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Experimental Study of Wood Chips Torrefaction in a Pilot-Scale Rotary Kiln

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This work aims to study the beech chips torrefaction in a continuous pilot-scale rotary kiln. The effects of operating parameters – temperature, residence time and solid hold-up – on the temperature profile of the solid bed along the kiln and the process mass yield are evaluated. It has been verified that an increase of the temperature level or residence time leads to a decrease of the process mass yield. Furthermore, it has been evidenced that an increase of the solid hold-up tends to decrease the mass yield too. Studying the temperature profile along the kiln has enabled to locate the drying and torrefaction zones. Torrefaction only begins in the last third of the heating zone. It has also been observed that an important solid hold-up induces a slower heating of the biomass. On the other side, for high temperatures and/or solid hold-up, the biomass temperature exceeded the set-point temperature, which evidences the occurrence of exothermic reactions.

1. Introduction

Biomass conversion is one of the major alternatives to the use of fossil fuels. Although some conversion ways, as direct combustion, are well known, others, as co-combustion or gasification, are always under development. For these processes, some technological and economic barriers remain. Indeed, the biomass is a heterogeneous material, whose properties are dependant of the species under consideration, the location of harvesting, etc. Moreover, the energy density of biomass is very low (in comparison with coal), which induces high transport costs. A grinding step will often be required to reduce particles sizes to the right dimension before its introduction in the burner. A solution can be to add a pre-treatment step in the chain of energy conversion (Svoboda et al. 2009). Torrefaction is one of the pre-treatments under evaluation and looks promising to improve the viability of the energy and biofuels productions from biomass (Uslu et al. 2008).

Torrefaction is a thermal treatment at low temperature (250 – 300 °C) in an oxygen-free atmosphere. The torrefied biomass is hydrophobic, more homogeneous, more brittle (Bergman et al. 2004) and has a larger energy density than the raw biomass. This is due to the degradation of the biomass components, especially hemicelluloses (Van der Stelt et al. 2011).

Although many studies investigated the torrefaction at lab-scale, just a few are conducted at a pilot-scale and present experimental results (Ratte et al. 2011) or modelling results (Casajus 2010). Among the reactors potentially suited to torrefaction (Batidzirai et al. 2013), the rotary kiln has been chosen for this study. Indeed, this technology is frequently used at the industrial scale and can process a lot of material types, such as coke, cement and minerals. Often used for biomass drying, it could easily be adapted for torrefaction. Finally, no work has been published concerning the torrefaction of wood particles in a pilot-scale rotary kiln.

In this work, several experimental runs are presented to evaluate the effect of operating parameters (temperature level, residence time and solid hold-up) on the mass yield of the process and on the torrefied biomass composition.

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2. Material and methods

2.1 Material

Beech wood chips are used in this study. Their main characteristics are presented in Table 1.

Table 1: Characteristics of wood chips

Wood specie	Beech
Particle length	5 - 15 mm
Particle width	2 - 7 mm
Particles thickness	1 - 3 mm
Moisture content	10 - 12 %
Bulk density	310 kg/m^3

Moisture content of wood chips is determined in accordance with standard method NF EN 14774-1: 2010–01 for each run.

2.2 Apparatus

The pilot rotary kiln consists of a rotating cylinder heated electrically. The cylinder is 4.2 m in length and 0.21 m in diameter and the inner wall is covered by a metal grid to increase the adhesion to the particles. The slope can vary between 0 and 7 ° and the rotational speed between 1 and 21 rpm. The furnace is composed of five independent heating zones, of 0.5 m length each, as presented in Figure 1.

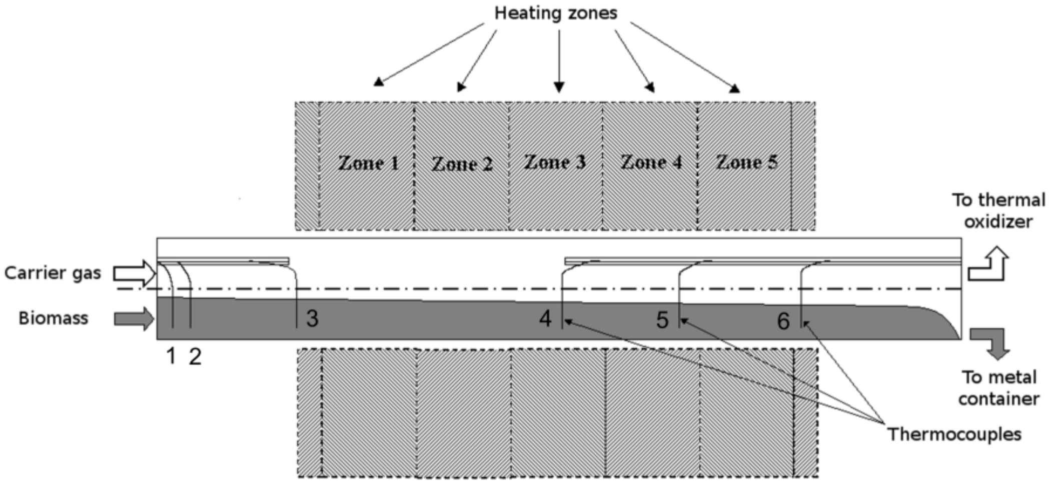

Figure 1: Schematic representation of the pilot rotary kiln

The temperature level of each zone can be controlled up to 1,000 °C (with an accuracy of ± 2 °C) and the end of the cylinder is outside the furnace, which allows the cooling of treated biomass.

The feeding system, consisting of a hopper and a vibrating conveyor, is continuously weighed. The inlet flow rate of wood chips can thus be controlled accurately. The cylinder is swept with a nitrogen flow to have an oxygen-free atmosphere. Several thermocouples are disposed along the kiln to provide a temperature profile inside the bed of solid.

At the end of the cylinder, torrefied wood chips are collected in a metal container. This one is closed hermetically and swept with nitrogen to avoid the oxidation of the product during cooling.

Gaseous species produced by torrefaction are carried away from the reactor with nitrogen to a thermal oxidizer. Volatile matters are thus destroyed before being vented out of the chimney.

2.3 Experimental runs

Wood chips flow in the rotary kiln has already been studied (Colin et al. 2013). A correlation between the bed depth profile and the operating parameters has been established. This profile allows the calculation of the solid hold-up – defined as the ratio between the volume of biomass in the cylinder and the volume of the cylinder – and of the mean residence time (MRT) of biomass in the kiln. As the residence time and the solid hold-up can be driven via the rotational speed, the inclination and the feed rate, the three parameters under investigation in this study are the temperature level, the residence time of biomass in the kiln and the solid hold-up.

It has been chosen to use an isothermal setpoint temperature profile along the kiln to simplify the study. Parameters of experimental runs are summarized in Table 2.

Table 2: Operating parameters (measured or computed) for the experimental runs

Run	Setpoint temperature (°C)	Rotation speed (rpm)	Inclination (°)	Inlet flow rate (kg/h)	MRT (min)	Hold-up (%)
1	250	2	2	4	69	9.8
2	280	2	2	4	69	9.8
3	280	4	2	4	35	4.7
4	280	4	2	8	33	9.6
5	270	2	2	4	69	9.8
6	300	2	2	4	69	9.8
7	270	3	1.5	6	55	11.7
8	270	3	1.5	8	56	16.4

When the steady state is reached, after typically 3 h, an empty container is then placed at the outlet of the kiln. The torrefied wood is sampled for 1 h. The filled container is nitrogen-swept and weighed after cooling. The mass yield η (in %), defined on a dry basis, is computed according to Eq (1).

$$\eta = \frac{M_{tor}}{\dot{M}_h} \times \left(1 + \frac{H}{100}\right) \times 100 \tag{1}$$

Where M_{tor} is the mass of torrefied wood chips (in kg), $\dot{M}_h$ is the inlet flow rate of raw wood chips (in kg/h) and H is the initial moisture content (wt. %).

The solid is analysed in terms of volatile matter (VM) and ash contents (AC) in accordance with standard methods AFNOR (NF EN 15148:2010-03 and NF EN 14775:2010-03, respectively). The fixed carbon content (FC in %) can then be calculated according to Eq (2).

$$FC = 100 - VM - AC \tag{2}$$

3. Results

Results of all runs are summarized in the Table 3.

Table 3: Mass yield, maximal temperature (Tmax) of the thermocouples and proximate analysis of torrefied biomass for each run

Run	Mass yield (%)	Temperature: Tmax (°C)	Temperature: Thermo-couple	Proximate analysis: VM (%)	Proximate analysis: FC (%)	Proximate analysis: AC (%)
1	98.3	238	5	83.6	15.8	0.6
2	83.6	286*	5	76.8	22.5	0.7
3	89.4	277	5	80.2	19.1	0.7
4	87.1	287*	6	79.5	19.8	0.7
5	88.2	270	5	79.2	20.1	0.7
6	75.0	304*	5	72.1	27.1	0.8
7	89.8	260	5	80.3	19.0	0.7
8	88.7	277*	6	80.1	19.2	0.7
Raw	-	-	-	85.0	14.5	0.5

*setpoint temperature exceeded

3.1 Effects of temperature and residence time

To investigate the effect of temperature level, runs 1, 2, 5 and 6 are compared. These four experiments have been carried with the same residence time and the same hold-up (see Table 2). In Figure 2, the mass yield is presented as a function of the maximal temperature measured and as a function of the set point temperature.

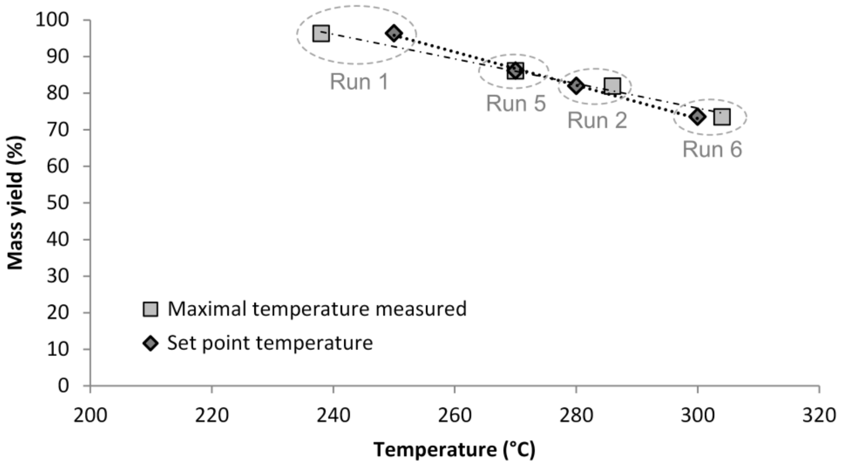

Figure 2: Effect of the torrefaction temperature on the process mass yield

As expected (Almeida et al. 2010), the higher the temperature, the lower the mass yield. The slope of the regression line depends on the considered temperature. Indeed, the two lines are crossing at around 270 °C, for a mass yield of 88.2 %. This could reflect that torrefaction becomes exothermic beyond a certain temperature, here 270 °C.

The effect of the mean residence time can be evaluated by comparing the results of runs 2 and 4. The higher the residence time, the lower the mass yield. In the two cases, the set point temperature is exceeded by 6-7 °C and maximal temperatures measured are very close. In the range studied, the effect of residence time on the exothermicity of reactions would be limited.

3.2 Effect of solid hold-up

The temperature profiles of the bed of solid are plotted on Figure 3 for runs 3 and 4. Vertical lines mark out the five heating zones (HZ_i), and the two short thermally insulated zones (IZ).

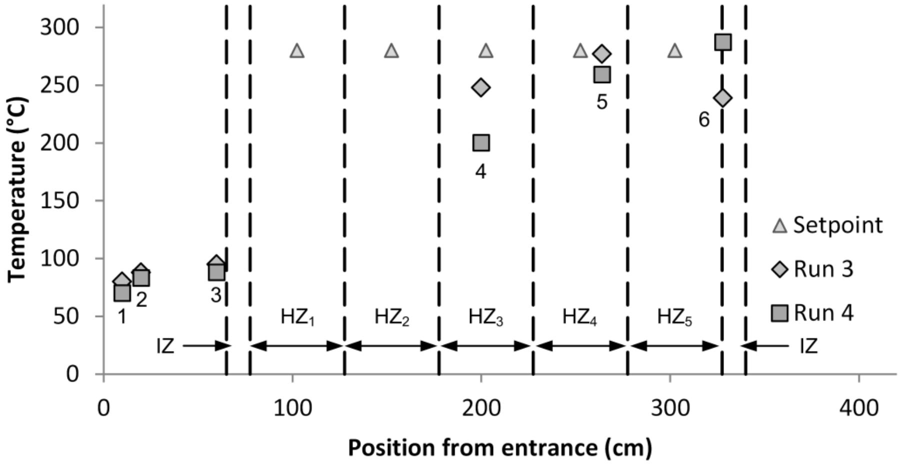

Figure 3: Temperature profile along the kiln for runs 3 and 4

These two runs were performed with the same set point temperature (280°C) and a similar mean residence time (about 34 min). The hold-up reaches 4.7 and 9.6 % for runs 3 and 4, respectively.

Fortunately, the torrefaction process starts in zones 3 or 4, depending on the operating conditions. The three temperatures at the entrance (thermocouples 1, 2 and 3) are below 100 °C, since this part of the cylinder is outside the heated shell. In the absence of temperature sensors in zones 1 to 2, drying and heating of the dry solid bed cannot be characterized.

As expected, the temperature of the bed is higher for run 3 in zone 3. For indirectly heated rotary dryers, heat transfer to the particles bed occurs mainly by conduction through the covered surface of the tube wall. When the hold-up increases, this surface increases slower than the quantity of biomass to heat. Consequently, when the solid hold-up is low, the rise in temperature is higher and torrefaction starts earlier. At the exit of the last heated zone, a significant difference is observed between the two runs. For run 3, the temperature decreases. On the contrary, for run 4, the temperature is still increasing and overshoots the set point temperature. The maximum value measured for this run is 287 °C. One plausible explanation is the appearance of exothermic reactions in the particles bed. When the hold-up is high, the overall heat of reaction cannot be evacuated and a thermal runaway takes place in the bed, resulting in an abnormal temperature increase. This temperature overshoot leads to a mass yield lower for the run 4 than for the run 3 (87.1 and 89.4 %, respectively) as presented in Table 3.

3.3 Impact of torrefaction on biomass composition

The volatile matter content of torrefied biomass has been correlated with the mass yield, as can be seen in Figure 4.

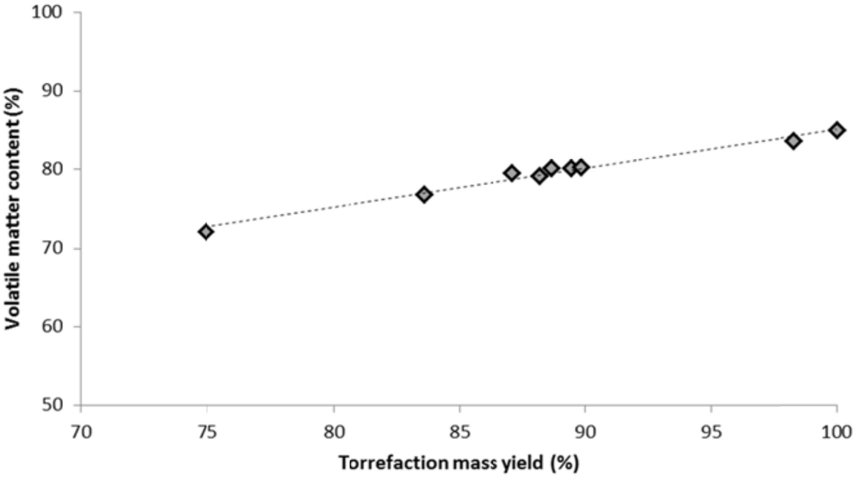

Figure 4: Effect of torrefaction on volatile matters content of biomass

The raw biomass is placed at the mass yield of 100 %. As expected, the volatile matters content decreases linearly when the torrefaction yield decreases. This results in an increase of the fixed carbon content. The ash content also slightly increases but remains very small (below 1 %).

From these observations, it appears that the volatile matter content could be used as a torrefaction severity indicator. Measuring the volatile matter content to estimate the mass yield will be especially useful to evaluate the inter-particles homogeneity of a large sample.

4. Conclusions

The torrefaction of beech chips has been successfully conducted in a continuous pilot rotary kiln. Several runs have been necessary to evaluate the impact of operating parameters on the behaviour of wood chips in the kiln. As expected, an increase in the residence time or in the temperature level induces a mass yield decrease. This confirms results obtained at the lab-scale. Another parameter of importance is the solid hold-up. Increasing this parameter surprisingly tends to decrease the mass yield too.

The final product has been characterized in terms of proximate analysis. The torrefied product contains less volatile matter than the raw beech. The fixed carbon is so more concentrated. The volatile matter content appears to be a suitable indicator of the torrefaction severity.

It has been shown that a high temperature and/or a high solid hold-up promote the appearance of exothermic reactions. Such reactions have been highlighted and discussed but the conjugated effect of operating parameters on this phenomenon remains difficult to evaluate.

For further investigation of these interactions, experimental results will be used to validate a predictive model under development. This model is based on a solid transportation model of the wood chips, on thermal transfer equations and on thermal degradation kinetics. It aims to predict accurately the temperature profile of the biomass bed along the kiln during torrefaction, to calculate the solid mass yield. This mass yield will then be correlated with torrefied wood properties such as grindability.

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