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1	Gasification of N-rich fibreboard in an air-blown
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5	Authors and affiliations:
6	M.Ruiz ^a , A. Schnitzer ^{a,b} , P. Arnoux ^a , G.Mauviel ^a
7	^a LRGP, CNRS, University of Lorraine, ENSIC, 1 Rue Grandville, Nancy, France
8	^b University of Lorraine, LERMaB, ENSTIB, 27 Rue Philippe Séguin, PO Box 1041, F-88051 Epinal,
9	France
10	
11	Corresponding author:
12	Miguel Ruiz (Miguel.ruiz@keemail.me)
13	
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21 1. Introduction

22 Gasification is a thermochemical conversion route to transform biomass and wastes to a gas vector 23 (syngas) with proven potential to replace fossil fuels in the production of heat, power and chemicals. 24 When air is employed as gasification agent, the resulting syngas is diluted by N_2 and, generally 25 referred as producer gas. Producer gas typically presents pollutants, such as: char/ash particles, tars 26 and inorganic gases that restrain its applications and jeopardize long term operation of gasification 27 plants. To resolve this issue, several physical, chemical and catalytic clean-up strategies have been 28 developed [1–3]. Depending on their positioning in the gasification system they can be classified as 29 primary and secondary methods. The combination of primary and secondary methods has shown 30 high efficiency in the reduction of pollutants but, as a general rule-of-thumb, the overall economy of 31 the process will be negatively affected with increasing complexity of the clean-up system. Ergo, 32 developing simple and inexpensive producer gas clean-up strategies is necessary to foster the 33 development of the gasification route.

34 Hot Gas Filtration (HGF) is a robust and simple clean-up technique with proven efficiency to 35 simultaneously remove dust particles and reduce tar concentration [4]. When a HGF is coupled 36 downstream a gasification reactor, particles transported in the producer gas flow are retained on the 37 filter surface and form the filter cake. These particles, hereafter referred as "dust", include char, soot, ash and material elutriated from the reactor in the case of fluidized bed reactors. The filter cake 38 39 build-up presents two major outcomes. Firstly, dust particles, in particular char, can act as 40 heterogeneous catalyst for tar abatement. Secondly, as the dust cake builds-up, the pressure drop 41 across the filter increases continuously compromising the long-term operation of the system. 42 Because of their high importance these two key aspects are discussed hereafter.

Catalytic activity of char for the abatement of tar is known and already exploited in the operation of staged gasification reactors [5]. In contrast to metal and mineral catalysts, chars are by-products of the gasification process and thus, cost-free materials. These two advantages explain the increasing interest of the community to unveil the reactional pathways and kinetics of tar decomposition reactions when char is used as catalyst. Available literature about the decomposition of tar model compounds over activated/non-activated char has been recently reviewed [6,7]. Main conclusions from these studies are summarised below:

Catalytic activity of char particles depends on several factors mainly related to the
 physicochemical properties and structure of the parent biomass particles, the char
 production parameters and the heterogeneous reaction conditions, in particular, the
 reaction temperature.

Carbon deposition (or coking) is the main mechanism of the decomposition of model tar
 molecules.

Coking leads to the loss the catalytic activity of char particles. Nevertheless, catalytic activity
 can be maintained if gasification rate of char/coke is equivalent or greater than the coke
 formation rate.

59 Although studies conducted under simulated environment are abundant and provide fundamentals, 60 HGF studies performed on real producer gas environment at bench/pilot scale are scarce. Indeed, 61 few data are available regarding the impact of dust particles accumulated on the HGF surface on the 62 composition and yields of pollutants. Tuomi and co-workers [8] studied the behaviour of tars produced from steam and air/steam atmospheric bubbling-bed gasification reactor coupled with a 63 HGF kept at 800°C and equipped with ceramic candles. GC-MS characterization of tars samples 64 65 recovered upstream and downstream the HGF unit revealed a decrease in total tars concentration 66 regardless of the used feedstock, bed material or gasifying agent but, contradictory results were 67 found regarding the impact of HGF on the heaviest tar fraction. Moreover, Chun-Zhu Li and coworkers [9–11] integrated a char fixed bed on the top of a pilot plant gasification reactor to perform hot gas cleaning of producer gas using char and iron loaded biomass char and coal catalysts. UVfluorescence spectroscopy analysis of tar samples indicated that iron loaded char was the most active catalyst in the decomposition of large aromatic ring compounds. Furthermore, catalyst integration in HGF candles is a strategy with great potential to reduce tar in producer gas [12–16]. However, higher cost and limited lifespan of the catalytic elements currently jeopardize its application into an industrial scale.

75 Long term operation is a key issue in HGF units. Two phenomena are closely linked to the progressive 76 loss in filter permeability. First, slag formation due to irreversible ash aggregation and sintering. This 77 phenomenon is generally intensified for filtration temperatures above 600°C and ash-rich feedstocks 78 [4], although stable filter operation can be achieved even at filtration temperatures close to 800°C 79 provided that bed material and back pulse parameters are carefully chosen [17]. Second, the 80 formation of a soot-rich sticky layer on the surface of the filter. This phenomenon is generated by the 81 polymerization of high molecular weight tar species and amplified in the case of a particle-poor and 82 tar-rich producer gas [18]. Oxidative HGF has been shown to provide a simple solution to overcome 83 this issue. Indeed, the oxidation of the soot-rich sticky layer is accomplished by the injection of an 84 additional air flow into the filter vessel. Lang et al.[19] performed oxidative filtration tests on an 85 air/steam blown 1 MW_{th} mixed-draft fixed-bed biomass gasifier at a filtration temperature between 86 400-600°C. These authors reported dust and tar removal efficiencies greater than 90% with stable 87 pressure drop for over 200 h but, no information was given regarding the impact of oxidative hot gas 88 filtration neither on the composition of tars nor on the content of acid gases.

In this study, the HGF strategy applied differs from the previous approach used for HGF in gasification processes. First, in our system, no back-pulse system was used to remove the dust cake accumulated on the filter surface during the HGF tests. The purpose of keeping in place the dust cake was to promote heterogeneous reactions between the dust cake particles and the producer gas. Second, the

filtration temperature targeted inside the HGF unit was in a "mild" range between 400-600°C. 93 94 Although the temperature targeted might be low to promote tar conversion, which is known to 95 become significant above 800°C [20], this mild temperature range was selected to reduce the 96 formation of ash deposits on the filter surface and thus, limit the irreversible agglomeration, melting 97 and sintering of ash in the porosity of the filter. Additionally, regarding construction cost of the HGF 98 unit, the utilisation of mild filtration temperature reduces the material requirements and thus, their cost. Third, in this study, a new technology of multilayer metallic filtration cartridges was selected 99 100 instead of ceramic candles. Fourth, and similarly to the research conducted by Lang and co-workers 101 [19], a controlled flow of secondary air was injected in the mainstream of producer gas at the entry 102 of the HGF unit.

103 Therefore, using this innovative strategy of oxidative HGF, a N-rich feedstock, consisting in pellets of 104 Medium Density Fibreboard (also known as MDF), was gasified in an air-blown bubbling bed reactor 105 at 800°C coupled with the downstream HGF unit. To the best of our knowledge, studies dealing with 106 the gasification of MDF feedstocks are scarce in literature and mostly concerns the thermal 107 degradation studies conducted under pyrolysis conditions [22,23]. Williams et al. [24] carried out 108 several gasification experiments with briquetted MDF feedstock in a down-draft air-blown reactor 109 coupled with a diesel engine generator. Authors reported smooth operation of the system and 110 calorific values of producer gas identical to those of standard hardwood chip fuels but, yet again, no 111 information was communicated on pollutant content of the gas. The present study seeks to address 112 this gap by the utilisation of complementary analytical techniques to map the fate of tars and 113 nitrogen derived species (NH₃ and HCN) during oxidative HGF. The effects of the secondary air flow 114 rate and the dust loading on gasification indicators and pollutant content were also investigated. 115 Additionally, filter clogging mechanisms were investigated based on SEM-EDX analyses of the filter 116 surface.

117 2. Materials and methods

118 2.1. Feedstock material

119 Feedstock material used in this study was Medium Density Fibreboard (MDF) waste from the 120 furniture industry provided by RAGT Energy (Albi, France). Grinding of waste MDF produced a very 121 low-density fluffy material with poor bulk flowability that systematically blocked the screw feeding system of the gasifier. To avoid flowability issues, the MDF fluffy material was pelletized. Table 1 122 123 presents proximate, ultimate analysis and elemental ash composition of the feedstock material. Proximate analysis was conducted according to French standards NF EN ISO18134. Ultimate analysis 124 125 was conducted according to standards ISO 16948 and ISO 16994. MDF typically presents a high content in Fuel Bounded Nitrogen (FBN) due to the utilisation of urea-formaldehyde resin for its 126 127 production. Ash melting temperatures of biomass samples were determined according to French standard CEN/TS 15370-1. 128

129 Table 1: Feedstock analyses.

Composition of MDF feedstock	
Moisture, wt.%	8.6
Volatile content, wt.% (db)	88
Ash wt. % (dry base)	0.42
Ultimate analysis, wt.%(db)	
С	49.6
Н	6.02
Ν	3.47
S	0.008
Cl	0.005
Ocalculated by difference	40.48
Major metallic elements in Ash	
composition, mg/kg _{feedstock} (db)	
Са	791
К	890
Mn	111
Mg	274
Na	61
Р	91
Si	<100
Minor metallic elements in Ash	
composition, mg/kg _{feestock} (db)	
As	<0.8
Al	45
Cd	<0.2
Cr	<1
Cu	1
Fe	41

Ni	<1
Pb	<2
Zn	16
Hg	<0.05
Со	<1
Мо	<2
Ті	3
Sb	<1
V	<1
Ash melting temperatures (°C)	
Initial deformation temperature	1070
Softening temperature	1420
Hemispherical temperature	1460
Fluid temperature	1490

130

131 2.2. Pilot-scale fluid bed gasification reactor system

A scheme of the pilot-scale gasification rig is depicted in Figure 1. Main elements of the experimental rig are fully described elsewhere [25]. For the present study, several modifications have been carried out with respect to the original system, in particular, regarding the fuel feeding system and feed injection point, as well as, the pollutant sampling set-up.





138 Figure 1: Scheme of the pilot-scale gasification rig. A picture of the installation was included in Appendix A.

139 Briefly, the experimental rig was composed of 4 main modules: (i) a continuous fuel feeding system, 140 (ii) a bubbling fluidized bed reactor, (iii) a cyclone and, (iv) a gas cooling and wet scrubbing cleaning 141 system. Feedstock material was continuously introduced from the fuel tank to the reactor bed, 142 approximately 15 mm above the distributor plate, by a double screw system. 20 L/min (STP) of pure 143 nitrogen was continuously feed through the feedstock alimentation system for inertization and 144 pressure stabilisation purposes. The gasification reactor was divided into three zones: the plenum (d=100mm, H=300mm), the bed zone (d=100mm, H=800mm), and the freeboard zone (d=140mm, 145 146 H=800 mm). The reactor was externally heated by four electrical resistances and thermally insulated. 147 Air was used as gasifying agent in all experiments. Primary air was injected at constant flow 4540 148 NL/h (Brooks 5851s) into the plenum zone of the reactor. Additionally, a second flowmeter (Brooks 149 5850s) was installed in parallel to assure system purge operations with pure nitrogen if required. For 150 each test, 4 kg of fresh olivine (VANGUARD[™], SIBELCO) was used as bed material (particle size 200-151 600 μ m). Fluidisation velocity was two times greater than the minimal fluidisation velocity (U_{mf}) 152 equals to 0.3 m/s at 800°C (as measured in this set-up). Under these conditions, gas residence time 153 inside the reactor was 4 s. Downstream of the gasification reactor, coarse solid particles were 154 removed from the main gas stream with a cyclone separator. Then, the producer gas was cooled 155 down in three heat exchangers before introduction in a wet venturi scrubber. To compensate 156 pressure-drop across the gasification rig, a side channel blower (SCL 06R, EFFEPIZATA) was installed 157 downstream the venturi scrubber and operated at constant flow rate during the tests. Finally, the 158 producer gas was burned before evacuation.

To carry out the filtration experiments, the cyclone separator was replaced by a HGF unit. A scheme of the HGF unit is depicted in Figure 2. The HGF unit was composed of a preheating zone, a gas mixing zone and a filter housing; each zone was electrically heated and thermally insulated. For all HGF tests, the temperature set-point of the filter housing heating system was fixed at 450°C. The temperature inside the HGF unit was continuously measured at different points (see Figure 2). Multilayer filtration cartridges, provided by the company GKD (Düren, Germany) [21], consisted of an 165 outer thin metal fabric with a mean pore size of 10 µm followed by a 2-3 mm layer of non-woven metal fibres supported on a metallic frame. To the best of our knowledge, these filters were used for 166 the first time downstream a gasifier. Two sets of two metallic cartridges each (ID=40 mm, ED= 60mm, 167 L=600 mm) were used in this study. No back-pulse system was employed in any of the filtration tests 168 169 in order to increase the contact time between the filter cake and the producer gas. Filter cake 170 oxidation was accomplished by the injection of a secondary air flow into the HGF unit. The temperature of the secondary air flow could be independently modulated by a preheater but, for all 171 172 filtration experiments, the preheater was switched off and the secondary air flow was injected at 173 ambient temperature. The main operational parameters of the HGF unit are detailed in Table 2. Face 174 filtration velocity was calculated as the ratio between the flowrate of producer gas and the total 175 filtration surface (see Equation A.1, Appendix A).



Figure 2: A schematic view of the hot gas filtration unit and the multilayer metallic filter mesh. Thermocouple T2 measured the temperature of the mixing zone and T3 measured the temperature of the dirty side. The temperature of the clean gas side was calculated as the average temperature measured by thermocouples T4 and T5, placed at the clean side of the filtration cartridges.

181 2.3. Sampling and Analytical methods

176

Permanent gases, tars and acid gases contained in the producer gas were sampled downstream of the first heat exchanger where the temperature of the producer gas was between 350 and 400 °C. A small flow of producer gas (5 to 7 L/min, STP) was continuously derived from the mainstream and

- sent through a heated line kept at 450°C to three sampling trains, namely: the μ GC, the tar protocol
- and the acid gas. Figure 3 depicts a scheme of the sampling system.



188 Figure 3: Scheme of the sampling system.

187

Producer gas composition was measured by a µGC analyser (Variant micro-GC 490, 4 modules) every 3 minutes. To avoid line clogging, producer gas was continuously scrubbed through an impinger train composed of 7 impinger bottles filled with glass beads (OD 5 mm) and 2-propanol. A bottle filled with silica gel balls was placed downstream the impinger train to adsorb moisture and protect the pump. N₂, CO, CO₂, H₂, CH₄, C₂H₂, C₂H₆, C₃H₄ and C₃H₆ were quantified by this technique using N₂ as a tracer.

195 Tar quenching was carried out based on a version of the standard method described in the European 196 Tar Protocol (CEN/TS 15439). A volume of 60 L (STP) of gas was scrubbed at 2 L/min through an 197 impinger train composed of 8 impinger bottles (500 mL) with 2-propanol (analytic grade). To assure 198 stable pressure drop across the impinger line, frits were replaced by glass balls beads (OD 5 mm). The volume of the glass balls beads was about 400 ml. The configuration of the impinger train is detailed 199 200 in Table A.1 (Appendix A). Liquid from the impingers 1 to 7 was added in a recipient and stocked at 201 15°C until analysis. Collection efficiency of the impinger train was systematically verified by analysing 202 separately the liquid collected in impinger n°8 by HPLC and GC/MS-FID. A bottle filled with silica gel 203 balls was placed downstream the impinger train to protect the pump. The precise volume of sampled 204 gas was measured with an auto-regulated pump (Gilian GilAir Plus) and corrected to standard

pressure and temperature. Impinger bottles and glass beads were thoroughly washed with acetone after utilisation. Compared to other tar sampling methods, such as Solid Phase Adsorption [26], relatively long sampling time (approx. 30 min) used in the wet method reduced the uncertainty linked to the fluctuations on the composition and tar content of producer gas along the time, as a result of small variations in the feed throughput. However, longer sampling time and labour required for the wet sampling method prevent its utilisation for time resolved tar analysis.

211 Low molecular weight tar species were quantified with a simplified version of the GC*GC/MS-FID-FID 212 method fully described elsewhere [27]. Briefly, one microliter of the solution (sample and internal 213 standard) recovered from tar protocol was injected with a split ratio 1:50 in an Agilent 7890 gas 214 chromatographer (HP-5MS column). The oven temperature program was: 50°C hold (hold for 7 min), 215 then increased at 10 K/min to 250°C (hold for 20 min). The exit of the HP-5MS was connected 216 simultaneously to the FID and to the MS detectors. Quantification was carried out according to 217 predictive FID response factor method of de Saint Laumer [28], using 1-tetradecene as internal 218 standard. A list of low Mw molecules quantified by this method can be found in Table A.2 (Appendix 219 A).

220 Quantitative analysis of high molecular tar species (Polycyclic aromatic hydrocarbons or PAH) was 221 conducted by HPLC (Shimadzu SCL-10Avp) coupled to UV detection (Shimadzu SPD 10Avp) operated 222 at 254 nm. Standard calibration lines were calculated for five levels of standard concentration (TCL 223 16 PAH Mix, Supelco) and each point was repeated at least 2 times. A PHENOMENEX Envirosep PP 224 C18 column (5 μ m particle size, 125 mm x 4.6 mm i.d.) was operated at ambient temperature with a 225 Shimadzu LC 10 ADvp pump. An elution gradient was applied using acetonitrile/water at a flow rate 226 of 0.8 ml/min. The injection volume was 10 µl. A list of high Mw molecules quantified by this method 227 can be found in Table A.2 (Appendix A).

Semi-Quantitative analysis of overall tar composition was conducted by UV-Absorbance (UV-A) and
 Synchronous Fluorescence Spectroscopy (SFS). Absorption spectra were recorded on a Shimadzu UV-

230 3600 UV-visible double beam spectrophotometer using a standard quartz cell with 1 cm path length 231 and 2-propanol as blank. Emission and Synchronous Fluorescence (SF) spectra were recorded on a 232 Horiba spectrofluorimeter Fluorolog FL3-222 equipped with 450 W Xenon lamp, a thermo-stated cell 233 compartment (25°C) and a Hamamatsu UV-visible photomultiplier R928. To perform semi-234 quantitative analysis, all analytical solutions were prepared by dilution in 2-propanol to 5000 ppm 235 (v/v). Analytical concentration was previously determined to obtain an absorbance value of 0,25 at a 236 wavelength value of 254 nm for a sample corresponding to the reference tests. Indeed, a high 237 dilution ratio of analytical samples is known to minimise the quenching effect while ensuring a high 238 dependence between the structure of a given PAH family and the spectral profile [29]. Moreover, the 239 SF spectra were recorded in a range between 200 and 600 nm with an offset ($\Delta\lambda$) of 3 and 20 nm and 240 a bandwidth of 2 nm. The values of $\Delta\lambda$ used in this study were selected with different analytical 241 purposes. On the one hand, the SF spectra recorded at $\Delta\lambda$ =3 nm gives a precise fingerprint of the 242 sample composition due to the reduction of spectral bandwidth and thus, of spectral overlaps [30]. 243 On the other hand, the SF spectra recorded at $\Delta\lambda$ =20 nm represent an acceptable trade-off between 244 the spectra intensity for most of PAH molecules and the spectra resolution, providing an overall 245 vision of the "gross" composition of the sample [31]. Furthermore, considering the heterogeneity of 246 $\Delta\lambda$ values and solvents employed in literature for the acquisition of the SF spectral data of aromatics 247 and model PAHs molecules, the SF spectra these molecules, typically present in high concentration in 248 the reference tests tar samples, were determined. Finally, to take into account the "dilution effect" 249 of the SF spectra (as a result of the injection of secondary air in the HGF unit), fluorescence intensity 250 was normalised with the volume of gas sampled and then, multiplied by the gas yield defined by 251 Equation B.2 (Appendix B).

Inorganic gases NH_3 and HCN were quenched separately in two impinger trains consisting in three glass impingers with frit, placed in series and kept in an ice bath (Figure 3). A bottle filled with silica gel balls was placed downstream the impinger train to protect the pump. The sampling procedure was adapted from previous articles [32,33]. Briefly, 150 mL of acid (H_2SO_4 0.1N) and basic (NaOH 0.1M) solution was poured in each impinger and cooled for 20 min in the ice bath before quenching.
A volume of 5 L (STP) of gas was sampled at 1 L/min with an auto-regulated pump (GilAirPlus, GILIAN)
and corrected to standard pressure and temperature. Liquid recovered in each impinger was
analysed separately to verify the collection efficiency. All samples were stored at -7°C until analysis.
Quantification of targeted ions was carried out by ion chromatography according to French
standards: NF X43 303 for NH₃ and NF T90-107 for HCN.

262 Filter dust cake particles were dislodged from the filter cartridge by gentle shaking and thoroughly 263 mixed to assure homogeneity prior to analysis. Analytical techniques used for the characterisation of 264 cyclone and dust cake particles include: elemental analysis, carried out with a Thermo Fisher 265 apparatus (Flash EA 1112), and inorganic element quantification by ICP-AES, carried out according to 266 French standards NF EN ISO 16967 and NF EN ISO 16968. Additionally, the PAH content of solid 267 particles recovered from the cyclone and the filter dust cake was compared by Synchronous 268 Fluorescence Spectroscopy after solvent extraction. Briefly, both samples were extracted with 2-269 propanol (0.1 g of solid / 100 mL of solvent) for 3 days under agitation at 30°C. Solutions were 270 filtered (0.45 μ m) and then analysed by SFS at $\Delta\lambda$ =20 nm without dilution. Finally, a Scanning 271 Electron Microscope (SEM) coupled with Energy Dispersive X-Ray (EDX) (JEOL JSM6490 LV) was used 272 to analyse the surface of the filter cartridge.

273 2.4. Experimental plan and calculation methods

As detailed in Table 2, nine experiments were conducted under different system configurations and operational parameters to assess the impact of oxidative HGF on gasification indicators and pollutant content.

277 Table 2: System configuration, nomenclature and target conditions for all experiments.

System configuration	Test code	ER _{reactor}	Secondary air flow rate in HGF unit (NL/h)	ER _{HGF}	ER _{total}	Test duration (h)
Reference	REF (x3)	0.25	0	0	0.25	2

(cyclone)	REF-0.3	0.3	0	0	0.3	2
thermal (HGF without filters)	th-0.05	0.25	910	0.05	0.3	2
	HGF-0	0.25	0	0	0.25	4
HGF (HGE with filters)	HGF-0.05	0.25	910	0.05	0.3	4
	HGF-0.1	0.25	1950	0.1	0.35	4
Cyclone + HGF	cy-HGF-0.05	0.25	910	0.05	0.3	4

278

First, a series of three reference tests (REF) was carried out under the standard cyclone configuration (depicted in Figure 1) and identical conditions to determine the experimental and analytical uncertainty. Operational parameters inside the gasification reactor, namely: the primary air flow rate, the reactor wall temperature, the primary air-to-feedstock equivalence ratio (ER) and the feedstock throughput, were kept constant at a value of 4500 NL/h, 800°C, 0.25 and 4.5 kg/h (as received), respectively. Results reported for REF test corresponds to the average value calculated from the three repeated tests. Standard deviation values were also included.

Second, the effects of a rise in the ER were determined in the REF-0.3 test under the standard cyclone configuration (see Table 2). For that, the ER inside the reactor was increased from 0.25 to 0.3 by reducing the feedstock throughput from 4.5 to 3.5 kg/h while keeping constant the flowrate of primary air. Therefore, fluidisation regime and residence time inside the reactor were roughly unchanged with respect to the reference tests.

Third, after replacing the cyclone separator by the HGF unit, a thermal test (referred as th-0.05) was conducted by injecting a flow of secondary air into the HGF unit but without any filtration cartridge inside. The aim of the thermal test was to determine the effects of secondary reactions in homogeneous (gas-gas) phase on gasification indicators and pollutant content.

Fourth, three filtration tests were conducted under the HGF configuration by placing two metallic filtration cartridges inside the HGF unit to study the effect of the secondary ER (referred as the ER_{HGF}). The three filtration tests, namely: HGF-0, HGF-0.05 and HGF-0.1, were carried out at secondary air flow rates values of 0, 1000 and 2000 NL/h, leading to ER_{HGF} values of 0, 0.05 and 0.1,
 respectively.

Finally, the effect of dust loading in the HGF unit was assessed in the test cy-HGF-0.05 by integrating the cyclone between the reactor and the HGF unit. The duration of all filtration tests was fixed to 4 h in order to amplify dust accumulation on the filter surface. Tar and acid gas sampling were systematically performed during the last 40 min of each test.

The performance of the gasification process was assessed using four output indicators, namely: Low Heating Value (LHV), Gas yield (η_{gas}), Cold Gas Efficiency (CGE) and Carbon Conversion (%C), fully described in the Appendix B. Gasification indicators were calculated excluding the benzene of the composition of the producer gas. Nevertheless, since the presence of benzene in produced gas is not an issue for engine application, gasification indicators were also calculated including benzene in the composition of produced gas and detailed in Table B.1 (Appendix B).

310 The conversion percentage of tars was calculated according to Equation 1, using the average value 311 determined for the three reference tests as reference value.

Conversion,
$$\% = \frac{(\gamma_i - \gamma_{REF})}{\gamma_{REF}} * 100\%$$
 Equation 1

312 Where γ represents the yield value of each group or molecule (in g/kg_{feed daf}) quantified in this study.

313 3. Results and discussion

314 3.1. System operation and process conditions

Table 3 details the results of the main operation parameters, gasification indicators, gas concentrations and product yields for all experiments conducted in this study. For the sake of clarity, tar yields were specified according to ECN tar classification [34]. The individual yield values of all gas and tar molecules quantified in this study were detailed in Table A.2 (Appendix A). The overall carbon 319 balance closures were above 80% in all tests, whereas for the hydrogen and oxygen balance closures 320 were between 45-50% and 65-80%, respectively. The low closures values obtained for hydrogen and 321 oxygen can be ascribed to the unquantified water. On the contrary, the deviation in carbon balance 322 can be firstly explained by a numerical artifact that arose from the small variations observed in the 323 instantaneous concentration of CH₄ and CO and the relatively long analytical time of the μ -GC. These 324 variations, that in any case exceeded ± 2 points of the average value, were generated by small fluctuations of the feed throughput. Secondly, it seems that not all carbon could be retrieved since 325 326 some deposits were formed inside the condensation system. However, the mass of these deposits 327 was negligible compared to the mass of feed used in each test.

328 Reactor temperature was close to the target value and remained steady for all tests. In the case of 329 the HGF unit, the temperature in both, the dirty side and the gas mixing zone of the HGF unit was 330 roughly consistent between the different filtration tests and close to the set point temperature 331 (450°C). On the contrary, the temperature in the clean side of the filter rose notably for the tests 332 HGF-0.05 and HGF-0.1 leading to values of 523°C and 631°C, respectively. In the case of the test HGF-0.1, the temperature of the clean and dirty side of the HGF showed a progressive and continuous 333 increase after the injection of the secondary air. Latter trend is further discussed in section 3.4.2. 334 335 Finally, the superficial filtration velocity was kept between 2 and 3 cm/s and residence time of the 336 gas inside the filter ranged between 12 and 16 s for all filtration experiments.

Table 3: Main operation conditions, gasification indicators, gas compositions and product yields for all tests conducted in
 this study. Relative deviations are presented for the reference tests and corresponds to three separate experiments.

Code of the test	REF	REF-0.3	th-0.05	HGF-0	HGF-0.05	HGF-0.1	Cy-HGF- 0.05
Gasifier							
Fuel feed rate, kg/h _(as received)	4.5 ± 0.1	3.5	4.5	4.4	4.5	4.5	4.4
Bed temperature, °C	800 ± 2	805	796	797	797	799	796
Freeboard temperature, °C	757 ± 1	758	761	758	758	759	759
ER _{reactor}	0.25 ± 0.01	0.33	0.26	0.26	0.26	0.25	0.26
Hot Gas Filtration unit							
Secondary air feed rate, NL/h	-	-	960	0	960	2040	960
Gas mixing zone temperature, °C	-	-	434	457	435	405	427
Filter temperature, °C (dirty side)	-	-	424	431	431	486	418
Filter temperature, °C (clean side)	-	-	455	453	523	631	465
Face filtration velocity, cm/s	-	-	-	2.3	2.9	3.4	2.8

Cas residence time inside the filter s			12.2	16 1	12.0	12.2	12.6
Gas residence time inside the inter, s	-	-	15.2	10.1	15.0	12.5	15.0
	-	-	0.05	0	0.05	0.11	0.06
ER _{total}	0.25 ± 0.01	0.33	0.31	0.26	0.31	0.37	0.32
Gas composition, %mol (N ₂ -free, dry)							
H ₂	17.4 ± 0.6	15.2	15.6	16.8	14.8	14.6	15.5
CO	29.3 ± 0.2	29.1	27.8	28.9	28.7	26.4	28.1
CO ₂	39.8 ± 0.4	42.9	39.5	40.1	42.6	47.1	39.9
CH ₄	9.1 ± 0.1	8.7	8.3	9.0	8.9	7.8	8.7
C ₂ H ₂	0.33 ± 0.02	0.32	0.29	0.30	0.2	0.05	0.28
C ₂ H ₄	3.0 ± 0.1	2.8	2.8	3.0	2.8	2.5	2.7
C ₂ H ₆	0.36 ± 0.01	0.32	0.34	0.34	0.35	0.29	0.33
C ₃ H ₄	0.04 ± 0.004	0.03	0.03	0.04	0.03	0.01	0.04
C ₃ H ₆	0.29 ± 0.04	0.25	0.28	0.37	0.29	0.19	0.29
O ₂	0.4 ± 0.2	0.4	5.1	1.2	1.4	1.0	4.3
Gasification indicators							
Gas Yield, Nm ₃ /kg _{feed (daf)}	1.78 ± 0.05	2.26	2.06	1.86	2.09	2.32	2.13
Gas Yield, Nm ₃ /kg _{feed (daf)} , (N ₂ -free)	0.65 ± 0.01	0.72	0.70	0.71	0.74	0.77	0.74
LHV, MJ/Nm ³	5.4 ± 0.1	4.7	4.6	5.4	4.7	3.9	4.7
%CGE	44.3 ± 0.02	48.4	44.7	46.0	46.2	43.4	46.8
%C	58.1 ± 0.02	67.9	61.3	62.0	65.7	66.7	64.2
%Н	48.0 ± 0.02	50.3	47.9	50.4	49.0	46.4	50.1
Tar yield ^a , g/kg _{feed (daf)}							
benzene	6.2 ± 0.1	7.7	7.0	6.9	6.9	7.2	6.0
Class II	0.61 ± 0.11	0.53	0.48	0.55	0.31	0.24	0.41
Class III	5.5 ± 0.2	6.3	5.6	6.0	4.9	2.7	4.8
Class IV	5.1 ± 0.4	5.4	4.3	6.4	4.3	2.7	4.3
Class V	0.31 ± 0.04	0.33	0.30	0.43	0.23	0.19	0.22
Total ^b	11.6 ± 0.2	12.5	10.8	13.4	9.8	5.9	9.7
Gas dew point ^c . °C	173	170	164	174	164	163	165
Volume gas sampled tar protocol, NL	~60	60.71	58.25	57.38	57.07	54.72	56.13
Water and acid aas vield, a/katad (dat)							
NH ₂	18.5 + 4.9	24.2	11.3	16.3	25.9	20.2	23.4
HCN	2.5 + 0.3	3.5	1.5	3.2	1.0	0.2	2.0
H ₂ O	341 + 13	347	348	308	331	346	338
220 at a success of a start of the start of		::::::::::::::::::::::::::::::::::::::		500	551		550

³³⁹ ^atar groups according to the ECN tar classification. ^bTotal tar yield is expressed on benzene-free basis.

340 Calculated using the complete model developed by ECN (www.thersites.nl)

341 3.2. Balances and characterization of products for Reference tests

342 Gas composition and gasification indicators values obtained for the reference tests (REF) are in line 343 with values typically reported in literature [35,36]. The total tar yield resulted in 1.16 wt.% (daf feedstock basis), which corresponds to a concentration of 10.0 g/Nm³ (dry gas) or 6.5 g/Nm³ (dry gas, 344 345 C₆H₆-free). The tar composition was in line with results typically reported for fluidized bed 346 gasification reactors and similar gasification conditions [37]. Water content of producer gas, 347 estimated from the hydrogen balance, resulted in a concentration value of approximatively 13.5 348 wt.% (wet gas), which compare well with water content values typically reported for bubbling bed 349 gasification of relatively dry feedstocks [37]. Oxygen balance closures, re-calculated on wet basis, led

350 to values in a range between 95-100%, indicating a relatively good accuracy of the indirect water 351 quantification method.

352 Figure 4 reproduces the SF spectra (recorded with a $\Delta\lambda$ of 3 and 20 nm) corresponding to the tar 353 protocol samples of the three REF tests. The overlapping of the SF spectra indicated a close chemical 354 composition between the REF samples, as well as, an excellent experimental and analytical 355 repeatability. Thereafter, and for the sake of clarity, only one of the three REF spectra was shown in 356 the SF figures. Moreover, it is well known that the emission wavelength band on the SF spectrum can 357 be correlated to the number of the aromatic rings, in particular, for linear PAHs [38–43]. According to 358 Kister et al. [29], molecules having 2-3 linearly condensed aromatic rings (PAHs with one naphthalene 359 skeleton) show a SF signal in a spectral range between 300-370 nm while, molecules having 3-4 360 linearly condensed aromatic rings (PAHs with one anthracene or benzofluoranthene skeleton) show a 361 SF signal in a spectral range between 370-460 nm and, molecules having four or more linearly 362 condensed aromatic rings (PAHs with one tetracene or benzofluoranthene skeleton) show a SF signal 363 in a spectral range between 460-580 nm. Based on Kister's assignment and in excellent agreement 364 with the results of quantitative chemical analysis, SF spectra revealed a chemical composition of REF 365 samples dominated by PAHs with 2 to 3 linearly condensed rings and their derivatives. Furthermore, 366 the relation between the emission wavelength band and the number of aromatic rings of the PAH 367 molecules present in REF samples was confirmed by the spectral ranges obtained for aromatics and 368 PAHs model molecules. As seen from Figure 4, the light tars molecules with 1-2 aromatic rings 369 present a spectral band between 250 and 320 nm whereas, heavier tar molecules having 3-4 370 aromatic rings present a spectral band from 320 to 400 nm. Moreover, as evident from Figure 4, spectra of model molecules at $\Delta\lambda$ =20 nm exhibits a better segregation vs. their molecular size and, 371 372 propanol does not present a signal (compared to the marked signal observed at $\Delta\lambda$ =3 nm). 373 Accordingly, SF spectra recorded at $\Delta\lambda$ =20 nm were used in this study.



374 375

Figure 4: Synchronous Fluorescence spectra recorded at offset=3 nm (left) and offset=20 nm (right) of three reference 376 experiments, 2-propanol and 14 model molecules.

377 The yields of NH₃ and HCN for the REF test were 18 g/kg_{feed(daf)} and 2.5 g/kg_{feed(daf)}, which correspond 378 to concentration values of 10.1 g/Nm³(dry gas) and 1.4 g/Nm³(dry gas), respectively. Nitrogen 379 partitioning, determined from the results of the nitrogen balance (Table 4), indicated that 43% of the Fuel Bounded Nitrogen (FBN) was converted to NH₃ and 4% to HCN. The char bounded nitrogen (N-380 381 char), calculated from elemental analysis of the char recovered from the reactor, the cyclone and the filter, was about 5% whereas, the tar bounded nitrogen (N-tar) was neglected because nitrogen 382 containing species were not detected by GC-MS/FID analysis. These results were close to partitioning 383 384 values reported for the gasification of N-rich biomass feedstocks [44,45]. The slight divergences can 385 be ascribed to the different nature of the FBN. For instance, in raw lignocellulosic biomasses, 386 nitrogen bearing species are intrinsically bounded to the molecular structure of the plant. In contrast, 387 in MDF materials, nitrogen is mainly contained in the resin used to stick the wood fibres of the 388 composite. Therefore, thermal decomposition mechanisms of nitrogen bearing species contained in 389 MDF might differs to those observed for raw lignocellulosic biomasses, impacting thus, the FBN 390 partitioning results. Moreover, the N_2 generated by the gasification reaction was determined by 391 difference since it was not possible to distinguish it from the total N_2 . Indeed, it is likely that nitrogen 392 oxides (NO_x) were also present because these molecules are typical products of the combustion of N-393 containing fuels [46,47]. On that basis, the results showed that approximatively 47% of the FBN was 394 converted to N_2 and NO_x . Finally, the error induced by the addition of the N_2 derived from the FBN to 395 the flow of total N₂ was marginal since the instantaneous flow rate of the former represents less than 396 1% of the instantaneous flow rate of the latter.

Table 4: Nitrogen repartition balance (%). N_2+NO_x values were calculated by difference. Quantified % represents the mass ratio between the nitrogen initially present in the biomass and the nitrogen quantified in NH_3 , HCN and char.

	REF	REF-0.3	th-0.05	HGF-0	HGF-0.05	HGF-0.1	Cy-HGF-0.05
NH3	44 ± 11	56	27	40	64	50	56
HCN	3.9 ± 0.6	5.1	2.2	5.0	1.6	0.3	3.0
Char	5 ± 2	5	6	14	6	8	4
N2+NOx	47 ± 13	34	65	41	29	42	37
% quantified	52	66	35	59	71	58	63

399 3.3. Thermal experiments: Effects of ER on indicators and products

400 In line with previous studies[48,49], the increase in the ER (from 0.25 to 0.3, see Table 2) of the 401 gasification reactor operated for the test REF-0.3 led to a rise in the gas yield, CGE, %C and %H 402 and a drop in LHV (see Table 3). The chemical analysis of tar samples showed only a slight 403 increment in overall tar yield, mostly due to a rise in the yield of benzene and tars of class III (in 404 particular of toluene, phenylethyne, styrene and indene), while class IV and V remained 405 unchanged. The lack of major variations on tar yields can be ascribed to the fact that the 406 temperature in bed and freeboard zone of the reactor was roughly unchanged with respect to 407 the REF tests. The SF spectra, depicted in Figure 5, did not show any marked difference in the 408 spectral fingerprint between the REF-0.3 and REF samples (at ER=0.25). The slight decrease in the 409 spectrum intensity can be ascribed to the reduction in the feed throughput operated for the test REF-0.3. Finally, the increase of the ER did not show a significant impact on the water yield 410

411 whereas, the yields of NH₃ and HCN rose of 33% and 36%, respectively. These results are in line

412 with the results reported by Broer and Brown [50], and confirms that the higher the ER inside of

413

the reactor, the more NH₃ and HCN are released from the feedstock material.





416 Compared to the reference test (REF), the results obtained for the test th-0.05, conducted by 417 injecting a flow of secondary air into the HGF unit but without filtration cartridges, showed a slight 418 increase on the gas and carbon yield and a drop on the LHV. The average oxygen concentration 419 measured during the test th-0.05 dropped with respect to the theorical oxygen concentration 420 obtained in the absence of secondary reactions, estimated to 7.5% vol (N_2 -free dry gas). As already 421 reported by Jiang et al.[51], the oxidation reactions of main combustible gas species contained in the 422 producer gas starts above 450°C while, the oxidation of solid dust particles was reported to start as 423 low as 150°C. During the test th-0.05, the temperature of the producer gas at the entrance of the gas mixing zone inside the HGF unit was about 460°C. Therefore, it is likely that partial oxidation 424 425 reactions of combustible permanent gases (H₂, CO, CH₄) and fine carbon-rich dust particles arriving to 426 the HGF took place to some extent, explaining the decrease in the LHV and slight increase observed 427 in the carbon yield.

428 Regarding the chemical analysis of tar, and despite the fact that the overall tar yield resulted 429 unchanged, our results indicated a slight increase in the yield of benzene, toluene and benzofuran 430 and a drop of 50% in the phenol yield, while the light and heavy tars of class IV and V remained 431 globally unchanged (within experimental uncertainty). The drop in the yield of phenol and the 432 increase in more stable aromatics (benzene) has been already pointed out as a consequence of staged injection of air [52]. The SF spectrum of the th-0.05 sample (Figure 5) did not revealed marked 433 434 differences in the spectral fingerprint compared to REF sample, supporting the marginal effect on 435 light and heavy tars observed by quantitative analysis. By contrast, the drop in the overall intensity of the spectrum indicated that producer gas dilution (as a result of the secondary air injection) 436 437 impacted the PAHs concentration in the gas flow. In conclusion, and consistent with thermal cracking 438 literature [53,54], these results provide evidence that mild temperature inside the HGF unit was too 439 low to activate the cracking reactions of refractive light and heavy PAHs. Finally, the yields of NH₃ and 440 HCN dropped of 38% and 43%, respectively. The drop in NH₃ can be ascribed to oxidation reactions in 441 homogeneous phase as these reactions can be initiated at about 427°C [55]. On the contrary, 442 oxidation reactions of HCN are known to take place at higher temperatures (>700°C) but, they can be 443 catalysed by the presence of some permanent gases (CO, CH₄) and the extended residence time 444 inside the filter [56].

445 3.4. Filtration experiments

446 3.4.1. Impact of oxidative HGF: homogeneous vs. heterogeneous secondary reactions

447 Secondary reactions inside an oxidative HGF unit can undergo through homogeneous (gas-gas) and 448 heterogeneous (gas-solid) reactional pathways. In the former case, the results obtained for the 449 thermal test (th-0.05) evidenced that, in spite of the mild temperature, partial oxidation reactions in 450 homogeneous phase took place to some extent impacting significantly the %C and LHV but, with little 451 effect on the yield of light and heavy tars. In the latter case, secondary heterogeneous reactions are 452 expected to result from the interaction between the syngas and either the dust cake particles, or the dense non-woven metal fibre layer of the filter, or both simultaneously. Thus, to isolate the effects of 453 454 secondary heterogeneous reactions, the results of the test HGF-0.05 were compared with those of the test th-0.05 indicating, as seen from Table 3, an increase of 3%, 7% and 2% in the CGE, carbonand hydrogen yields.

457 Regarding the chemical composition of tars, results showed a drop of 10% on the overall tar yield 458 between the tests th-0.05 and HGF-0.05, mainly due to the reduction of tars of class II, III and V. In 459 the case of aromatics of class II and III, the most market drop was observed on phenol and 460 phenylethyne yields, showing a decrease of 36% and 12%, respectively. The unchanged value 461 observed in the yield of tars of group IV can be ascribed to opposite trends between acenaphthylene (which yield increased by 12%) and the rest of the group (see Table A2, Appendix A). Moreover, the 462 463 drop in the overall SF spectrum intensity observed between the HGF-0.05 and th-0.05 samples 464 (Figure 5) corroborate the reduction observed by quantitative analysis.

Finally, the yields of water and HCN were unchanged with respect to th-0.05 (within experimental 465 466 uncertainty) whereas, the yield of NH₃ rose by 129%. A possible explanation for the substantial 467 increase in the yield of NH_3 is the release of NH_3 from dust cake particles as a result of partial oxidation reactions. Indeed, the rise of 90°C observed between the temperature of the clean and 468 469 dirty side of the filter during the test HGF-0.05 and the increase in the carbon yield evidenced that 470 exothermic partial oxidation reactions happened on the filter surface. Therefore, N-containing 471 species in solid (N-char) and, to a lesser extent aerosol (N-tar), phases arriving to the filter were likely 472 converted to NH₃. Consistent with latter hypothesis, the fraction of quantified N-species (see Table 4) 473 showed its highest value for the test HGF-0.05.

474

475 3.4.2. Impact of secondary air on the operation of the HGF unit

The impact of secondary air flow rate was assessed based on the results of the three filtration tests, namely: HGF-0, HGF-0.05 and HGF-0.1. These tests were conducted with the same set of filter cartridges following the next order: 1st) HGF-0.05, 2nd) HGF-0 and, 3rd) HGF-0.1. In each of the three

- 479 tests, a dust cake of approximatively 10-20 mm thickness was accumulated on the filter surface. In
- 480 the case of the tests HGF-0.05 and HGF-0, the dust cake was loosely adhered to the filter surface and
- 481 fell off spontaneously during the off-line cleaning operations. On the contrary, for the test HGF-0.1,
- the dust cake was more stable and did not fall off easily (Figure 6).



483

484 Figure 6: Photograph of the dirty side of the HGF unit after the test HGF-0.1

485 Figure 7 depicts the differential pressure across the filter for all filtration tests and the temperature 486 profiles measured inside the HGF unit during the test HGF-0.1. The lack of exhaustive cleaning of filter surface before the tests HGF-0 and HGF-0.1 explains the rapid rise in the pressure drop at the 487 488 beginning of these tests in comparison with the smooth increase observed for the test HGF-0.05. Regarding the long-term trends, results showed a similar rate of pressure drop increase during the 489 490 tests HGF-0.05 and HGF-0 that contrast with the change in the slope observed for the test HGF-0.1 491 beyond 2 h. The sharp change in the slope was caused by the formation of a low permeability ash 492 layer on the filter surface as a result of the presence of excess amount of oxygen and the higher 493 temperature. Indeed, 2 h after the start of the test HGF-0.1, the temperature of the clean side of the 494 filter was 145°C higher than the temperature on the dirty side (see Table 3) clearly indicating that dust cake particles were oxidised to a large extent. The presence of ash deposits on the dust cake 495 496 was confirmed by visual inspection after the test HGF-0.1 (Figure 6).



498 Figure 7: Temperatures inside the HGF unit during the test HGF-0.1 and pressure drop across the filter for the tests: HGF499 0, HGF-0.05, HGF-0.1 and cy-HGF-0.05.

To gain further insight on the state of the outer filter surface, several samples of the filter mesh (approximate size of 1-2 cm²) were carefully extracted from the lower, medium and upper part of the filter and analysed by SEM-EDX (Figure 8A-D). To be noted that prior to sample extraction, the remaining dust cake was dislodged by gentle shaking and vacuum aspiration.



504

497

505 Figure 8: SEM images of the surface of the dirty side of the filter cartridge after the test HGF-0.1.

As evident from Figure 8A-D, slagging, sintering and aggregation phenomena between the particles deposited in the inter-wire space of the outer filtration membrane took place, blocking the porosity and thus, reducing drastically the filter permeability. Based on particle morphology shown in Fig.8C-D, deposits mainly consisted on: (a) discrete angular sharp micro-particles of olivine and, (b) micronand sub-micron residual ash particles of irregular shape. Additionally, as seen in Fig.8D, an ash layer was developed on the surface of the metallic wires. This sticky layer is known to favour the pick-up of micro-particles and inorganics [57].

To reveal the nature of the ash deposits formed in the porosity of the filter, EDX spot analyses were conducted in several characteristics points of the filter surface. Spot location and the estimated elemental composition of each spot were detailed in Figure 9.

516 Figure 9: SEM-EDX spot analysis of the dirty side of the filter cartridge after the test HGF-0.1. Yellow crosses show the 517 points (spots) where the EDX analysis was carry out. Estimated elemental composition is expressed in mass basis.

		wt.% (by EDX)			
	Element	Spot 1	Spot 2	Spot 3	Spot 4
	С	4.61	11.64	36.01	31.92
Charles and a second second	0	41.46	21.18	31.85	38.3
	Mg	0.31	0.21	16.53	13.19
and the second	Al	38.51	0.15	0.04	0.43
The second s	Si	0	0.54	11.4	8.47
ALL MALLER AND	Cr	3.04	12.31	0.31	0.32
A CARLES AND A CARLE	Fe	10.43	48.21	3.38	5.15
	Ni	1.54	4.21	0	0
	Р	0	0.16	0	0.27
	S	0	0.77	0	0
	К	0	0	0.42	0.34
	Ca	0	0	0	1.47
50 µm HT = 20 kV Mag = 500 X	Mn	0.11	0.62	0.05	0.13

518

According to the EDX analysis of spot 4, the ash deposit accumulated on the inter-wire space of the outer membrane was primarily composed of: K, Ca, P, O, C, Mg, Si and Fe. Strictly considering the ash melting temperatures determined for the parent feedstock particles (Table 1), melting phenomena was not expected to take place on the dust cake because maximal temperature measured inside the HGF unit during this study was 630°C. However, SEM observations evidenced sintering and 524 aggregation of ash particles in the inter-wire space of the filter. Therefore, and taking into account 525 the complex phase chemistry of multicomponent ashes, the formation of consolidated ash deposits 526 likely resulted from the combination several factors, such as: (i) the occurrence of high temperature 527 spots resulting from the exothermal oxidation of carbon-rich dust particles, (ii) alkali melting on the 528 surface of olivine micro-particles elutriated from the reactor and deposed on the filter surface, (iii) 529 the small particle size and, (iv) the elevated residence time [57-60]. Notably, the softening 530 temperature measured in Table 1 is associated to the softening of the ashes as mainly oxide species. 531 Elutriated particles from the fluidized bed are still rich in carbon which can enhance their carbo-532 reduction. Furthermore, the reduction of metal species present in the carbon-rich ashes may be 533 further promoted by the producer gas (rich in CO, H_2 , etc.). It is known that an increased mobility of 534 the metallic species occurs near their Tammann temperature, which is defined as the temperature 535 that lies in the range 0.3 to 0.5 times the melting point [61]. All these phenomena can explain a so 536 low temperature of agglomerate formations compared to the high temperature of ashes softening 537 measured by the common normalised test.

538

Alkali melting on the surface of olivine particles was confirmed by EDX analysis of spot 3. As seen from Figure 9, spot 3 corresponds to a discrete and angular sharp particle containing Mg, Si, O and Fe, which are known to be the main chemical elements of olivine. High amount of K detected in spot 3 suggests the formation of K-bearing species on the surface of the olivine particle. The low melting points of K-bearing species and the propensity of these species to form low melting eutectics in between K-bearing species and/or with other mineral phases have been already reported [62,63]. This phenomenon promotes the irreversible aggregation of particles of ash and olivine.

Finally, the elemental composition of spot 1 indicated a high content of aluminium and oxygen. From a morphological point of view, these deposits did not appear to be originated through the same mechanisms detailed previously for the deposition of ash. Instead, these deposits were likely originated from the alumina-rich product used during the assembling fabrication process of the filtration mesh. The aluminium oxide deposit was also identified in specific locations of the clean side of the filter (see Figure A.1, Appendix A).

552 The SEM-EDX results clearly present that increasing the secondary air flow rate leads to the 553 formation of ashy deposits, reducing the permeability of the filter. Irreversible character of ash 554 deposition mechanisms (aggregation, melting, sintering) is expected to reduce efficiency of back 555 pulse cleaning. Therefore, secondary air flow rate must be selected in order to limit the extent of 556 oxidation reactions. Based on the results described above, an ER_{HGF}=0.05 represent a good trade-off 557 between reactivity and stability of the filtration operation for a dust particle mass flow rate entering 558 into the filter of ca. 120 g/h and mild filtration temperatures. To be noted that the ER_{HGF}=0.05 was 559 calculated based on the feedstock composition and throughput. Alternatively, the ER_{HGF} can be also 560 calculated based on the composition and volumetric flow rate of the producer gas entering into the 561 filter, leading to values of 0.15 and 0.30 for the tests HGF-0.05 and HGF-0.1, respectively.

562 3.4.3. Impact of secondary air on the gasification indicators and products

563 Compared with the reference test (REF), gasification indicators values obtained for tests HGF-0, HGF-564 0.05 and HGF-0.1 revealed that an increase in the secondary air flow rate inside the HGF unit lead to 565 a rise in the gas yield and %C and, a drop in the %H and LHV. The CGE slightly increased for the tests 566 HGF-0 and HGF-0.05 and, decreased for the test HGF-0.1. Variations on gasification indicators mainly 567 stem from the rise in the yield of CO_2 and the drop in the yield of C_2H_2 , C_3H_4 and C_3H_6 (see Table A.2, Appendix A) since, for the rest of the gases, no clear trend emerged within the experimental 568 569 uncertainty. The reduction in the yield of C_2 - C_3 hydrocarbons, in comparison with the unchanged 570 yield of CH₄, may be explained by the lower stability of C_2 - C_3 molecules, compared to CH₄.

571 The chemical analysis of tars showed a drastic decrease in the overall tar yield with increasing flow 572 rate of secondary air. Thus, for test HGF-0.1, the overall tar yield dropped as much as 49% with 573 respect to the REF test (see Table 3). In this instance, the yield of tar groups of class II and III dropped of 60% and 51% whereas, the decrease of class IV and V was of 46% and 37%, respectively. Latter trends were corroborated by the SFS results plotted in Figure 5. In contrast to the REF sample, the SF spectrum of the HGF-0.1 sample showed a decrease in the overall intensity and a shift to lower wavelengths, indicating a reduction in the content of heavy PAHs molecules.

578 Moreover, the yield of water and HCN showed a decreasing trend with the increase in the secondary 579 air flow whereas, the yield of NH₃ peaked for the test HGF-0.05 and then decreased with increasing 580 secondary air flow rate. A possible explanation of the variation observed in NH₃ and HCN is the 581 occurrence of simultaneous releasing-abatement mechanisms inside the HGF unit. Thus, on the one 582 hand, the more severe oxidation of dust cake particles increases the amount of NH_3 and HCN 583 released to the gas. In the other hand, the abatement reactions undergo through homogeneous and 584 heterogeneous pathways as a result of the excess presence of oxygen and the elevate temperature. 585 However, from the data available it is difficult to unveil the precise mechanism because of the lack of 586 NO_x quantification. Therefore, in future research dealing with the fate of N-containing species from 587 air-blown gasification it is advised to quantify NO_x species, as well as, the use of another μ -GC tracer 588 gas different than N₂.

589 Finally, it is interesting to note the increase of 16% in the overall tar yield of the test HGF-0 with 590 respect to the REF test, primarily caused by the rise in the yields of light and heavy tars of class IV and 591 V by 27% and 29%, respectively. In terms of individual yields, the most marked variation corresponds 592 to pyrene, showing a rise of 53%. These unexpected results are supported by the slight increase in 593 the intensity of the SF spectrum for the HGF-0 sample within a wavelength range of 330-400 nm (see 594 Figure 5). Moreover, the yield of major gas compounds did not change notably with respect to the 595 reference values, only propylene showed a rise of 26% on its yield. Regarding on-line gas 596 concentrations, only propylene and acetylene showed slight downward trends during the test HGF-0.

597 As pointed out in [64], the catalytic cracking of substituted aromatics on the surface of char particles 598 leads to the formation of larger PAHs molecules, probably via phenyl radical intermediates. 599 Nevertheless, these reactions are known to initiate above 600°C and become significant at 800°C[65]. 600 In this study, temperature inside the filter during the test HGF-0 was kept between 430°C and 450°C. 601 Thus, catalytic cracking of substituted tars molecules was not expected to take place on the surface 602 of dust particles. A possible explanation for the slight increase observed in the yield of tars of class IV 603 and V is the gasification of carbon-rich dust cake particles by reactive gaseous species of the 604 producer gas, in particularly: CO_2 and H_2O . These reactions are known to take place at higher 605 temperatures but, they can be catalysed by the small particle size and the high inorganic content of 606 dust cake particles [20,66]. Consistent with latter hypothesis, Ravenni and co-workers[64] reported 607 upwards trends for naphthalene, anthracene and pyrene molecules during the catalytic cracking of a 608 real producer gas with a bed of char particles kept at 800°C. Considering similarities between the 609 spatial velocities (7.2 NL/g_{char}.h in [64] and, 9.7 NL/g_{char}.h in this study) and water content of producer 610 gas 10-15 %(v/v), greater production values obtained in [64] for these molecules must have been 611 caused by the gap of more than 300°C in the cracking temperature between these two studies.

612 3.4.4. Impact of dust loading on the operation of the HGF unit

613 As expected, the integration of the cyclone separator between the gasification reactor and the HGF 614 unit operated for the test cy-HGF-0.05 lead to a notable reduction of the mass of dust accumulated 615 on the filter. The mass yield of the dust cake recovered after the test cy-HGF-0.05 was 0.7 wt.%, far 616 below the 3.7 wt.% estimated for the test HGF-0.05. Visual inspection of the filter after the test cy-617 HGF-0.05 revealed a dust cake about 5-10 mm thickness, composed of very fine particles without any 618 apparent sign of ash formation (see figure A.2, Appendix A). In this case, the dust cake did not fall 619 spontaneously during off-line cleaning operation and thus, could be entirely recovered. Pressure-620 drop profile of the test cy-HGF-0.05, shown in Figure 7, evidenced that integrating the cyclone led to 621 a reduction of the rise in the pressure drop. Finally, temperatures inside the HGF unit during the test 622 cy-HGF-0.05 were close to those measured for the thermal test (th-0.05) with the exception of the 623 10°C gap observed between the clean and dirty side the filter.

The morphology and composition of dust particles accumulated on the outer filter surface were assessed by SEM-EDX analyses of a sample of metallic mesh extracted following the procedure beforehand detailed. As seen from Figure 10A-D, the outer surface of the filter was rather pristine and only minor dust deposits were observed. From a morphology point of view, dust deposits were mainly composed of discrete particles with irregular shapes agglomerated in disperse clusters. Dust particles appeared to be loosened adhered to the surface of the metallic wires and no signs of interparticle aggregation were observed. Olivine particles were almost non-existent.



631

Figure 10: SEM images at different magnification of the surface of the dirty side of the filter cartridge after the test cy-HGF-0.05

Moreover, elemental composition of dust particles recovered from the cyclone and the filter dust cake after the test cy-HGF-0.05 was compared in Table 5. Results showed a lower carbon and higher nitrogen content for the filter dust cake particles. The presence of a considerable amount of olivine 637 particles in the cyclone sample resulted in ash contents greater than 50 wt.%, which prevent an 638 accurate comparison to be made. Instead, ash content of cyclone particles was supposed to be equal 639 to the ash content measured for the char particles recovered from the reactor after the test cy-HGF-640 0.05. In this instance, particles of char could be easily isolated from olivine by manual mesh sieving 641 because of the marked difference in particle size. Keeping in mind this latter approximation, results 642 indicated a marked increase of the ash content for the filter dust cake particles. In line with these results, ICP-AES quantification showed a significant enrichment in the content of alkaline (Na, K), 643 644 alkaline earth (Ca), P and Mn for the filter dust cake particles. The results obtained for Mg, Fe and Si 645 were not examined because of the possible presence of olivine particles in the samples. Several 646 reasons can explain the higher inorganic content of the filter dust cake particles, such as: (i) the 647 tendency of inorganic material to concentrate in the lower particle size fraction of the ground 648 lignocellulosic feedstock and thus, of the char particles[67], (ii) the enrichment in volatile inorganics 649 through condensation/agglomeration mechanisms catalysed by extended exposition to producer 650 gas[60] and, (iii) the partial oxidation of dust cake particles as a result of extended residence time, 651 suitable temperatures (400-500 $^{\circ}$ C) and the presence of O₂ [19].

Table 5: Analysis of cyclone and filter cake particles recovered after the test cy-HGF-0.05. Note that ash content of cyclone particles was estimated from the ash content of the char particles remaining in the reactor.

sample	Cyclone particles	Dust cake					
sample	eyclone particles	particles					
Ash, wt.%(as received)	1.5 ± 0.1	16.4 ± 1.7					
Ultimate analysis, wt.%	(as received)						
С	76.7 ± 1.1	60.0 ± 0.8					
Н	1.04 ± 0.03	1.4 ± 0.1					
Ν	3.1 ± 0.1	8.2 ± 0.5					
Ocalculated by difference	17.6 ± 1	13.9 ± 0.3					
Metallic element analysis (mg/kg, db)							
Si	113550 ± 3700	31260 ± 17800					
Mg	164590 ± 21400	28670 ± 3200					
Са	5370 ± 230	30000 ± 2670					
К	4900 ± 100	9570 ± 580					
Na	530 ± 22	880 ± 58					
Р	534 ±4	4200 ± 140					
Al	4990 ± 2950	1280 ±910					
Fe	27770 ± 1560	5940 ± 600					
Zn	41 ± 1	1450 ± 1600					
Mn	790 ± 100	3330 ± 45					

655 From an engineering view point, lack of aggregation, sintering and melting phenomena on the filter 656 surface are key features to assure long-term operation of HGF units. Indeed, mild filtration 657 temperature and controlled concentration of O_2 limited the extent of oxidation reactions of the dust 658 cake particles and thus, the formation of high temperature spots on the filter surface, preventing the 659 irreversible blocking of the filter porosity by aforementioned mechanisms. On the other hand, as 660 clearly evidenced in Figure 10C-D, dust micro-particles penetrate the outer filter membrane and 661 were retained by the second layer composed of non-woven metallic fibres. Although, penetration of 662 sub-layers by micron and submicron particles is generally identified as a negative phenomenon 663 regarding the filter lifespan, for example in ceramic candles [19], the open structure of the outer 664 layer of the metallic cartridges used in this study is likely to have a positive effect on the removal of 665 these particles by back-pulse cleaning and thus, preserve long-term filter permeability. Furthermore, 666 extended lifespan and total recyclability of metallic cartridges could compensate the higher cost of 667 metallic elements in comparison to ceramic candles. However, it is noteworthy that the time-on-668 stream of the set of filter cartridges used for the test cy-HGF-0.05 was limited to 4 h and therefore, 669 complementary experiments are required to further explore the long-term behaviour.

670 Furthermore, results detailed on Table 5 support the idea that properties of cyclone and dust cake 671 particles have the potential to be in compliance with the limits indicated by the European Biochar 672 Certificate for application as EBC-Agro biochar of class III [68]. Indeed, both cyclone and dust cake 673 particles fulfil thresholds values for properties such as: organic carbon content, H/C and O/C ratios 674 and heavy metal content. Concerning PAH content, only dust cake particles appear to comply with 675 EBC's limit values. Latter conclusion was inferred from the comparison of the SF spectra of liquid extracts from particle samples collected from the cyclone and the filter dust cake after the test cy-676 677 HGF-0.05 (Figure 11). In line with the results reported by [64], the release of PAH molecules from 678 char particles is strongly reduced after the exposition of these particles to reducing/oxidizing 679 atmospheres at mild-to-high temperature for long periods of time. This reduction would be linked to 680 the stabilisation effect of secondary carbon deposition, oxidation and/or gasification reactions on the surface of the char particles. However, it should be noted that analytical methods employed in this
study for char characterization differ slightly from those reported on the EBC's guidelines. Thus,
complementary analyses, including PAH quantification, are required to draw an accurate conclusion.



684

Figure 11: Synchronous Fluorescence spectra ($\Delta\lambda$ =20 nm) of 2-propanol extracts of the cyclone and dust cake particles recovered after the test cy-HGF-0.05.

687 3.4.5. Impact of dust loading on gasification indicators and products

Gasification indicators values obtained for the test cy-HGF-0.05 were close to those obtained for the test HGF-0.05. The average concentration of O_2 measured during the test cy-HGF-0.05 was higher than the concentration measured during the test HGF-0.05 and close to the concentration measured during the test th-0.05, indicating that partial oxidation reactions took place but to a small extent. It appears that the dust particle flow rate entering into the filter (estimated to 30 g/h) was too low to impact significantly oxygen concentration.

694 The overall tar yield obtained for the test cy-HGF-0.05 was roughly identical to that obtained for the 695 test HGF-0.05. Lack of major deviations on the overall tar composition was confirmed by the overlapping of SF spectra between HGF-0.05 and cy-HGF-0.05 samples (see Figure 5). In terms of 696 697 individual compound yields, the decrease in the dust loading only impacted significantly the yield of 698 phenol, reducing it conversion from 50%, in the case of the test HGF-0.05, to 32% in the case of the 699 test cy-HGF-0.05. Moreover, slight variations were also observed on other tar compounds with 700 respect to the test HGF-0.05 but no conclusion could be made within experimental uncertainty. 701 Overall, these results suggest that secondary heterogeneous reactions inside the HGF unit arose

mainly from the interaction between the tar molecules transported in the gas phase and the dense non-woven metal fibre layer of the filter. Therefore, the thickness of the dust cake had only a minor impact on the gasification output indicators and tar content. Latter observation could be ascribed to the high porosity of the filter cake and the low probability of interaction between the dust cake particles and the tar molecules transported in the gas phase.

Finally, compared with the test HGF-0.05, the yield of HCN and H_2O did not differ significantly whereas, in the case of NH₃, the production percentage decrease from 43% to 29% with the reduction of the dust loading. Lower production of NH₃ observed with the reduction of dust loading confirmed the release mechanism previously proposed as a result of the partial oxidation of dust cake particles.

712 **4.** Conclusion

The present study examines the effect of oxidative HGF on the gasification indicators and pollutants of producer gas. Pellets of N-rich particle board were gasified in an air-blow bubbling bed reactor at 800°C coupled with a downstream HGF unit under different HGF operational conditions. Metallic cartridges with multilayer structure were used as filtration media. The fate of pollutants (tars, NH₃ and HCN) was assessed by complementary analytical techniques and the filter surface was characterised by SEM-EDX. The following conclusions could be drawn:

7191) Under reference gasification conditions, tar concentration was 6.5 g/Nm³ (dry gas, C_6H_6 -free)720and the nitrogen repartition indicated that approximatively 43% of FBN was converted to721NH3 and 4% to HCN. The rest of FBN was mostly converted to gaseous N2 and NOx but,722neither one was quantified.

723

The increase in the ER of the reactor showed a marginal impact on tar yield. Lack of major
 changes on tar composition was ascribed to roughly unchanged reactor bed and freeboard

726

temperatures with respect to reference tests. Conversely, the yields of NH_3 and HCN rose of 33% and 36%, respectively.

728

727

A thermal test, conducted by injecting secondary air into the HGF unit without filtration
 cartridges inside, confirmed that secondary partial oxidation reactions in homogeneous
 phase took place to a small extent inside the HGF unit. The overall tar yield was unchanged
 whereas the yields of NH₃ and HCN dropped by 38% and 43%, respectively. Oxidation of NH₃
 and HCN was likely catalysed by presence of permanent gases and extended residence time.

734

7354) Oxidative HGF implies secondary reactions in homogeneous and heterogeneous phase.736Comparison between thermal and oxidative HGF tests (both conducted with an $ER_{HGF}=0.05$),737provided a way of isolating the effects of heterogeneous reactions. Heterogeneous reactions738had a slight impact on gasification indicators and led to a 10% drop in overall tar yield.739Oxidation of dust cake particles increased the release of NH3 as much as 129%.

740

5) The increase in the secondary air flow rate (until ER_{HGF}=0.1) in the HGF unit resulted in a more severe oxidation of the dust cake particles, rising notably the temperature inside the filter unit and, impacted significantly the gasification indicators. SEM images evidenced the occurrence of irreversible melting, aggregation and sintering phenomena of ash deposits formed in the porosity of the filter. Overall tar yield dropped substantially with the increase in the secondary air flow rate and, a simultaneous release-oxidation mechanism was proposed to explain variations observed in NH₃ and HCN yields.

748

Dust loading on the filter surface showed a minor effect on gasification indicators and tar
 content, suggesting that heterogeneous reactions inside the HGF unit mainly arose from the

751 interaction between the molecules transported in the gas phase and the dense non-woven752 metal fibre layer of the filter.

Finally, this study showed that for oxidative HGF at mild temperature (400-600°C), secondary air flow rate should be carefully controlled and limited to $ER_{HGF} \le 0.05$, in order to minimise the exothermic oxidation of dust cake particles, which lead to the formation of ash deposits that impact negatively long-term operation. Further studies should assess the long-term behaviour of metallic cartridges under oxidative conditions and mild-hot temperature, and compare it with the behaviour of standard ceramic candles.

759

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Graphical abstract

