	wt % d.b.	1.7	3.0
CaO	wt % d.b.	37	26
Fe ₂ O ₃	wt % d.b.	0.6	1.2
K ₂ O	wt % d.b.	8.3	15
MgO	wt % d.b.	4.8	1.7
MnO	wt % d.b.	0.06	0.05
Na ₂ O	wt % d.b.	0.9	1.6
P ₂ O ₅	wt % d.b.	4.5	6.1
SO ₃	wt % d.b.	11	7.3
BaO	wt % d.b.	0.03	0.01
SrO	wt % d.b.	0.05	0.01
TiO ₂	wt % d.b.	<0.2	<0.2
ZnO	wt % d.b.	0.01	0.08

a. Calculated by balance.

Table 2. Set parameters and characteristics during stationary combustion phase obtained to all test period at conditions leading to the maximum load attainable for each fuel. Average values are given with standards deviations.

Parameter		Pop	Br
Operation conditions			
Energy input in fuel (load)	kW _{th}	207	161
Useful output	kW _{th}	193 ± 1	148 ± 1
Primary/secondary air distribution	%	58/42	75/25
Lambda total, λ _T	Adim.	1.9 ± 0.1	2.1 ± 0.1
Pusher on/off working period	Adim.	4/100	5/50
Draught	mmca	12.0	8.1
Unburnt matter	%	2.84	3.43
Temperature profile			
Burner mean	°C	880 ± 55	1013 ± 153
Burner minimum	°C	765	774
Burner maximum	°C	1039	1232
T ₁ and T ₂ (mean)	°C	847 ± 31	802 ± 12
T ₃ and T ₄ (mean)	°C	913 ± 55	1119 ± 37
Temperature at the exit of the combustion chamber, T ₅	°C	653 ± 8	668 ± 16
Temperature in the exhaust gases, T ₇	°C	165 ± 2	155 ± 1
Flue gas composition during all test period at maximum load			
O ₂	vol % d.g.	10 ± 1	12 ± 1
CO (1200 mg/Nm ³ at 10 % O ₂) ^a	mg/Nm ³ (10 % O ₂)	231 ± 91	908 ± 655
CO (135 mg/MJ at 10 % O ₂) ^b	mg/MJ (10 % O ₂)	103 ± 34	495 ± 377
Flue gas composition during best conditions at max. load			
O ₂	vol % d.g.	10 ± 1	11 ± 1
CO (1200 mg/Nm ³ at 10 % O ₂) ^a	mg/Nm ³ (10 % O ₂)	196 ± 38	286 ± 95
CO (135 mg/MJ at 10 % O ₂) ^b	mg/MJ (10 % O ₂)	91 ± 17	143 ± 50
Thermal efficiency, η	%	93	92

a. Reference values according to the European Standard EN-303-5 [23].

b. Reference values according to the Austrian law art.15a B-VG [24].