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Impact of Torrefaction on Woody Biomass Properties

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Abstract

In this work, Norway spruce stem wood, stump and bark were torrefied in a tubular reactor. The effects of feedstock type and torrefaction process parameters such as torrefaction temperature and residence time on the grindability and chemical properties of the torrefied biomass samples were investigated. In comparison to torrefaction temperature, torrefaction residence time had smaller effects on the grindability of stem wood and stump. For raw bark, much less grinding energy is required compared to those for raw stem wood and stump. Torrefaction has minor effects on grindability of the bark. The cellulose contents of stem wood and stump were reduced slightly at a torrefaction temperature of 275 °C. On the contrary, the cellulose content of the torrefied bark drastically decreased already at a torrefaction temperature of 275 °C, with only trace amounts left in the 300 °C torrefied products.

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Keywords: stem wood, stump, bark, torrefaction, grindability, chemical composition

1. Introduction

Faster development of bioenergy has been hindered by drawbacks of biomass properties, including low bulk density, poor grindability, high moisture content and relatively low calorific value. Torrefaction is an efficient way to upgrade biomass into high quality solid fuel [1]. Torrefaction is usually conducted in inert atmosphere in a temperature range from 200 to 300 °C, driving out the moisture, and parts of the volatile organic compounds in the biomass [2,3]. Torrefied biomass retains most of its chemical energy and can be grinded easily in comparison to the raw biomass. In addition, torrefied biomass has increased uniformity with respect to product quality in terms of physical and chemical properties [4].

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The Norwegian government has a goal to reduce the greenhouse gas emissions by 30% by 2020 according to *World Energy Outlook* 2009 [5]. Bioenergy will play a significant role in meeting this goal. Norway has abundant forest resources and more than 40% of the land is covered by forest [1]. Biomass materials from the forest has a great potential to provide suitable feedstocks for bioenergy production. Stem wood is normally the main product of forest harvesting with harvesting or thinning residues such as tops and branches and stump wood as waste streams usually left behind in the forest, while bark is a waste product in the pulp and paper and sawmill industries. The tops and branches and stump wood represent a large bioenergy potential and is an underutilized resource for energy production, while the bark usually is burnt to produce heat in the mentioned industries. It has been reported that stump constitute 22-24% of the stem volume of a mature conifer tree, i.e. representing a very significant bioenergy potential [6].

Until now, the raw biomasses subjected to torrefaction studies have mainly been stem wood from different wood species, agricultural wastes and short rotation coppice [6]. Only a few studies have been carried out to investigate torrefaction behaviors of tops and branches, bark and stump and their properties after torrefaction treatment [2,3,6]. In addition, the studies have focused on the effect of process conditions on the mass loss of biomass and the properties of torrefied biomass for further thermal conversion applications. Less attention has been paid to the change of chemical composition and grindability of biomass upon torrefaction treatment.

The objective of the present work was to study the effects of torrefaction on the chemical composition and grindability characteristics of woody biomasses including stem wood, bark and stump from Norway spruce.

2. Materials and Methods

2.1 Raw biomass

In the present work stem wood, bark and stump from Norway spruce (*Picea abies*) were investigated. The Norway spruce trees harvested in South Norway were divided into three parts including trunk (with bark), stump and tops and branches. The tops and branches were not studied in this work. The trunk wood was debarked to get stem wood and bark. The stem wood was cut into strips and further into cubes with sides of 1 cm. The stump was shredded into chips and those with size of 3-5 cm were subjected to further experiments. The bark was chipped into pieces and the pieces with size of 5-7 cm were used. The stem wood cubes, bark and stump chips were dried at 105 °C for 24 hours for further analysis and torrefaction experiments.

2.2 Torrefaction experiments

The torrefaction experiments were conducted in a bench-scale tubular reactor. It includes a tubular vessel, an electrical gas pre-heater with a temperature controller, a condensate receiver and a gas supply system. For one torrefaction experiment, around 80 grams of raw biomass sample was loaded into the vessel for torrefaction treatment. After sample loading, the tubular vessel was closed tightly and connected with the gas supply system and the condenser as well. The tubular vessel was then placed inside an electrically heated furnace and purged with 1 l/min nitrogen to generate inert atmosphere. The sample was heated up at a heating rate of 15 °C/min to three final temperatures (225, 275 and 300 °C).

The residence time for one sample at each final temperature was 30 and 60 minutes, respectively. After each torrefaction experiment, the reactor was cooled down spontaneously and the torrefied biomass was discharged.

2.3 Assessment of torrefied biomass

For raw and torrefied biomass samples, the contents of carbohydrates were analyzed according to the slightly modified method reported by Sluiter et al. [7]. The raw and torrefied biomass samples were digested by a two-step acid hydrolysis. The suspensions of each digestion product were filtered and washed by distilled water through gas filter crucibles. The filtered supernatants were analyzed with high performance liquid chromatography (HPLC) for determining the sugar concentrations (glucan, mannan and galactan). The solid residues remaining after washing were dried at 105 °C until reaching a constant weight, and consist of acid-insoluble organics and ash. The dry solid residues were heated at 550 °C in air to determine the content of acid-insoluble ash. The Klason lignin content was calculated by deducting the acid-insoluble ash content from the dried acid-insoluble residue content.

The grindability of the raw and torrefied biomass samples was assessed by grinding them in a cutting mill. In the pre-grinding stage, the stem wood cubes and bark and stump chips with and without torrefaction treatment were fed into the cutting mill without a bottom sieve to reduce their sizes. Fine grinding of the grains and particles produced from the pre-grinding stage was carried out in the same cutting mill equipped with a 1 mm bottom sieve. The electricity consumed during the pre- and fine grinding stages was recorded by a digital wattmeter. The powder samples produced in the fine grinding stage were sieved by a vibrating sieving machine (Fritsch Analysette 3 Pro) with the following mesh sizes: 1 mm, 0.5 mm, 0.3 mm, 0.2 mm, 0.1 mm and 0.063 mm. The sample particles collected from the different sieves were weighed and presented as a percentage of the initial sample mass.

3. Results and Discussion

3.1 Torrefaction experiments

As can be seen in Table 1, the stump has similar properties as those of the stem wood. The fixed carbon content of the stump is even 1.3% higher than that of the stem wood. On the other hand, the bark contains as much as 23.0% fixed carbon, but also 2.1% ash. Fig. 1 shows the mass yields of the torrefied samples as a function of the final temperature and residence time. Obviously, temperature plays a critical role in realizing the mass yields in the performed torrefaction experiments. As the torrefaction temperature increased to 275 °C, there are significant mass losses for the three studied biomass samples, which is related mainly to the decomposition of hemicellulose. Compared to stem wood, the stump is more sensitive to temperature increase. At 300 °C torrefaction temperature, about 44 and 54% mass losses were recorded from the stump with holding time of 30 and 60 minutes, respectively, whereas stem wood lost only 30 and 42% mass, respectively.

Table 1. Properties of the studied fuels

Sample	Stem wood	Bark	Stump wood
Volatile matter content (wt%, dry basis)	88.1	74.9	86.7
Ash content (wt%, dry basis)	0.3	2.1	0.4
Fixed carbon content (wt%, dry basis)	11.6	23.0	12.9

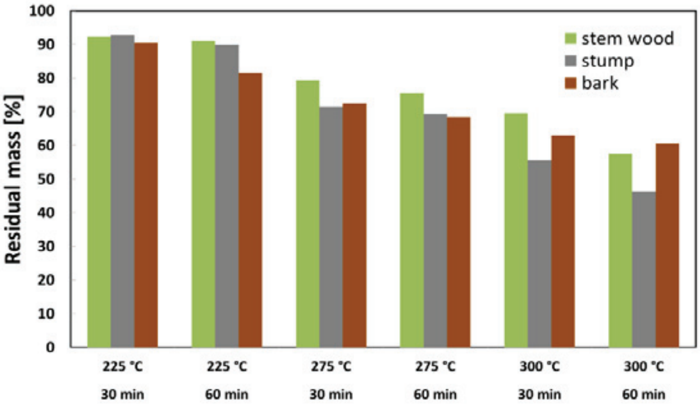

Fig. 1. Mass yields of torrefied samples.

3.2 Characterization of raw and torrefied samples

Compositional analysis of raw and torrefied biomass samples was carried out to understand the conversion behavior of the samples during torrefaction. As shown in Fig. 2, bark has the highest Klason-lignin content (40.8%), while stump has the highest hemicellulose content (23.0%). The stem wood has a similar composition as that of the stump, but an evident high cellulose content (42.6%). During torrefaction, lignocellulose materials decompose to different degrees upon torrefaction severity [7,8]. The decrease of glucan, mannan and galactan reflects decomposition of cellulose and hemicellulose in the samples. As also shown in Fig. 2, hemicellulose (measured as the sum of mannan and galactan) is the least thermally stable component of the studied biomass samples during torrefaction. After torrefaction at 275 °C, more than half of the hemicellulose content in the three studied biomass samples was degraded. The hemicellulose content of them further decreased and only a minor fraction was measured for samples torrefied at 300 °C. Fig. 2 also shows that the content of cellulose, indicated by the content of glucan, does not decrease evidently even at the torrefaction temperature 275 °C for stem wood and stump. However, a significant decrease is observed for bark. On the other hand, the Klason-lignin content of the torrefied samples increased considerably with increasing torrefaction temperatures.

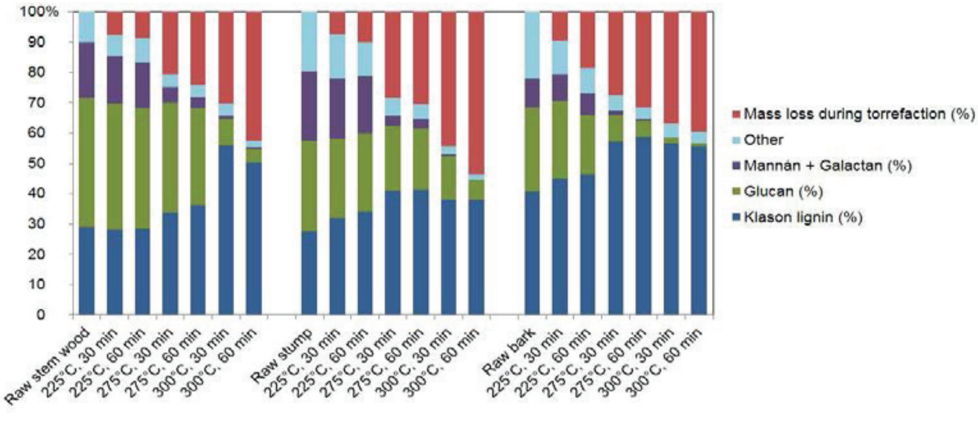

Fig. 2. Composition of raw and torrefied stem wood, stump and bark (dry basis).

3.2 Effect of torrefaction on grindability

Fig. 3 shows the total energy required for grinding the raw and torrefied biomass samples, which includes energy consumed for both the pre-grinding and fine grinding steps. For stem wood and stump, the energy required for grinding the samples was reduced significantly due to torrefaction treatment. This trend is in good agreement with those reported in literatures for the grinding of stem wood [1]. It indicates that significant energy savings associated with size reduction can be achieved by torrefying stem wood and stump, even at a mild torrefaction condition. Compared to stem wood and stump, much less energy is needed for grinding the raw bark, and the torrefaction treatment has no evident effects on the energy consumption for grinding bark. The differences in energy required for grinding stem wood, stump and bark are partially due to their compositional differences [6,8]. Fig. 4 shows the evident decrease of the amount of large particles (0.5 mm < d < 1 mm) of stem wood and stump after torrefaction at high temperature and prolonged holding time. For the raw bark, the percentage of large particles (0.5 mm < d < 1 mm) is quite small, in comparison to stem wood and stump. The major fraction of the raw bark particles has a size in the range of 0.3 mm < d < 0.5 mm, which decreases evidently after torrefaction treatment. Moreover, the percentage of fine bark particles (d < 0.063 mm) increases considerably upon the increase of torrefaction temperature.

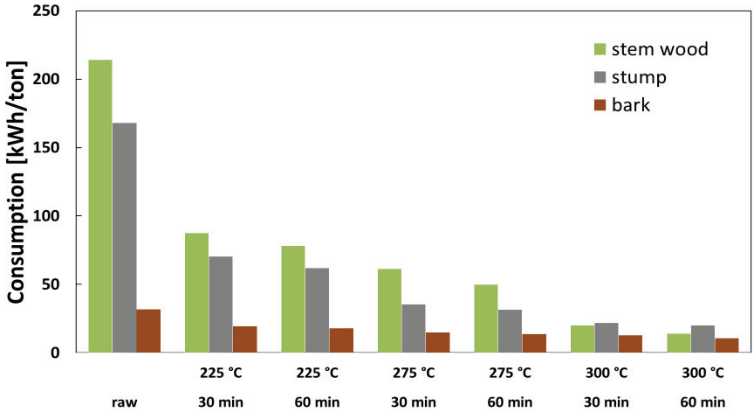

Fig. 3. Energy required for grinding raw and torrefied samples.

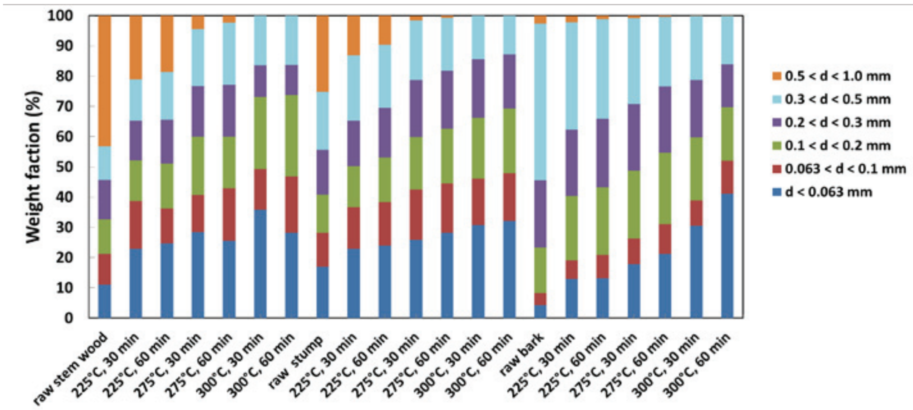

Fig. 4. Particle size distributions for the stem wood, stump and bark as a function of torrefaction severity.

4. Conclusion

In the present work, the effects of torrefaction on the grindability and chemical compositions of Norway spruce stem wood, stump and bark were investigated. The results showed that both torrefaction temperature and residence time had effects on the grindability and chemical compositions of the studied biomass samples. However, the torrefaction temperature was more influential. The grindability of the stem wood and stump was significantly improved after the torrefaction treatment. For the stem wood and stump torrefied at 225 °C, only approximately half of the grinding energy was needed compared to those required for grinding the dried raw feedstocks. In addition, the coarse particles with sizes in the range of 0.5 to 1 mm were completely reduced after grinding when the stem wood and stump were torrefied at 275 °C. In addition, the hemicellulose contents of the torrefied stem wood and stump decreased with increase of torrefaction temperature and residence time, with only trace amounts left at 300 °C. Much less energy was required for grinding bark, and torrefaction did not affect the grinding energy requirement significantly. The fraction of fine particles ($d < 0.063$ mm) increased considerably in the ground torrefied bark. In addition, the cellulose content in the bark decreased evidently as the bark was torrefied at 275 °C.

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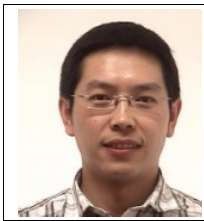

Biography

Liang Wang is a research scientist at SINTEF Energy Research in Trondheim Norway. His research focuses on characterization of biomass and wastes using combined analytical instruments and techniques, advanced biomass carbonization technology, experimental and kinetic study of torrefaction, pyrolysis, gasification and combustion, of biomass and charcoal, ash chemistry during biomass and waste thermal conversion.