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Full Length Article

Quantification of the torrefaction effects on the grindability and the hygroscopicity of wood chips

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HIGHLIGHTS

- Beech wood chips are torrefied in a continuous pilot-scale rotary kiln.
- A minimum of hygroscopicity is obtained for a mass loss between 1.7 and 7.4%.
- A method is developed to determine accurately the grinding energy requirement.
- The surfacic grinding energy is divided by 6.3 between wet and dry chips.
- Torrefaction can divide surfacic grinding energy by 8.1 for a mass loss of 25%.

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ABSTRACT

In the field of biomass torrefaction, lots of product properties have been widely investigated at the lab scale but some uncertainties remain about the gains in terms of grindability and hygroscopicity of torrefied products. In this study, beech wood chips (with an initial moisture content of 10–12%) have been torrefied in a pilot-scale rotary kiln. The torrefaction severity was controlled by adjusting the temperature, the treatment duration and the solid hold-up in the kiln. Mass losses ranging between 1.7% and 25% have been obtained. Properties of torrefied wood chips were then analyzed in terms of composition, heat content, hygroscopicity and grinding energy requirement. Dynamic vapor sorption measurements show that a minimum of hygroscopicity is reached for a mass loss (ML) between 1.7 and 7.8%. The moisture uptakes for mass losses above this optimum remain stable at values twice lower than that of raw biomass. Finally, a new method is proposed to estimate the grindability of wood chips. This method takes into account the grinding energy consumption and the particle size distribution of ground samples. A reduction by a factor of 6.3 of the apparent specific surface grinding energy is observed between a moisture content of 41% and the dryness. This energy measurement is in turn reduced by a further factor of 8.1 after torrefaction with a 25% mass loss.

1. Introduction

The development of renewable energy supply chains is a major issue in the actual context of global warming and fossil fuels depletion. Worldwide, bioenergy represents 80% of the total amount of renewable energy produced in 2012 [1]. Moreover, the use of biomass for power generation is expected to double in the EU by 2020, as part of the 20/20/20 target. Considering bioenergy, the two main pathways are the use of solid biofuels (mainly valorized by combustion) and the production of gaseous biofuels (especially syngas obtained via gasification). These applications classically use wood chips as a source of energy. In the case of combustion, one way to produce heat and/or electricity at a large scale is to convert existing coal-fired power-plants into co-firing plants (simultaneous combustion of coal and biomass), with limited impact on efficiency and operations. The main existing method uses injection of milled biomass through pipes but the biomass-coal ratio remains very low because the combustion behavior of biomass is too far from the one of coal [2]. Concerning the second pathway, an efficient gasification, for example in an entrained-flow reactor, requires a high accessibility of wood to the gaseous reactants (CO_2, H_2O...). The external surface of particles is thus classically increased by means of grinding that represents a very costly step [3]. The main limitations to the use of large amounts of biomass at the industrial scale are thus its low energy density, its inappropriate composition compared to coal and the large energy

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requirement of the grinding step. These drawbacks could be overcome by performing torrefaction.

Torrefaction of biomass is a thermal treatment at low temperature (250–300 °C) under inert atmosphere [4]. Under heat effect, hemicelluloses of wood are decomposed. This leads to a biomass with a modified chemical composition presenting new properties. Torrefied biomass is for example considered as more brittle [5], less hygroscopic [6] and has a higher energy density than raw biomass [7]. Even if these aspects have been often studied at the laboratory scale, one of the major challenges is now the research of the optimal degree of torrefaction [8]. One of the main objectives is then to correlate the mass loss with the operating parameters on the one hand and with the product properties on the other hand. In the literature, the main operating parameters identified to control the torrefaction process are the temperature, the treatment duration [9] and the atmosphere composition as shown by Rousset et al. [10] and Wang et al. [11]. Effects of these parameters on the mass yield are now well known. In the same manner, the composition and the heat content of torrefied products have been widely investigated but some properties have not yet been clearly correlated with the mass loss. This is the case of the hygroscopicity about which some uncertainties remain: it is not clear if the hygroscopicity is correlated to the mass loss on the whole torrefaction domain or if the hygroscopicity remains stable above a given mass loss. Several authors have identified evaluation issues related to the grinding energy consumption. The most used indicator is the Hardgrove Grindability Index (HGI) initially developed for coal. Applied to biomass, this indicator could lead to unfavorable results as reported by Bergman et al. [12]. Indeed, only the most resistant part of the material is considered with this method, even if it represents a minor part of the overall matter in the case of wood. Other methods classically used to compare the grindability of various kinds of biomass are the energy consumption during a grinding experiment [13] or the comparison of the particle size distributions of ground samples [14]. Only one attempt has been made to take simultaneously into account the grinding energy consumption and the particle size. Repellin et al. [5] proposed to divide the grinding energy by the volumetric fraction of particles smaller than 200 μm. Even if this indicator is more reliable than the grinding energy alone, it looks insufficient to exhaustively compare ground samples with various particle size distributions. Finally, Temmerman et al. [15] proposed a comparison between the classical milling theories and recent published works on grinding energy requirement of biomass. They concluded that there is a lack of consensus in the literature on the calculation methods to determine the grinding energy of biomass. Since then, they evidenced that the Von Rittinger constant could be used to accurately establish the grindability of wood chips and pellets. However, this constant does not take into account the entire distribution of the ground product since it uses only the distribution median.

In this paper, the influence of operating parameters on torrefaction performed in a pilot rotary kiln is studied. The properties of torrefied biomass are evaluated in terms of ultimate, proximate and fiber analysis, hygroscopicity and grindability. A new method to characterize biomass grindability is proposed and applied to wet, dry and torrefied wood chips.

2. Materials and methods

2.1. Materials

Biomass used for this study is made of beech wood chips provided by a French Company (SPPS, Frasne, France). As received, the moisture content of wood chips was 10–12% on a dry basis (db). The dimensions of the chips are 5–15 mm in length, 2–7 mm in width and 1–3 mm in thickness. These dimensions have been measured for about 200 particles. Wood chips are bark-free, dust-free and calibrated to be easily handled. The bulk density of this feedstock is 280 kg/m^3.

2.2. Torrefaction process

The torrefaction of wood chips has been conducted in a pilot-scale rotary kiln (Fig. 1) made of a rotating cylinder electrically heated. The cylinder is 4.2 m in length and 0.21 m in internal-diameter. The inner wall is covered by a metal grid to increase the adhesion to the particles and favor their progress along the kiln. This grid is made of 4 mm stainless steel rods and each grid cell is 250 mm long and 40 mm wide. The kiln slope can vary between 0 and 7 ° and the rotational speed can be set between 1 and 21 rpm. The furnace is 2.5 m in length and its extremities are insulated to limit heat losses. It can be controlled from room temperature to 1000 °C. A thin layer of air separates the cylinder from the furnace. At the quite low torrefaction temperatures, the cylinder is thus mainly heated by convection and, to some extent, by radiation.

Wood chips are fed into the cylinder from the hopper with a vibrating conveyor whose amplitude is controlled by measuring continuously the overall mass of the feeding system. The inlet mass flowrate is thus accurately controlled (±2%). At the kiln-end, 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 the cooling phase. Volatile matters produced by torrefaction are carried away from the reactor with nitrogen into a thermal oxidizer. The entire kiln is swept with nitrogen (1 Nm^3/h) to maintain an overpressure.

In a previous study [16], the solid hold-up H (ratio between the volume of wood chips in the kiln and the volume of the cylinder) and the mean residence time (MRT) of particles have been correlated with the operating parameters (inclination, rotational speed and feed rate). The operating parameters retained here are thus the solid hold-up, the mean residence time and the furnace temperature T. Parameters used during experimental runs are summarized in Table 1.

For each run, once the steady state is reached – after usually 4 h – an empty container is placed at the outlet of the kiln. The torrefied wood is then sampled during 1 h. The filled container is nitrogen-swept and weighed after cooling. The mass yield η (in %), defined on a dry basis, and the mass loss ML (in%) are computed according to Eqs. (1) and (2), respectively.

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

$$ML = 100 - \eta \quad (2)$$

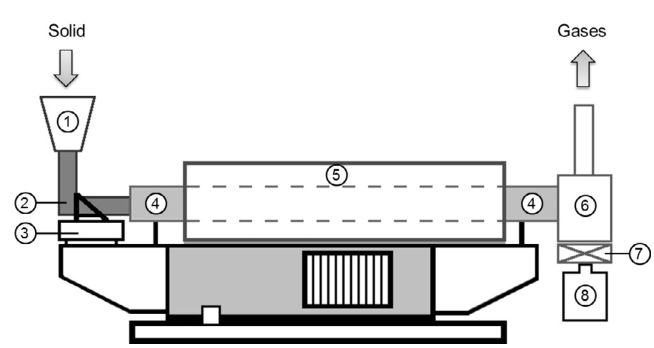

Fig. 1. Schematic representation of the pilot-scale rotary kiln. 1: feeding hopper, 2: vibrating conveyor, 3: weighing system, 4: rotating cylinder, 5: furnace, 6: heated outlet, 7: gate valve, 8: metal container.