



## Full Length Article

# Fluidized bed air gasification of solid recovered fuel and woody biomass: Influence of experimental conditions on product gas and pollutant release



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## ABSTRACT

The aim of this work is to study the air gasification of solid recovered fuel (SRF), and to compare it to the gasification of woody biomass (beech wood sawdust, and waste wood). This study focuses on the influence of several operating parameters: temperature – between 800 and 910 °C –, O<sub>2</sub>/C ratio – between 0 (pyrolysis conditions) and 0.34, and addition of steam. Experiments are performed in a bubbling fluidized bed at 1.5 bar, with a solid feeding rate of 1–3 kg/h. The yield and composition of the product gas is particularly looked at, together with the repartition of carbon into the different types of products (gas species, tar molecules). Sulphur release to the gas phase is also investigated.

Temperature has mainly an influence on H<sub>2</sub> and CO yields, which is attributed to char gasification enhancement. The addition of steam in fluidising gas induces an increase in oxygenated gas species yields (CO + CO<sub>2</sub>), related to char gasification improvement. It does not have any reforming influence on light hydrocarbon and tar, with even a slight inhibiting effect. Woody biomass and SRF show significant differences in product yields, which are qualitatively explained by the initial elemental composition and material content of each type of fuel.

From a process point of view, the conversion efficiency improvement by varying the gasification conditions for SRF is limited compared to the higher efficiency obtained with woody biomass. Co-gasification of biomass – possibly waste wood – and SRF, could be a way to improve the overall efficiency, and limit pollutant content.

## 1. Introduction

Gasification of solid wastes with a sufficiently high energy content is gaining more and more interest. Similarly to biomass gasification, waste gasification allows producing a gas which can be used for production of heat/electricity. Compared to biomass, the cost of solid wastes is significantly lower, which make them attractive for improving the economical balance of energy production process. Moreover, the energy valorization of solid wastes which cannot, up-to-date, be recycled as materials, could help fulfilling the goals of landfilling reduction set in Europe [1]. On the other hand, production of energy from wastes with a biogenic fraction allows avoiding some greenhouse gas emissions if replacing production of energy from fossil fuel.

Among the solid wastes with significant availability, as well as sufficient higher heating value to produce a calorific product gas, are waste wood and solid recovered fuel (SRF). The terminology “SRF” is used for very different types of wastes, as their content can widely vary depending on their site of production and on the sources of wastes from which they come [2]. SRF can be produced either in mechanical

biological treatment (MBT) or in mechanical treatment (MT) plants. SRF coming from MT plants shows a higher energy content, generally over 18 MJ/kg (dry basis) [3].

One of the main reactor technology investigated for solid waste gasification is fluidized bed, which can also handle biomass of different types, and be used for co-gasification of biomass and wastes.

SRF gasification has been studied by several teams, using fluidised bed reactors of different capacities. Arena et al. [4,5] performed several studies in a pilot fluidised bed having a feedstock capacity of 30–100 kg/h. The rather large size of the pilot allowed performing gasification tests in autothermal conditions with probably limited thermal loss, and thus performances close to the ones of large fluidised beds [6]. Several types of solid wastes were gasified in the form of pellets, among which SRF, Refuse Derived Fuel (RDF) prepared from municipal solid waste (MSW), plastic wastes and food packaging wastes (plastic, paper, aluminium). Robinson et al. [7] used a bubbling fluidised bed (0.15 m in diameter) with feeding rates between 12 and 20 kg/h of pellets made of RDF prepared from MSW, and pellets of woody biomass. The reactor was operated autothermally and the

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influence of temperature on gasification efficiency and tar content was especially investigated. However, as temperature directly depended on the equivalence ratio, both parameters could have an influence on the results. Recari et al. [8,9] performed experiments in a lab-scale fluidised bed reactor (23.8 mm in diameter). The reactor was electrically heated, and the temperature on the one hand, and air/fuel or  $O_2$ /fuel ratio on the other hand, were varied independently. Two types of SRF were tested in the form of particles of about 1 mm: one of them mainly containing plastics and textiles, with a low content of biomass and paper, and the other mainly containing biomass, waste paper and plastics. The aim was to focus on the influence of several parameters: temperature, bed material (sand, olivine or dolomite), and fluidizing agent (air or mixture of  $O_2$  and steam) – on gasification efficiency and contaminant contents.

Our objective is here to study the air gasification of solid recovered fuel prepared by mechanical treatment from industrial, bulky and furniture wastes, and to compare it to the gasification of woody biomass (beech wood sawdust, and waste wood). The experimental results were analysed with the objective to decorelate the influence of different operating parameters: temperature, air/fuel ratio, addition of steam. Even in autothermal gasifiers, these parameters are linked with each other, our objective was to give a comprehensive analysis of their respective influence. One pyrolysis test of SRF was performed in inert atmosphere to investigate, by comparison with gasification experiments, how the presence of  $O_2$  modified the conversion. Our objective was not only to study the overall conversion performance, with indicators such as Cold Gas Efficiency, or tar content, but also to try to give a comprehensive analysis of the mechanisms which control the product yields. Thus, the yield and composition of the product gas was particularly looked at, together with the repartition of carbon into the different types of products (gas species, tar molecules). Sulphur release to the gas phase was also investigated.

## 2. Experimental

### 2.1. Description of the facility

The fluidized bed facility is shown in Fig. 1 and was described in details in a previous publication [10]. The facility is composed of an internal reactor and feeding screws surrounded by an external vessel

designed to sustain a pressure of 40 bars. The internal reactor is heated by 9 independent electric resistance heaters. The biomass conveying screw can also be heated by 2 heating elements. The maximum temperature is 1000 °C. The reactor is composed of a lower part – 0.124 m internal diameter, 0.95 m height – followed by a freeboard of 0.20 m internal diameter and 1.54 m height. Metallic filters are implemented in the upper part of the freeboard.

Gas temperature in the bed is measured with three thermocouples located at 6 cm, 8 cm and 10 cm respectively from the gas distributor. The solid fuel to be gasified – SRF or wood – is stored in a pressurized bunker and is introduced in the reactor with two feeding screws: a dosing one followed by a conveying screw with a high rotation velocity of 75 rpm. Argon is injected in the bunker to avoid syngas back flow.

For the present experiments, the fluidizing gas was  $N_2$  for pyrolysis, and air mixed with  $N_2$ , as well as steam in one case for gasification. The gas distributor is a plate supplied with 12 nozzles with 4 holes of 1 mm diameter on each of them.

At the reactor output, gas temperature is kept at 600 °C until it flows through 3 cold traps in series, where water and tars are condensed. These traps are cooled at about 15 °C, 0 °C and –5 °C respectively. The condensed water flowrate is measured online thanks to a pressure drop transducer measuring the height of condensed water in a column.

Gas composition is analysed online using a micro Gas Chromatograph ( $\mu$ GC) coupled with a Thermal Conductivity Detector (TCD). The analyser is equipped with four columns. The compounds which can be detected are: Ar,  $O_2$ ,  $CO_2$ , CO,  $CH_4$ ,  $N_2$ ,  $H_2$ ,  $C_2H_2$ ,  $C_2H_4$ ,  $C_2H_6$ ,  $C_3H_6$ / $C_3H_8$ ,  $C_6H_6$  (benzene),  $C_7H_8$  (toluene),  $C_8H_{10}$  (xylene and ethylbenzene),  $H_2S$ , COS,  $H_2O$  in vapor phase. An analysis is performed every 3 min. The lower limit of quantification is 3 ppm for each gas.

Tar sampling is performed following the tar protocol method [11] using isopropanol as solvent. Tar species are then identified and quantified by GC-FID (Gas Chromatography – Flame Ionization Detection).

### 2.2. SRF and wood preparation and characterization

Several types of feedstock were gasified in the fluidised bed. Most of the experiments were performed with SRF prepared from industrial, bulky and furniture wastes. It mainly contained plastics, wood, paper, cardboards, and textiles. Two types of SRF (“SRF1” and “SRF2”), prepared by the same SRF producer with slightly different process from the same type of wastes, were tested. They mainly differ by their ash content, slightly lower for SRF2 (Table 1). Most of the tests were performed with SRF1, provided in several batches, with a few deviations in the elemental composition of each of them. Only one test was performed with SRF2. Overall, no significant difference could be detected between the results obtained with the different batches of SRF1, nor between SRF1 and SRF2. The analysis results of the different batches of SRF1 are thus presented all together as a range of values in Table 1. The SRF were grounded and pelletized for feeding in the fluidized bed.

One test was performed with waste wood, prepared with a knife mill for which the sieve size was 1 mm. Moreover, the results were compared with those obtained with stem beech wood sawdust of 1–2 mm.

The composition and characteristics of the three types of feedstock are given in Table 1. Only the inorganic elements with the higher contents (determined by ICP on the raw fuel) are shown.

### 2.3. Conditions of the experiments

Before each test, 5 kg of fresh bed material were poured into the reactor. For most of the tests, olivine, coming from Austria, was used. Its particle size is between 200 and 500  $\mu$ m. For one test with beech wood as fuel, silicon carbide powder – mean diameter: 304  $\mu$ m – was used as bed material.

The reactor, gas input and output lines were first electrically heated to their set points (between 720 and 850 °C). Ar and  $N_2$  – flowrates of

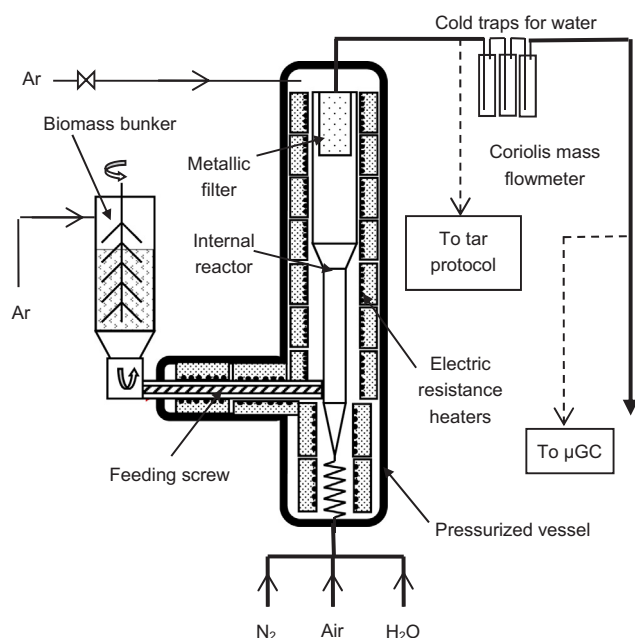


Fig. 1. Schematic diagram of the fluidised bed facility.

**Table 1**

Composition and characteristics of feedstock (all values on dry basis except moisture – for SRF 1, minimum and maximum values are indicated depending on the batch).

	SRF1	SRF2	Waste wood	Beech wood
Moisture (as received)	4.7–5.0%	7.8%	8.8%	8.3%
Ash at 550 °C			4.0%	0.7%
Ash at 815 °C	16.4–16.6%	13.7%	4.0%	
C	45.1–48.0%	51.2%	47.9%	49.6%
H	6.0–6.1%	6.8%	5.45%	5.69%
N	1.20–1.33%	1.30%	1.9%	Under 0.3%
S	0.47–0.51%	0.62%	0.10%	410 ppm
Cl	1.14–1.25%	1.18%	582 ppm	300 ppm
O (by difference)	27.4–29.3%	25.2%	40.6%	44%
Al	6220–6420 ppm		2756 ppm	36 ppm
As	< 2 ppm		12 ppm	< 0.1 ppm
Ba	225–270 ppm			
Cd	2–3 ppm		1 ppm	< 0.4 ppm
Ca	30,640–34,120 ppm		11,194 ppm	1300 ppm
Cr	99–175 ppm		54 ppm	< 0.8 ppm
Co	3–4 ppm		7 ppm	
Cu	137–158 ppm		40 ppm	
Fe	3020–3130 ppm		2078 ppm	59 ppm
Mg	2100–2360 ppm		1005 ppm	300 ppm
Mn	118–124 ppm		112 ppm	180 ppm
Hg	0.1 ppm		0.1 ppm	< 0.05 ppm
Ni	18–26 ppm		13 ppm	< 1.5 ppm
P	327–360 ppm		306 ppm	74 ppm
Pb	134–141 ppm		172 ppm	1 ppm
K	2150–2320 ppm		1769 ppm	730 ppm
Si	30,660–34,900 ppm		10,181 ppm	380 ppm
Na	4180–4490 ppm		1293 ppm	71 ppm
Ti	1370–1580 ppm			3 ppm
Zn	677–697 ppm		609 ppm	3 ppm
Lower Heating Value (MJ/kg)	19.8–20.5	20.2	17.6	18.1

10.1 and 55 NL/min – were then fed in the bunker and at the bottom of the reactor respectively. Ar injection was kept constant all along the experiment. After stabilization of the pressure in the fluidised bed at 1.5 bar, continuous feeding of the SRF/wood was started, and N<sub>2</sub> was progressively replaced by air. When the stabilised experimental conditions were reached (Table 2), electrical heating along the fluidised bed was shut down and the temperature in the bed was controlled by exothermic reaction between air and the solid fuel. However, electrical heating was maintained at 720 °C along the feeding screw and along the freeboard in the upper part of the reactor (Fig. 1). Fluidising gas was also still electrically pre-heated during the whole experiment.

One test with SRF was performed in “pyrolysis” conditions, with N<sub>2</sub> only as fluidising gas. Electrical heating was then kept constant all along the experiment.

**Table 2**

Conditions and process efficiency results of experiments – bed material is olivine for all except beech wood experiment (silicon carbide).

	Solid feeding rate (kg/h)	In-bed temperature (°C)	O <sub>2</sub> /C (mol/mol)	ER	Steam/C (mol/mol)	Product gas yield (N m <sup>3</sup> /kg daf)	Product gas LHV (MJ/N m <sup>3</sup> )	CGE	Tar content (g/N m <sup>3</sup> )
SRF1 1st reference test	2.040	868	0.27	0.25	0	2.0	6.0	0.49	/
SRF1 2nd reference test	0.992	854	0.34	0.31	0	2.6	4.4	0.47	13.1
SRF2 SRF preparation influence	1.630	866	0.30	0.26	0	2.3	5.6	0.54	18.6
SRF1 T influence	1.934	801	0.24	0.22	0	1.7	6.6	0.47	21.2
		857	0.26	0.25	0	2.1	6.3	0.52	/
		908	0.28	0.26	0	2.2	6.7	0.58	13.6
SRF1 Steam influence	1.962	868	0.25	0.24	0	1.9	6.8	0.53	
		869	0.27	0.25	0.22	2.1	6.3	0.53	20.5
		858	0.26	0.24	0.73	2.1	6.9	0.59	
SRF1 Pyrolysis	0.929	796	0	0	0	/	/	0.54	/
Waste wood	3.225	843	0.18	0.19	0	1.6	7.0	0.61	7.9
Beech wood	2.152	849	0.21	0.23	0	1.9	7.1	0.75	10.7

For each experiment, SRF/wood was fed for 2–4 h. In some cases, gasification conditions were slightly varied (temperature, or steam addition) in one-day experiment (Table 2). The results reported hereafter were then obtained after stabilisation of at least 30–60 min.

The mean biomass/SRF feeding rate was calculated after weighing the biomass/SRF in the bunker before and after each test. N<sub>2</sub> was fed along with air (and steam) so as to reach a total flowrate in the distributor of about 55 NL/min. This ensured a fluidizing velocity of about 3–4 times the minimum fluidization velocity of the bed material, independently of the air/(SRF or biomass) ratio.

Each condition was defined with the in-bed temperature, as well as the O<sub>2</sub>/C ratio (mol/mol) and the steam/C (mol/mol) ratio. The steam/C and O<sub>2</sub>/C ratios represent the molar flowrate of steam and O<sub>2</sub> respectively fed into the reactor (in air for O<sub>2</sub>) over the molar flowrate of carbon (in SRF or biomass). The O<sub>2</sub>/C ratio was selected because it can directly represent the degree of oxidation of carbon in any solid fuel, whatever its elemental composition, contrary to the Equivalence Ratio (ER) which also depends on the hydrogen and oxygen content of the fuel. ER represents the flowrate of O<sub>2</sub> fed into the reactor over the rate needed for stoichiometric combustion of the solid fuel. Temperature and O<sub>2</sub>/C are dependant parameters, however we tried to decorrelate them in some cases by varying the preheating temperature of fluidising gas, controlled by the electrical power delivered by the 2 bottom heaters (Fig. 1).

The in-bed absolute pressure was 1.5 bar for every test. The gas residence times in the bed zone and in the freeboard were estimated at 2–3 s and 8–12 s respectively.

### 3. Results and discussion

In the present section, results concerning product gas yield and composition are first presented for SRF, with a special attention paid to the influence of the following parameters: gasification temperature, O<sub>2</sub>/C ratio, and steam addition in fluidizing gas. At last, results for SRF are compared to those obtained with woody biomass.

Tar content in product gas and tar composition are then presented, followed by inorganic non condensable pollutant content.

#### 3.1. Product gas yield and composition

Product gas yield and Lower Heating Value (LHV), together with the Cold Gas Efficiency (CGE), are given in Table 2 for each operating condition. Product gas yield (in N m<sup>3</sup>/kg of daf – dry ash free – solid fuel) and LHV (in MJ/N m<sup>3</sup>) are calculated for the product gas, without considering the additional N<sub>2</sub> fed to maintain fluidisation, nor Ar in feeding line. This correction allows calculating more realistic values at industrial scale since these two streams are specific to our lab-scale facility.

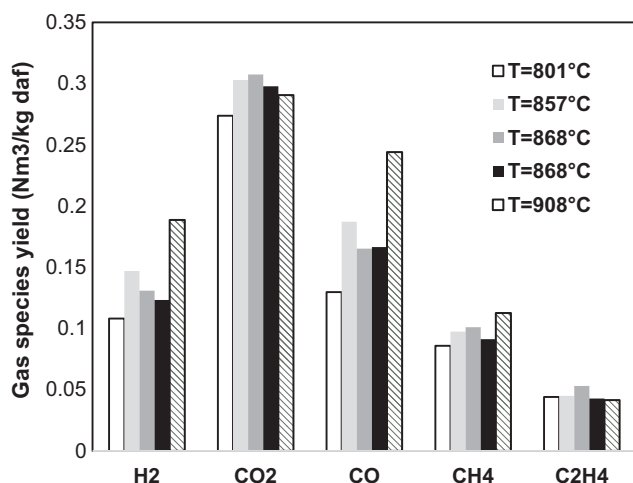


Fig. 2. Major gas species yields as a function of temperature for SRF1.

The CGE is calculated as follows (Eq. (1), in which  $Q_i$  is the mass flowrate of  $i$  in  $\text{kg}\cdot\text{s}^{-1}$  and  $\text{LHV}_i$  is the Lower Heating Value of  $i$  in  $\text{J}\cdot\text{kg}^{-1}$ ; “fuel” stands for SRF or biomass):

$$\text{CGE} = \frac{\sum_i (Q_i \times \text{LHV}_i)}{Q_{\text{fuel}} \times \text{LHV}_{\text{fuel}}} \quad (1)$$

Figs. 2, 4, 6 and 8 illustrate the influence of each parameter on major gas species yield expressed in  $\text{Nm}^3/\text{kg daf}$ . The yield of each gas species was calculated from the composition of dry gas measured by  $\mu\text{GC}$ , and from the total gas flowrate calculated using  $\text{N}_2$  as tracer gas. The carbon conversion into the different gas species is shown in Figs. 3, 5, 7 and 9.

### 3.1.1. Influence of temperature on gas yield and composition from SRF

The influence of temperature was investigated with the results from the test with this specific aim (Table 2), together with two others. For all selected conditions, the  $\text{O}_2/\text{C}$  ratio lied between 0.24 and 0.28. The lowest value was at 801 °C, and the highest one at 908 °C.

For the three conditions with temperature between 857 and 868 °C, the gaseous product yields are similar (Fig. 2), with a rather good reproducibility for the two conditions at 868 °C. When temperature increases from 801 to 908 °C,  $\text{H}_2$  and CO yields significantly increase.  $\text{CH}_4$  yield seems to be slightly higher at 908 °C, while  $\text{C}_2\text{H}_4$  yield is not much affected. Recari et al. [8] also measured a large increase in  $\text{H}_2$  and CO yields with temperature between 750 and 850 °C in SRF air gasification,

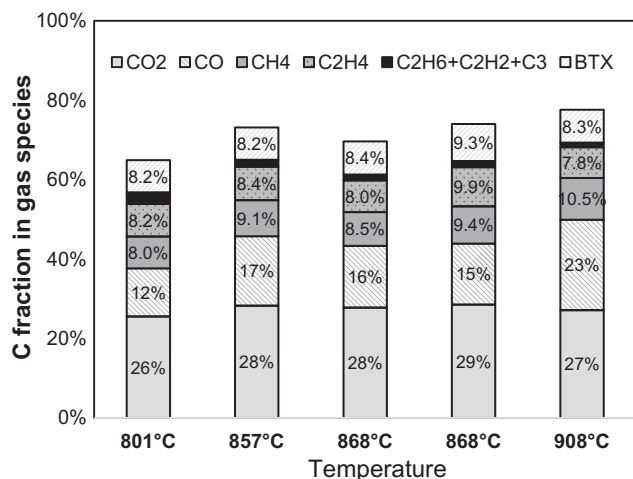


Fig. 3. Carbon conversion into gas species as function of temperature for SRF1.

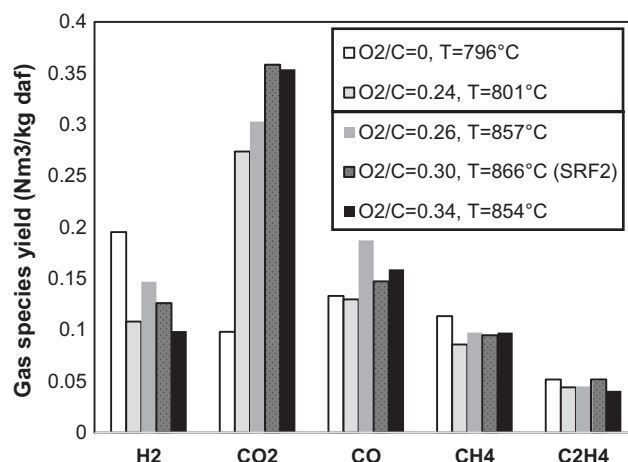


Fig. 4. Major gas species yields as a function of  $\text{O}_2/\text{C}$  ratio at 2 temperature levels.

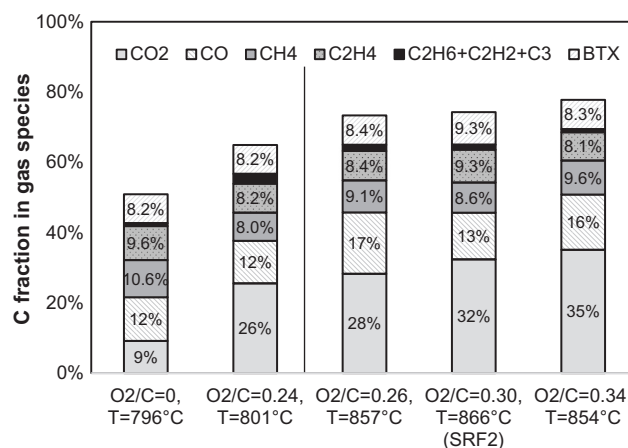


Fig. 5. Carbon conversion into gas species as function of  $\text{O}_2/\text{C}$  ratio at two temperature levels.

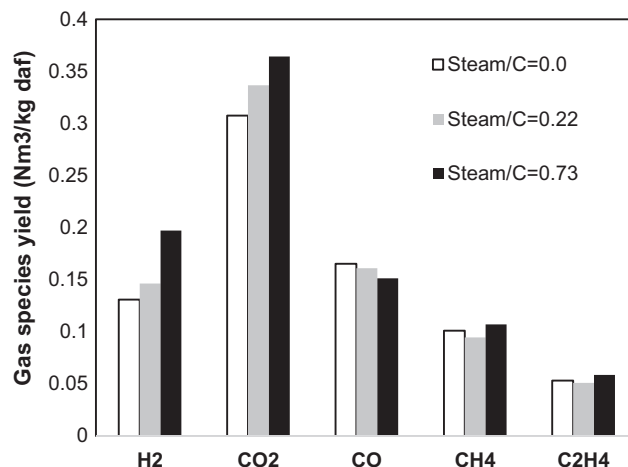


Fig. 6. Major gas species yields as a function of Steam/C ratio (SRF1,  $T = 858\text{--}869^\circ\text{C}$ ,  $\text{O}_2/\text{C} = 0.25\text{--}0.27$ ).

together with a slight increase in  $\text{CH}_4$  yield. For the “FL” SRF (made of biomass, paper and plastic wastes), whose elemental composition is the closest to ours, the  $\text{H}_2$  and CO yields are multiplied by 2 and 1.8 respectively between 750 and 850 °C. In our case, the  $\text{H}_2$  and CO yields are multiplied by 1.7 and 1.9 respectively between 801 and 908 °C. The

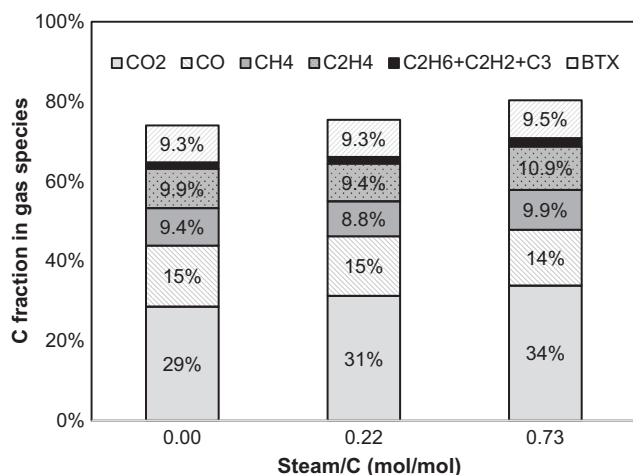


Fig. 7. Carbon conversion into gas species as a function of Steam/C ratio (SRF1, T = 858–869 °C,  $O_2/C = 0.25$ – $0.27$ ).

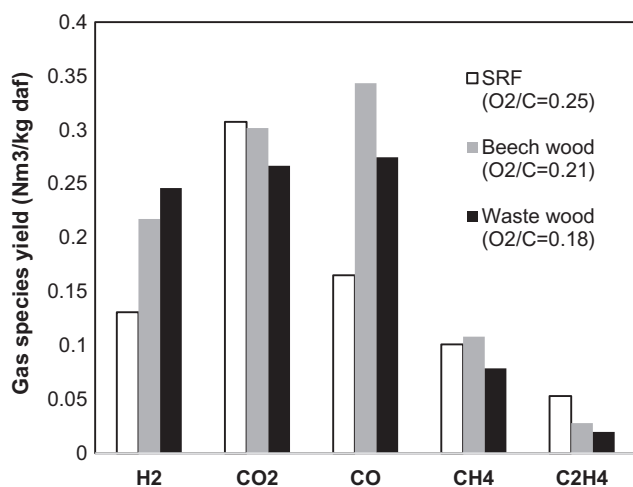


Fig. 8. Major gas species yields for SRF, beech wood and waste wood.

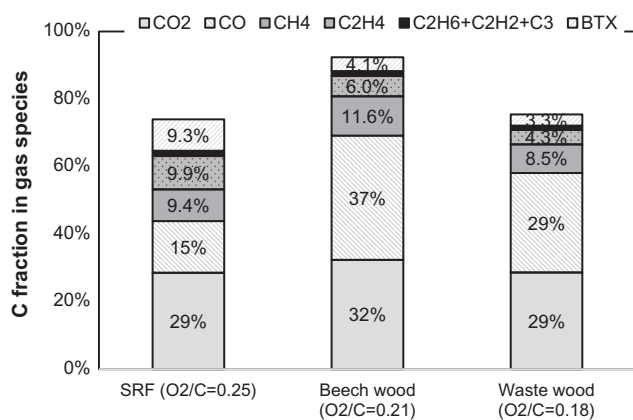


Fig. 9. Carbon conversion into gas species for SRF, beech wood and waste wood.

global tendency is thus similar, even if the results cannot be directly compared since the temperature range is not the same. In the present study, the increase in H<sub>2</sub> and CO yields is much more pronounced between 860 °C and 900 °C than between 800 and 860 °C. At 800 °C, the  $O_2/C$  ratio is a bit lower than at 860 °C (Table 2), with, as will be shown in next section, a lower H<sub>2</sub> yield as  $O_2/C$  increases. This means, that

with perfectly equal  $O_2/C$  ratios in our tests, the influence of temperature could have been even more visible.

The carbon fraction in gas compounds slightly increases with temperature, from 65% at 801 °C to 78% at 908 °C (Fig. 3). In agreement with gas yields results, this increase is mainly linked to the increase of C fraction in CO, and in a lesser extent to the increase of C in CH<sub>4</sub>. The contribution of the other carbonaceous gas species do not significantly vary with temperature. The slight increase of C fraction in CH<sub>4</sub> with temperature tends to demonstrate that CH<sub>4</sub> reforming is not favoured. More CH<sub>4</sub> could be formed as temperature increases by conversion of tar species, as will be presented in Section 3.2. The global increase in the fraction of C in oxygenated gas species (CO + CO<sub>2</sub>) as temperature increases, while the C fraction in other incondensable products does not decrease, tends to show that temperature allows enhancing char gasification and/or tar oxidation. However, as will be shown in Section 3.2, the decrease of C fraction in tar as temperature increases cannot quantitatively totally explain the increase of C fraction in CO + CO<sub>2</sub>. Thus char gasification is more probably then enhanced.

The CGE increases from 0.47 to 0.58 when temperature goes from 801 to 908 °C (Table 2). The energy content of gas mainly comes from hydrocarbons (CH<sub>4</sub> included), while only 1/4 of the CGE comes from CO and H<sub>2</sub>. The total product gas yield slightly increases with temperature, from 1.7 at 801 °C to 2.2 Nm<sup>3</sup>/kg daf at 908 °C. However, the gas HHV, comprised between 6.0 and 6.8 MJ/Nm<sup>3</sup>, do not significantly vary with temperature (Table 2).

### 3.1.2. Influence of $O_2/C$ ratio on gas yield and composition

The influence of  $O_2/C$  ratio was investigated at 2 temperatures: firstly at about 800 °C by comparing the results of the pyrolysis test with results obtained for  $O_2/C = 0.24$ , and secondly at about 855–865 °C ( $O_2/C = 0.26, 0.30$  and  $0.34$ ). SRF2 and SRF1 gasification behaviours were also compared, the test at  $O_2/C = 0.30$  being performed with SRF2. At each of the two temperature levels, the CO<sub>2</sub> yield increases with  $O_2/C$  ratio (Fig. 4). This result can easily be explained by the increase of combustion extent as  $O_2/C$  increases. The H<sub>2</sub> and CH<sub>4</sub> yields decrease when  $O_2/C$  increases (only at 800 °C for CH<sub>4</sub>), which could be due to a partial combustion of these gas species. At 855 °C, the CH<sub>4</sub> and C<sub>2</sub>H<sub>4</sub> yields are not impacted by  $O_2/C$  ratio. No big difference is measurable for SRF2 in comparison with SRF1.

At each of the two temperature levels, the fraction of C in gas species increases with  $O_2/C$  (Fig. 5). At 855 °C, the increase in total C fraction in gas with  $O_2/C$  is nearly only due to the increase of C fraction in CO<sub>2</sub>, while the repartition of C in the other gas species is hardly affected. This shows that in these conditions, when  $O_2/C$  is increased above 0.26, the supplementary O<sub>2</sub> reacts with species other than incondensable ones, namely condensable tar or char, to produce CO<sub>2</sub>. As shown later in the present article (Section 3.2), the variation of carbon content in tar between the different conditions is too low to totally explain such variations. So the increase of C content in CO<sub>2</sub> when  $O_2/C$  increases at 855 °C is due to char oxidation.

At 800 °C, going from pyrolysis to gasification conditions, the increase in C fraction in CO<sub>2</sub> could be partly explained by partial combustion of CH<sub>4</sub> and C<sub>2</sub>H<sub>4</sub> (Fig. 5), but is also linked to char combustion.

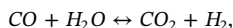
Whatever the conditions, in presence of air, the fraction of C in CO<sub>2</sub> is very close to the  $O_2/C$  ratio. Note that this relation can be verified with all air gasification conditions tested for SRF.

At 800 and 855 °C, the CGE slightly decreases when  $O_2/C$  increases (Table 2). This is linked to the decrease of the yields of gas species with non-null heating value (H<sub>2</sub>, CH<sub>4</sub>, CO). More significantly, when  $O_2/C$  increases from 0.26 to 0.34 at 855 °C, the product gas yield increases from 2.1 to 2.6 Nm<sup>3</sup>/kg daf, while the product gas HHV decreases from 6.3 to 4.4 MJ/Nm<sup>3</sup>, both due to the higher proportion of N<sub>2</sub> in product gas as air/fuel ratio increases. This influence was already observed, even in autothermal conditions in which temperature increases with  $O_2/C$  ratio [5].

### 3.1.3. Influence of steam addition on gas yield and composition

The influence of steam addition on SRF air gasification was investigated in one specific test (Table 2) at  $T = 858\text{--}869^\circ\text{C}$ , with an  $\text{O}_2/\text{C}$  ratio of 0.25–0.27. Two steam quantities were tested, corresponding respectively to Steam/C ratios (in mol/mol) of 0.22 and 0.73. The first value would be equivalent to a moisture content of 14% which is quite close to the moisture content of the raw SRF (before pelletizing).

When Steam/C increases from 0 to 0.73,  $\text{H}_2$  and  $\text{CO}_2$  yields regularly increase, while  $\text{CO}$  yield slightly decreases (Fig. 6). These evolutions can be partly explained by a shift in the equilibrium of water-gas shift reaction as  $\text{H}_2\text{O}$  is added:



However, as  $\text{H}_2$  and  $\text{CO}_2$  yield increases are higher than  $\text{CO}$  yield decrease, a gasification improvement also seems to take place. This is confirmed by the small increase of the total C fraction in gas with Steam/C ratio (Fig. 7).

The  $\text{CH}_4$  and  $\text{C}_2\text{H}_4$  yields are not significantly impacted by steam addition (Fig. 6). So  $\text{CH}_4$  and  $\text{C}_2\text{H}_4$  steam reforming are not enhanced by steam addition in these conditions. A slight inhibiting effect of steam addition on hydrocarbon conversion could even take place with the highest Steam/C ratio (Figs. 6 and 7). Addition of steam in fluidising gas in air gasification of SRF was also previously reported to increase  $\text{C}_2\text{H}_6$ ,  $\text{C}_2\text{H}_4$  and  $\text{C}_2\text{H}_2$  contents at  $850^\circ\text{C}$  [8]. The non-existent or even inhibiting influence of the addition of steam on methane conversion was reported in other types of studies, dealing with methane conversion in a mixture of gas representative of wood pyrolysis ( $\text{CO}$ ,  $\text{H}_2$ ,  $\text{CO}_2$  and  $\text{CH}_4$ ) [12], or in entrained flow gasification of woody biomass [13]. According to Dufour et al. analysis with detailed kinetic mechanisms [14], OH radicals which participate in oxidation reactions of hydrocarbons (reforming) are largely produced from  $\text{CO}_2$  in a  $\text{CO}_2$ -rich gas:  $\text{CO}_2 + \text{H} = \text{CO} + \text{OH}$ . The addition of steam do not significantly modify the concentration of OH radicals then, nor the extent of oxidation reactions.

The product gas yield slightly increases with Steam/C ratio, from 1.9 to  $2.1 \text{ N m}^3/\text{kg daf}$  (Table 2). The product gas LHV does not significantly vary with Steam/C. The CGE is the same (0.53) for Steam/C of 0 and 0.22, but higher (0.59) for Steam/C of 0.73. This higher value is mainly due to the higher  $\text{CH}_4$  and  $\text{C}_2\text{--C}_3$  yields in this condition.

### 3.1.4. Influence of fuel type (SRF/woody biomass) on gas yield and composition

The results obtained with woody biomass (beech wood and waste wood) were compared to SRF results obtained in as close as possible gasification conditions. In the selected conditions, the  $\text{O}_2/\text{C}$  ratios were 0.21, 0.18 and 0.25 for beech wood, waste wood, and SRF respectively (ER of 0.23, 0.19 and 0.24). The temperature was respectively 849, 843 and  $868^\circ\text{C}$ . The fluidising material was silicon carbide for beech wood, and olivine for all the other tests. Silicon carbide is an inert material, whereas olivine is largely used in gasification with the aim to enhance tar conversion. However, previous studies showed that the catalytic influence of olivine was not, or only slightly effective in air gasification of RDF [4,15]. This was attributed to the presence of inorganic pollutants in RDF which inhibited the catalytic effect of iron in olivine [4].

The comparison of results obtained with woody biomass versus those for SRF shows some differences of much greater importance than those noted for the influence of  $T$ ,  $\text{O}_2/\text{C}$  or Steam/C. The  $\text{H}_2$  and  $\text{CO}$  yields are at least 60% higher for woody biomass than for SRF (Fig. 8). On the other hand, the  $\text{CO}_2$  and  $\text{CH}_4$  yields are very close for SRF and beech wood, and lower for waste wood. Note that for SRF with a closer  $\text{O}_2/\text{C}$  ratio to the ones of woody biomass, the  $\text{H}_2$  and  $\text{CO}$  yields would have probably been a bit higher, as the  $\text{H}_2$  and  $\text{CO}$  yields were shown to decrease as  $\text{O}_2/\text{C}$  increases (Fig. 4). However, considering the slight variations in Fig. 4 with  $\text{O}_2/\text{C}$ , the  $\text{H}_2$  and  $\text{CO}$  yields would have stayed most probably right under wood values. The lower  $\text{CO}_2$  yield value for waste wood can be linked to a lower  $\text{O}_2/\text{C}$  ratio than the one of beech

wood. The  $\text{C}_2\text{H}_4$  yield is lower for woody biomass than for SRF. Robinson et al. [7] also reported a higher content of  $\text{C}_2$  and  $\text{C}_3$  hydrocarbons in gas from RDF pellets compared to gas from wood pellets.

In agreement with previous results, the fraction of C in  $\text{CO}$  is much higher for beech and waste wood than for SRF (Fig. 9). On the other hand, the fraction of C in all types of hydrocarbons, excepted  $\text{CH}_4$ , is clearly lower for woods than for SRF. These observations can be explained by the composition of the initial solids, which already at devolatilization stage, lead to different composition of pyrolysis gas. SRF contains a significant part of plastics. Among the main plastics that may be found in SRF, most only contain C and H atoms (polyethylene, polypropylene, polystyrene). Only PET (polyethylene terephthalate) also contains O atoms. Once heated to the gasification temperature, these polymers are mainly converted into condensable hydrocarbons, and to some lighter hydrocarbons:  $\text{CH}_4$ ,  $\text{C}_2\text{H}_6$ ,  $\text{C}_2\text{H}_4$ ,  $\text{C}_3\text{H}_8$ ,  $\text{C}_3\text{H}_6$ , ... as well as  $\text{H}_2$  [16]. As for woody biomass, its higher O content than SRF one (Table 1) is in agreement with a higher fraction of oxygenated product gas species ( $\text{CO}$  and  $\text{CO}_2$ ). This was observed for pyrolysis of RDF and refuse paper and plastic fuel compared to wood pyrolysis at  $700\text{--}900^\circ\text{C}$  [17].

The total carbon conversion into gas is much lower for SRF than for beech wood (74% versus 92%). As for waste wood, the limited total conversion (75%) could be linked to the lower  $\text{O}_2/\text{C}$  ratio as well as a slightly lower temperature ( $843^\circ\text{C}$ ). The same reasons could explain the slightly lower product gas yield for waste wood ( $1.6 \text{ N m}^3/\text{kg daf}$ , Table 2) than for SRF and beech wood ( $1.9 \text{ N m}^3/\text{kg daf}$ ). The product gas LHV is very close for the three types of feedstock. The CGE is much lower for SRF (0.53) than for waste wood (0.61) and beech wood (0.75). The difference is especially linked to the higher energy content in  $\text{H}_2$  and  $\text{CO}$  for woody biomass. As mentioned before,  $\frac{3}{4}$  of the CGE comes from hydrocarbons ( $\text{CH}_4$  included) for SRF, although this contribution is  $\frac{1}{2}$  for woody biomass. The differences between SRF and woody biomass may come in our case partly from the form of the solid fuel (pellets for SRF, small particles for wood). However, the pellets are probably rapidly disintegrated when they enter the high-temperature reactor. Robinson et al. did not see any significant difference between the CGE of wood pellets and RDF pellets at  $800^\circ\text{C}$  in air [7]. On the other hand, in another study, a higher CGE for wood pellets than for wood-PET pellets was found [18].

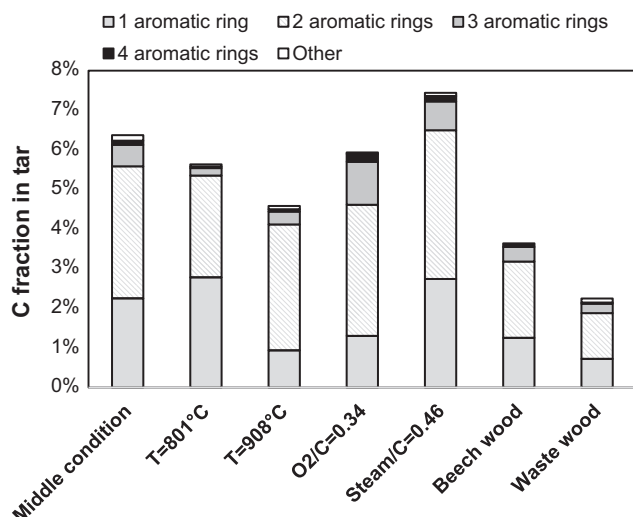
### 3.2. Tar content and composition

Tar sampling by tar protocol was performed for some of the tested conditions. The tar contents (in  $\text{g/N m}^3$  of product gas, without considering additional  $\text{N}_2$  and Ar) are given in Table 2. Benzene, toluene and xylenes (BTX) are not considered here as tar molecules.

One “middle condition” was defined among the conditions for which tar content is available. This condition corresponds to the gasification of SRF2 with a temperature of  $866^\circ\text{C}$  and an  $\text{O}_2/\text{C}$  ratio of 0.30. The tar content is then equal to  $18.6 \text{ g/N m}^3$ . As mentioned before, SRF2 and SRF1 do not show any big difference in gasification.

The influence of steam addition or lower temperature ( $801^\circ\text{C}$ ) on tar content in  $\text{g/N m}^3$  of product gas is not significant (Table 2). On the other hand, with a higher temperature ( $908^\circ\text{C}$ ), the tar content is slightly lower ( $13.6 \text{ g/N m}^3$ ). Woody biomass gasification yields lower tar contents ( $7.9$  and  $10.7 \text{ g/N m}^3$  for waste wood and beech wood respectively), even with lower  $\text{O}_2/\text{C}$  ratio, air/solid fuel ratio and  $\text{N}_2$  dilution than in the SRF middle condition (air/fuel ratio of 1.0, 0.6 and  $0.5 \text{ kg/kg daf}$  respectively for SRF middle condition, beech wood and waste wood).

The analysis of C fraction in tar allows comparing all results without any influence of dilution with inert gas from air. The results are presented in Fig. 10 for all conditions. Tar are classified according to their number of aromatic rings. All quantified tar molecules are presented in Table 3. The major ones are styrene (especially for SRF), indene and naphthalene. Tar classes with one or two aromatic rings are the major



**Fig. 10.** Carbon fraction in tar for the middle condition (SRF2,  $T = 866^\circ\text{C}$ ,  $\text{O}_2/\text{C} = 0.30$ ) and all other conditions referenced according to the main variable parameter (all other parameters presented in Table 2).

ones.

The  $\text{O}_2/\text{C}$  ratio, nor the lower temperature of  $801^\circ\text{C}$ , seem to have a significant influence on the C fraction in tar. Robinson et al. [7] did neither see any significant evolution of tar content for RDF gasification varying the temperature between  $725$  and  $800^\circ\text{C}$  (and ER between  $0.24$  and  $0.31$ ).

A temperature of  $908^\circ\text{C}$  leads to a relative decrease of about 28% of the C fraction in tar compared to the middle condition (Fig. 10). The C fraction in tar compounds with one aromatic ring is then especially lower. With addition of steam, the C fraction in tar increases of 22% in comparison with the middle case. All tar classes are then impacted. Similarly to what was observed for light hydrocarbons (Section 3.1.3), it seems that addition of steam could have an inhibiting role towards tar conversion. Even if this inhibiting effect was not reported, the inefficiency of steam addition for tar conversion was already observed. Hwang et al. [17], who compared RDF pyrolysis and steam gasification at several temperatures, from  $500$  to  $900^\circ\text{C}$ , observed that C fraction into tar strictly depended on temperature but was not influenced by pyrolysis/steam gasification conditions. Jess [19] studied kinetics of thermal conversion of benzene, toluene and naphthalene in a typical pyrolysis gas and put into evidence that steam had no or only little influence on reaction rates.

At last, the carbon fraction in tar is 43–65% lower for beech wood and waste wood than for SRF in middle condition. Similarly to what was stated before for light hydrocarbons, this can be linked to the presence of polymers coming from plastics, foams and polystyrene in our SRF pellets, which tend to form more heavy hydrocarbons than biomass.

**Table 3**  
Quantified tar molecules.

1 aromatic ring	2 aromatic rings	3 aromatic rings	4 aromatic rings	Other
Ethylbenzene	Naphthalene	Phenanthrene	Pyrene	Thiophene
Styrene	1-methylnaphthalene	Anthracene		Pyridine
$\alpha$ -methylstyrene	2-methylnaphthalene	Fluoranthene		
Benzofuran	Biphenyl			
Indene	Acenaphthylene			
Phenol	Acenaphthene			
	Dibenzofuran			
	Fluorene			

### 3.3. Inorganic non condensable pollutant content

The inorganic elements which are released from the reactor in gas phase are nitrogen (in  $\text{NH}_3$  mainly), chlorine (in  $\text{HCl}$  and  $\text{KCl}$ ), and sulphur (in  $\text{H}_2\text{S}$ ,  $\text{COS}$  and sulphur containing tars, such as thiophene). In our experiments, the measurements of nitrogen and chlorine were not satisfactory, with elemental balances far from being closed. Only results concerning  $\text{H}_2\text{S}$  and  $\text{COS}$ , quantified by  $\mu\text{GC}$  are thus presented. Among the different parameters that were varied in the present study, the gasification temperature and steam addition were found to have a significant influence on the fraction of sulphur in  $\text{H}_2\text{S}$  and  $\text{COS}$ . The results obtained with and without steam addition are thus presented separately as a function of temperature in Fig. 11. The results obtained for woody biomass, and for SRF pyrolysis, are also presented separately. Fig. 11a and b show respectively the fraction of S in  $\text{H}_2\text{S} + \text{COS}$ , and the concentration of  $\text{H}_2\text{S}$  in  $\text{g}/\text{N m}^3$  of dry product gas, without considering additional  $\text{N}_2$  and Ar.

The fraction of sulphur in  $\text{COS}$  is always more than 10 times lower than the fraction of sulphur in  $\text{H}_2\text{S}$ . In air gasification of SRF, the S fraction in  $\text{H}_2\text{S}$  and  $\text{COS}$  lies between 43 and 70%, and globally tends to increase with temperature (Fig. 11a). A higher S fraction is especially noticeable at the highest temperature. As for  $\text{H}_2\text{S}$  concentration, its evolution with temperature is less clear; the  $\text{H}_2\text{S}$  content in dry gas for SRF air gasification is comprised between 1 and  $2\text{ g}/\text{N m}^3$ . The  $\text{COS}$  content (not represented) is comprised between  $0.1$  and  $0.2\text{ g}/\text{N m}^3$ . The addition of steam to air in SRF gasification clearly induces a higher S fraction in  $\text{H}_2\text{S}$  and  $\text{COS}$ , as well as a higher  $\text{H}_2\text{S}$  concentration. For steam/C ratio of  $0.73$ , almost 100% of sulphur is in gas phase. On the other hand, for pyrolysis conditions, only a few percent of sulphur are released in  $\text{H}_2\text{S} + \text{COS}$ . Sulphur could then mainly remain in the solid. In gasification conditions, reaction of  $\text{O}_2$  with the char could lead to S release with formation of  $\text{H}_2\text{S}/\text{COS}$ . When steam is added or temperature is the highest, char gasification was shown to be enhanced, inducing a higher sulphur release in  $\text{H}_2\text{S}/\text{COS}$ .

At last, the S fraction in  $\text{H}_2\text{S}/\text{COS}$  seems to be slightly lower for woody biomass than for SRF for the same temperature. As sulphur content in biomass is much lower than in SRF, the  $\text{H}_2\text{S}$  content is also much lower (under  $0.25\text{ g}/\text{N m}^3$ , Fig. 11b), while the  $\text{COS}$  content is under  $0.05\text{ g}/\text{N m}^3$ .

## 4. Conclusion

Our objective was to study fluidized bed air gasification of solid recovered fuel, and to compare it to the gasification of woody biomass (beech wood sawdust, and waste wood). The experimental results were analysed with the objective to decorrelate the influence of several operating parameters: temperature,  $\text{O}_2/\text{C}$  (air/ fuel) ratio, addition of steam.

Temperature, varying between  $800$  and  $900^\circ\text{C}$ , was shown to increase  $\text{H}_2$  and  $\text{CO}$  yields, which was mainly attributed to char gasification enhancement. The influence of temperature on hydrocarbon yields was rather limited, excepted at  $908^\circ\text{C}$ , at which  $\text{CH}_4$  yield was increased and C conversion to tar decreased.  $\text{CH}_4$  may then has been

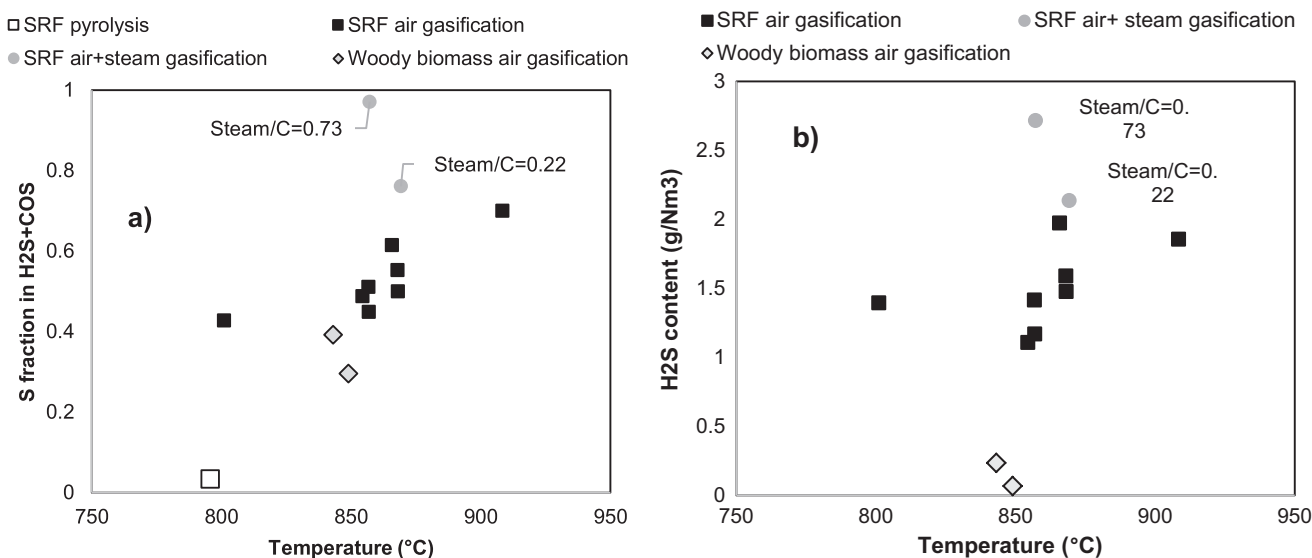


Fig. 11. a) S fraction in  $H_2S$  and  $COS$  – b)  $H_2S$  content in dry gas – as a function of temperature.

formed from tar conversion.

As  $O_2/C$  ratio was varied between 0 (pyrolysis conditions) and 0.34, the  $CO_2$  yield was increased accordingly, in agreement with an increasing extent of partial combustion reactions. Compared to pyrolysis conditions, the main species which seemed to be oxidised by  $O_2$  were  $CH_4$ ,  $C_2H_4$ ,  $H_2$  but also char.

The addition of steam in fluidising gas induced an increase in oxygenated gas species yields ( $CO + CO_2$ ), related to char gasification improvement. On the other hand, the addition of steam did not have any reforming influence on light hydrocarbon and tar, and a slight inhibiting effect could even be detected.

Woody biomass and SRF had significantly different product yields. The differences were qualitatively explained by the initial elemental composition of each type of fuel: the biomass having a much higher O initial content, its devolatilization leads to higher  $CO + CO_2$  yields. The higher hydrocarbon yields obtained with SRF are also to be related to their significant plastic contents.

Sulphur release to the gas phase was shown to be very low in pyrolysis conditions, to slightly increase with temperature in gasification conditions, and to be nearly total with addition of steam. This was linked to char partial combustion going from pyrolysis to gasification conditions, and to a higher char gasification extent with higher temperature or addition of steam.

From a process point of view, these results show that a higher temperature should be preferred to enhance gasification efficiency and decrease tar content. Addition of steam could also be effective to enhance gasification, but seem to have a negative influence on tar production. However, the efficiency improvement by varying the gasification conditions for SRF is limited compared to the higher efficiency obtained with woody biomass (CGE and carbon fraction into gas of 75% and 92% respectively for beech wood, compared to 59% and 80% maximum respectively for SRF). Co-gasification of biomass – possibly waste wood - and SRF, could be a way to improve the overall efficiency of the conversion, and limit pollutant content.

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