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FUEL FLEXIBILITY OF A PILOT PLANT GASIFIER USING TORREFIED PELLETS AS FEEDSTOCK

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ABSTRACT: The aim of this study is to investigate the possibility of enhancing the gasification process using a pre-treated biomass that presents higher heating value, higher C/O ratio and less moisture content than untreated biomass. The aim is to assess the gasification parameters that can be modified in order to achieve the best performance of the gasification system. These research studies have been carried out in collaboration with the Centre RAPSODEE (UMR CNRS 5302, IMT Ecole de mines Albi-Carmaux, France) and the Free University of Bolzano (Italy). The torrefaction of standard pellets is realized using a lab scale rotary kiln unit at RAPSODEE. On the contrary, the gasification tests are carried out at the Free University of Bozen-Bolzano by means of a fixed bed open top gasifier. The tests of pellets torrefaction has been carried out at 250°C and 270°C with two repetitions in order to obtain about 60 kg of pellets for each torrefied condition. The used feedstock is a standard French pellets produced from sawdust of oak and beech following the standard EN 14961-2 ("Wood pellets for non-industrial use"). The pellets are characterized before and after the torrefaction pre-treatment. The gasifier used for the gasification tests is an open top pilot-scale gasifier placed at the Bioenergy and Biofuel Lab of the Free University of Bolzano. The plant is an open top downdraft system, where both gas and feedstock move downward as the reactions proceed. The main difference between un-treated and torrefied pellets is the moisture content. In addition, a slight increase in terms of carbon content and LHV and a slight decrease in terms of volatile matter are observed by moving from standard to torrefied pellets. The torrefied pellets seem to reach lower performances in terms of cold gas efficiency (CGE) and char yield with respect to the standard pellets. However, the trends in terms of ER and CGE suggest that moving toward higher values of ER, higher values of CGE could be reached independently of the material used.
Keywords: biomass, pellet, torrefaction, gasification, fixed bed.

1 INTRODUCTION

In the field of biomass pre-treatment, torrefaction has gained an increasing attention due to the possibility, by means of this process, to enhance the physical and chemical property of biomass e.g. increasing energy density, making uniform the biomass properties and avoiding the biological degradation thanks to its hydrophobicity [1–4] . Similarly, studies have been performed on the use of torrefied biomass in gasification process [5–7] . The idea is to enhance the gasification process using a pre-treated biomass that presents higher heating value, higher C/O ratio and less moisture content than untreated biomass [8]. On the contrary, the volatile compounds decrease in biomass after torrefaction.

These research studies have been carried out in collaboration with the Centre RAPSODEE (UMR CNRS 5302, IMT Ecole de mines Albi-Carmaux, France) and the Free University of Bozen-Bolzano (Italy).

The aims of this collaboration are on the one hand evaluating the torrefaction pre-treatment staring from standard pellets and on the other hand using the torrefied pellets in gasification test in order to evaluate the valorisation of this feedstock in the gasification process itself.

2 MATERIALS AND METODS

2.1 Standard and torrefied pellets

The standard pellets used in this research work are produced from sawdust of oak and beech following the standard EN 14961-2 ("Wood pellets for non-industrial use") [4]. The pellets were characterized before and after the torrefaction pre-treatment at the Centre RAPSODEE. The moisture content is determined using an oven. The sample is placed in the lab oven at 105°C and weighed before and after the analysis according to the standard method: "UNI EN ISO 18134-3:2015 - Methods for the determination of moisture content - Oven dry method [9]. The sample is usually place in the oven for a time lower than 24h in order to prevent the unnecessary losses of volatile compounds. The determination of ash content involves the use of a muffle furnace. The procedure includes a specific heating program for the sample incineration in according to the standard "UNI EN ISO: 18122:2016 - Solid biofuels – Determination of ash content" [10]. The elemental composition in terms of Carbon (C), Hydrogen (H), Nitrogen (N) and Sulphur (S) was determine using a Flash 2000 Elemental Analyzer (Thermo scientific). In addition, volatile matter content was determine following the standard UNI EN 18123:2015 ("Solid biofuels - Determination of the content of volatile matter") [11]. The fixed carbon was calculated by difference. The calorific value analysis of the biomass samples was carried out at the Bioenergy and Biofuels LAB of the Free University of Bolzano-Bozen [12]. The equipment employed is an IKA C200 calorimeter. The moisture content of standard and torrefied pellets are analyzed before each gasification test using the same methodology described previously [9].

The most important parameter in the study of the gasification process is obviously the producer gas composition. Therefore, after a gas cleaning system, gas is analyzed using a gas chromatograph Agilent 490 Micro GC (μGC) able to detect H_2, O_2, N_2, CH_4 and CO in a Molsieve column and CO_2 in a Plot-U column coupled with a TCD detector using Argon and Helium respectively as carrier gas. The producer gas is analyzed every 3 min, corresponding to the time required for the chromatographic separation and analysis of the extracted gas samples. Before each test, the instrument was calibrated using a one cylinder containing a mixture of certified gases.

2.2 Experimental setup

The torrefied pellets described in this work was performed using a pilot scale rotary kiln unit installed at the Centre RAPSODEE. The kiln consists of a steel (nickel/chromium) cylinder of 4.2 m in length and 0.21 m of internal diameter [13]. The central part of the cylinder is placed into a heating shell for about 2.75 m. The heating zone is formed by five independent parts heated using electrical resistances embedded in alumina fiber.

The feeding system consists of a hopper of 26 kg of capacity and a vibrating cylindrical screw conveyor connected with the kiln cylinder. After being torrefied, the pellets exiting the rotary kiln pass through an exit chamber and are collected in a storage tank that is connected in a sealed manner in order to prevent air contact.

The gases produced during the treatment are evacuated towards a post-combustion chamber fed with propane that allows their combustion before releasing them outside. To prevent any overpressure in the reactor, a rupture disk has been installed at the exit chamber, limiting the electrical tracing to 200°C.

The overall feeding system is continuously weighed. All torrefaction experiments were done with 6 kg/h biomass mass flow rate. The biomass residence time according to a cold test is around 38 minutes.

Torrefied biomass collection, gas and bio-oil sampling start after 2h (once the steady state is reached) in order to establish the mass balance. The tests of pellets torrefaction has been carried out at 250°C and 270°C with two repetitions in order to obtain about 60 kg of pellets for each torrefied condition.

The gasifier used for the gasification tests is an open top pilot-scale gasifier placed at the Bioenergy and Biofuel Lab of the Free University of Bolzano (Figure 1).
The plant is an open top downdraft system, where both gas and feedstock move downward as the reactions proceed. The gasification reactor, a gas cleaning system, a flare and a monitoring and controlling system compose the experimental set-up [14].

In order to increase the char temperature in the reduction zone, a part of char can be burned injecting secondary air into reactor. In this way, the reactor can be used as a double stage gasifier modulating the air in two separate zone in order to control the gasification process and to adapt it to different feedstock properties. The secondary air injected into reactor is measured by a mass flow meter and controller [15].

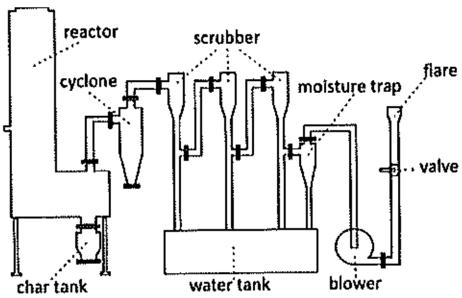

Figure 1: overall schematic of the pilot-scale open top gasifier system.

The experimental tests were performed using a manual configuration regarding the biomass feeding and an automatic system to control the char discharge. The biomass (pellets) is introduced into the reactor from the top and the char is discharged from the bottom of the reactor using a screw conveyor. When the char is removed from the reactor, the gasification front moves down, the reactor is filled with fresh biomass until full charge and the cycle start again. The char sample is collected in a tank and extracted before the next cycle.

The idea is to perform every cycle of char discharge when a definite temperature is reached in a certain point of the reactor. The cycle can be repeated in this way many times and the process can be consider continuous.

Both char and biomass weights are measured using a lab digital balance and the time interval between the cycles is recorded. In this way, the mass flow rates (biomass and char) can be calculated at every cycle of char discharge and biomass feeding.

Knowing the biomass and char composition and their mass flow rates, the producer gas and air compositions, their mass flow rates can be calculated using a linear system considering the ash balance, the carbon balance, the nitrogen balance and the total mass balance of the system.

Char yield is estimated using Equation 1, considering the ratio between the biomass weight introduced in the reactor at the beginning of the cycle and the weight of the char extracted from the reactor at the end of the gasification cycle.

$$Y_{char} = \frac{\dot{m}_{char\ OUT}}{\dot{m}_{biom.\ IN}} \quad (1)$$

where: $\dot{m}_{char\ OUT}$ is the measured mass of residual char at the end of the test and $\dot{m}_{biom.\ IN}$ is the measured mass of the initial biomass fed into the reactor.

It is well accepted that a reference parameter for the gasification process is the equivalence ratio (ER), the ratio between the air supplied and the air required for a stoichiometric combustion reported in Equation 2.

$$ER = \frac{\dot{m}_{air}}{\dot{m}_{stoic.\,air}} \quad (2)$$

where: $\dot{m}_{air}$ is the mass flow rate of the air supplied and $\dot{m}_{stoic.air}$ is the mass flow rate of the air which is needed for the stoichiometric combustion.

Apart from the lower heating value of the producer gas, it is also interesting to relate the energy production to the consumption of biomass by introducing the parameter named specific producer gas energy (SGE) that can be expressed as the ratio between the energy in output as producer gas and the mass of fuel in input:

$$SGE = \frac{LHV_{pgas} \cdot \dot{m}_{pgas}}{\dot{m}_{fuel}} \quad (3)$$

where: LHV_{pgas} is the lower calorific value of the producer gas, $\dot{m}_{pgas}$ is the mass flow rate of the producer gas and $\dot{m}_{fuel}$ is the mass flow rate of biomass consumed.

The efficiency of the gasification process can be assessed based on the gas cold efficiency (CGE) of the process, defined as the ratio between the power associated with the flow rate of the cold producer gas and the power supplied with the input biomass:

$$CGE = \frac{LHV_{pgas} \cdot \dot{m}_{pgas}}{LHV_{fuel} \cdot \dot{m}_{fuel}} \quad (4)$$

where: LHV_{fuel} is the lower calorific value of the biomass.

3 RESULTS AND DISCUSSION

3.1 Torrefaction tests

Four torrefied tests are conducted in order to produce the samples for the gasification experiments. The samples selected for the gasification tests are reported in Table I, where the experiment codes are related with the rotary kiln temperature set up (250°C and 270°C), with the first test (A) and its repetition (B) and the torrefaction cycle is indicated with an increasing progressive number.

Table I: Standard and torrefied pellets composition and calorific value

sample	moisture	fixed carbon	volatiles	LHV
	[%wt] w.b.	[%wt] d.b.	[%wt] d.b.	[MJ/kg] d.b.
STDP	7.88	16.44	82.68	17.5
T250_B2	4.45	18.73	80.44	17.6
T250_B3	4.41	19.37	79.88	18.1
T250_B4	4.60	19.29	79.95	18.1
T270_A2	4.16	22.71	76.49	18.7
T270_A3	4.05	21.68	77.53	18.3

Knowing the characteristics of the pre-treated pellets, some pellets samples were selected for the gasification tests. In particular, samples of torrefied pellets made in the same experiment (T250 and T270) were selected in such a quantity that they could be fed into the gasification tests for a few hours.

The torrefied material absorbs the humidity present in the environment in a different way than the original biomass. For this reason, the collected samples were placed in paper bags and left in the laboratory for a month before the gasification tests in order to obtain the biomass moisture stabilization.

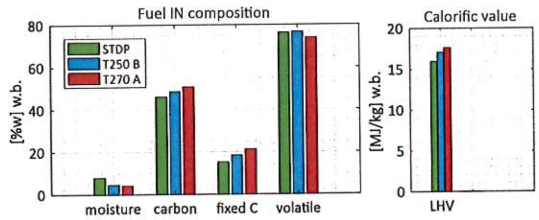

Figure 2: Standard and torrefied pellets after moisture stabilization – average composition and calorific value on w.b.

The average values of composition of biomass and calorific value for each gasification test performed are shown in Figure 2. It can be seen that the moisture content of the normal pellets to the torrefied pellets is significantly reduced. At the same time, there is an increase in carbon content and fixed carbon, a slight decrease in volatile compounds and an increase in calorific value from standard to torrefied pellets.

The primary difference between STDP and T250 is the moisture content, although a minor difference was observed with respect to VC (volatile compounds).The stronger hydrophobic character of torrefied biomass is possibly represented at more than 250 ° C, the clearest result of the torrefaction cycle.

On the contrary, there has been a growing trend in terms of total carbon content, fixed carbon and untreated biomass LHV values.

3.2 Gasification tests

Three gasification experiments have been carried out using standard pellets (STDP), torrefied pellets at 250°C (T250) and torrefied pellets at 270° (T270). Pellets samples were taken before each gasification test in order to carry out the laboratory tests in terms of water and ash content and calorific value.

The secondary air flow rate influences the reduction zone temperature of the reactor. In particular, increasing the air flow rate the temperature increases and, as a consequence, the carbon conversion due to the Boudouard reaction increases; the char production decreases and the carbon monoxide in the producer gas increases.

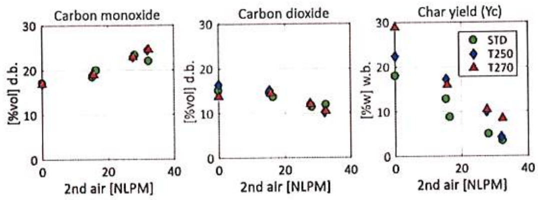

Figure 3: Carbon conversion in terms of CO, CO_2 and char yield VS secondary air flow rate

Figure 3 shows the values of CO and CO_2 concentrations on a dry basis measured and the value of the yield in char. It is possible to see that as secondary air increases it leads to an increase in the conversion of carbon in biomass in terms of CO and CO_2. In particular, an increase in secondary air leads to an increase in CO and a decrease in CO_2 production, and a clear reduction in terms of char production.

Figure 4 shows the concentrations of the producer gas in terms of H_2, CH_4 and N_2. Hydrogen content decreases (against CO trend), methane content decreases slightly, and nitrogen content increases slightly due to the introduction of more air in the lower part of the reactor.

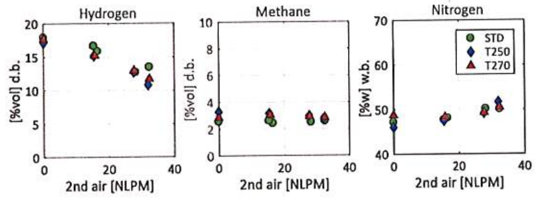

Figure 4: Producer gas composition in terms of H_2, CH_4 and N_2 VS equivalence ratio (ER)

The same analysis can be done considering the carbon conversion versus the equivalence ratio (ER) of the gasification process (Figure 5). It is quite evident that the secondary air influences the value of the equivalence ratio. It can be note that in case of the same ER the torrefied material presents a higher CO production at the expense of lower CO_2 production. The interesting thing is the char production that it follows the trend of ER regardless of the gasified material.

In Figure 6 some important gasification parameter are reported in terms of gas specific energy (SGE) as a ratio between the gas energy content per kg of biomass used (on dry and wet basis) and the cold gas efficiency (CGE) versus the equivalence ratio.

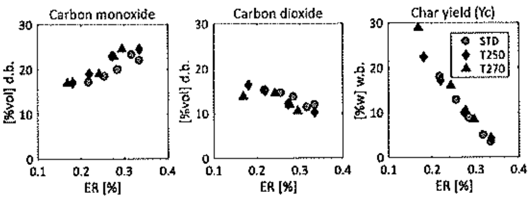

Figure 5: Carbon conversion in terms of CO, CO_2 and char yield VS equivalence ratio (ER)

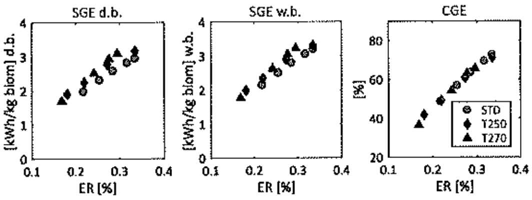

Figure 6: Specific gas energy on dry and wet basis and cold gas efficiency

It can be seen that there is an increase in the gas specific energy (SGE) in terms of energy produced by the gas relative to the amount of biomass used on a dry basis, with the use of torrefied material. This effect is reduced on a wet basis, taking into account the same parameter. This is even more evident when considering the efficiency of the process in terms of CGE in relation to ER.

In this scenario, it would seem that the plant 's output is more related to the achieved ER values than to the material used.

4 CONCLUSIONS

In conclusion, the gasification process can be optimized for all feedstock tested (standard and torrefied pellet) using a secondary air flow rates in order to control the equivalence ratio of the process, enhancing the carbon conversion (increase the carbon monoxide content in the producer gas and decrease the char production).

A significant difference in producer gas LHV was not reported as regards the gasification process. Using the same secondary air condition, the torrefied pellet tends to achieve less efficiency with respect to the cold gas efficiency and the char yield whit to the standard pellets. However, an improvement in terms of specific gas energy is reported using torrefied pellets under the same ER conditions. The trends in terms of cold gas efficiency versus equivalence ratio, however, suggest that going towards higher ER values, higher CGE values may be accomplished independently of the feedstock used.

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