**An experimental study to investigate the effect of torrefaction temperature and time
on pyrolysis of centimeter-scale pine wood particles**

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Abstract

The aim of this study is to investigate the effect of torrefaction on pyrolysis of centimeter-scale pine wood particles at 520 °C. The experiments were conducted in a vertical tube furnace and the yields and compositions of bio-oil were measured. We found that torrefaction at 225°C and 250°C for 15, 25 and 35 minutes had little effect on the pyrolysis products. However, when wood was torrefied at 275°C and 300°C, significant char formation and transformation occurred. During the pyrolysis processes, lower weight loss rate and higher char fraction were observed for wood torrefied at 275°C and 300°C, but the center temperature profiles were not affected. Conversion time for pyrolysis was also not affected by the torrefaction conditions. Pyrolysis yields of liquid, gas and char were calculated and found to be affected by the torrefaction conditions. GC/MS analysis of bio-oil obtained from torrefied wood shows that the acid content decreases with increasing torrefaction intensity, implying improvement of bio-oil quality. Further, phenol content increases and guaiacols content decreases with the increase of torrefaction intensity. On the other hand, no novel species were detected and the overall effect of torrefaction was less remarkable than anticipated for the temperatures tested.

Keywords

Torrefaction, Pyrolysis, Centimeter-scale wood particles, bio-oil.

1. Introduction

Finding renewable alternatives to fossil fuels is one of the most important challenges of the twenty-first century. In this context, biomass is an important source of renewable energy. It is the fourth largest source of energy in the world, and can be considered carbon neutral as its carbon is recycled from the atmosphere [1–3]. Wood chips are a common feedstock for processing biomass into other forms of fuel. This is typically accomplished by biological, chemical or thermochemical means. Of these the thermochemical process such as fast pyrolysis rapidly converts woody biomass into bio-oil, bio-char and syngas in the absence of oxygen without extensive equipment. Hence it is more convenient for remote locations. However, bio-oil contains a large amount of oxygen (~40%) and has a large water fraction; these lower its energy content. Also the presence of a carboxyl group (COOH) makes it highly acidic (pH~2) and unstable [4] and thus difficult to store. All these constraints provide numerous application barriers.

A potential method to reduce the oxygen content of biomass and improve the bio-oil quality is to decompose hemicellulose in a relatively low temperature range of 225–300°C, a process known as torrefaction[5–7]. O/C ratio of the wood decreases during torrefaction, causing the energy density of the torrefied wood to increase compared with untreated wood[8,9]. Additionally, after torrefaction biomass has hydrophobic characteristics that makes storage of torrefied biomass more attractive [10,11]. Furthermore, the reactivity and grindability of woody biomass are also enhanced after torrefaction[12,13]. These characteristics benefit further processes such as combustion, gasification and fast pyrolysis.

Another key parameter that affects the pyrolysis process is the size of the biomass particles. Reducing biomass particle size will increase the heat and mass transfer rates and reduce the secondary tar reactions, and thus most lab-scale studies on biomass pyrolysis have been carried out with particles in a narrow size range to fulfil the requirements of rapid heating [2,4]. On the other hand, experiments with mallee woody biomass implies negligible effect of particle size on the yields of three lumped product (liquid, char, gas) after the size exceeds 1.5 mm [14]. A number of studies also suggest that the bio-oil yield is not significantly affected by the particle size in a certain range of 0.5-2 mm [15,16]. Considering that biomass is voluminous with low energy density and widely distributed over large and remote areas, local feedstock grinding in remote areas with no utilities to ≤ 1.5 mm is impractical and is economically inefficient. Producing fine particles as feedstock requires a substantial amount of energy and effort for size reduction. However, centimeter-scale particles produced by a wood chipper can be easily used, but their pyrolysis enhances secondary tar decomposition producing acids and other small molecular species found in bio-oil. Thus it would be useful to find a way to increase the bio-oil quality obtained from centimeter-scale biomass particles. Pre-torrefaction is one possibility.

There has been a fair amount of research on pyrolysis of torrefied wood, and torrefaction is considered as an effective pretreatment strategy for fast pyrolysis to produce high quality bio-oil [17–20]. However, studies regarding pyrolysis of torrefied wood were rarely done on centimeter-scale biomass particles, and dynamic changes of temperature and solid mass fraction were seldom reported. The objective of this study is to investigate the effect of torrefaction on pyrolysis of centimeter-scale pine wood particles. This influence was

analyzed in terms of the pyrolysis process, product yields and the chemical composition of the bio-oil obtained. Temperature and weight loss measurements were also made.

2. Materials and methods

2.1 Materials

The feedstock used in this study was pine wood cuboid with a dimension of $0.75 \times 0.75 \times 3$ inches ($19.1 \times 19.1 \times 76.2$ mm). These wood particles were dried in an oven at 105°C overnight for 12 hours before the pyrolysis experiments to remove free moisture, and subsequently stored in an airtight glass container. Measured properties of pine wood samples are given in Table 1. The elemental composition was analyzed by Atlantic Microlab, Inc., the ash content was measured by EMSL Analytical, Inc., and the volatile matters and fixed carbon content were determined by a Perkin-Elmer TGA-7.

2.2 Experiments setup and procedures

Experiments were carried out under atmospheric pressure in a tube furnace shown in Fig. 1. The tube (length: 460mm, ID: 57mm, OD: 64mm) was made from mullite and the total heated zone was 300 mm. Nitrogen was used to purge the furnace and carry away the pyrolysis gases. The N_2 mass flow rate was 0.05g/s and controlled by a sonic orifice and a pressure gauge.

A wire holder made from stainless steel was used to hold the wood sample to ensure the radiation from the furnace can directly reach the sample. After the furnace temperature became stable, wood was put in the holder and first positioned at the cooling zone of the reactor for 2 minutes, allowing the nitrogen to purge the air that may have leaked in when biomass was fed; then it was immediately inserted into the heating zone of the furnace.

After the furnace was heated to the desired temperature (225°C, 250°C, 275°C or 300°C) and reached a steady state, dry wood particles were inserted into the reactor center and torrefied for different times (15 min, 25 min and 35 min). These torrefied wood samples are denoted by T_X_Y , where X is the torrefaction temperature and Y is torrefaction time. The weight loss (Y_L , wt. %) of pine wood after torrefaction was determined by $Y_L = 100 \times (1 - m_t/m_0)$, where m_0 is the initial mass of pine wood and m_t is the residual mass after torrefaction.

All the experiments for the pyrolysis of wood particles were conducted at 520°C. Pyrolysis vapors exited the furnace and entered a condensation system consisting of a jacketed Vigreux condenser cooled by ice-water (where 70% of the liquid was collected and chemically analyzed), a cotton wool filter tube and a gas sampling tube (The cotton wool filter tube is used to collect small droplets in the pyrolysis vapor that are not collected in the condenser, The remaining uncondensed gases are measured by continuous gas analyzers).. In each case, two separate experiments were conducted for the same conditions. One was used for bio-oil production and temperature measurement; the other one was used for continuous measurements of weight loss. The liquid yield was calculated by weighing all the condensable products trapped in the condensation system. Char was measured as the final solid mass fraction. The amount of gas was determined by the difference between the weight of biomass and that of char and liquid.

Quantification analysis of the liquid was performed by a Shimadzu GC/MS – QP 2010 which is equipped with an auto-sampler, an auto-injector and a DB-5 capillary column (30 m $\times$ 0.25 mm $\times$ 0.25 μ m). Helium was used as carrier gas. The column was programmed to stay at 40°C for 4 min, increase to 235°C at 5°C/min and held at this final temperature for 5

min. Pyrolysis liquid was dissolved in acetone (10 wt. % pyrolysis liquid) and a volume of 0.5 μL was injected in split mode (split ratio was 50:1). Injection and GC/MS interface temperature were 235°C. The mass spectrometer was operated in scan mode with a mass range (m/z) of 40 to 400. Compound identification was based on comparison with the NIST library[21].

3. Results and discussion

3.1 Torrefaction of pine wood

During torrefaction, biomass loses weight by thermal degradation of hemicellulose and cellulose at elevated temperatures, so the weight loss can be used to characterize the intensity of torrefaction processes. Table 2 summarizes the weight loss of pine wood after torrefaction under different conditions. As we can see, the sample weight loss is greatly dependent on the torrefaction conditions. With the increase of reaction temperature and time, the weight loss changes from 0.72% to 23.88%. It's also interesting to note that the weight experiences little change when wood is torrefied at 225°C and 250°C. However, the weight loss increases sharply after 275°C and a very large weight loss, 23.88%, is observed at the temperature of 300°C, indicating severe decomposition has occurred.

Temperature is a key factor affecting the wood decomposition. To better understand what is going on during torrefaction, the center temperature variation of the wood block is plotted in Fig. 2. The indicated furnace temperature settings are generally $\sim 5^\circ\text{C}$ higher than the steady state center temperature because of N_2 convection in the furnace tube. For 275°C and 300°C cases, the measured peak temperatures exceed the equilibrium temperature by about 3°C and 11°C respectively, indicating exothermic reactions which are caused by char

formation and transformation. These torrefied wood samples were used to produce bio-oil. Charring during torrefaction is expected to reduce the carbon content of bio-oil.

3.2 Profiles of solid mass fraction and temperature during pyrolysis

Solid mass fraction was calculated as: $Y = m(t)/m_0$, where $m(t)$ is the measured sample weight during the experiments and m_0 is the initial sample weight. Fig. 3 shows the solid mass fraction profiles of various torrefied wood during pyrolysis. The corresponding measured particle center temperature is shown in Fig. 5. In all cases, a mild weight loss rate is observed at the beginning, indicating hemicellulose starts to decompose at low temperature. As temperature increases, the solid mass fraction decreases rapidly and the rate of weight loss remains approximately constant over a wide range where the majority weight loss occurs. After the decomposition of most of hemicellulose and cellulose, the solid mass fraction changes slowly due to the pyrolysis of leftover lignin and finally becomes constant at the completion of wood pyrolysis.

In the same manner as the results shown in section 3.1, where there exists a small difference between 225°C and 250°C, torrefaction at 225°C and 250°C also exerts a negligible influence on the weight loss features. However, after being torrefied at 275° and 300°C, pine wood exhibits totally different profiles of solid mass fraction vs. time, as characterized by a lower weight loss rate and a higher leftover fraction as the torrefaction time increases. This phenomenon is not obvious in Fig. 3a where torrefaction time is only 15 minutes, but it becomes clear when the torrefaction time is increased to 25 and 35 minutes, especially for the 275°C and 300°C cases (Figs. 3b and 3c).

The conversion time, which is defined as the time when 95% of the total volatile matters are released, is presented in Fig. 4. It varies between 300s and 330s and doesn't change too much with torrefaction conditions even in the cases where wood undergoes severe torrefaction at 300°C. Di Blasi[15] reported the conversion time varied by a factor of ~2 between wood particle pyrolysis and wood block pyrolysis, which implies that particle size had a significant effect on the conversion time of wood pyrolysis. This is easy to understand since smaller particles are heated faster and the volatiles will be released sooner. In our study, however, the influence of torrefaction on the conversion time of large particle pyrolysis was not significant.

Temperature profiles at the center of pine wood during pyrolysis are shown in Fig. 5. It's necessary to mention that wood was first placed in the cold zone of the reactor for a short time where the temperature gradually increased to 65°C ~ 80°C before the wood was inserted into the hot reaction zone where the temperature was recorded. Pyrolysis of centimeter-scale wood particle has been studied by many investigators[15,22,23] and generally there exist four stages in the temperature profile during the pyrolysis process, which are also observed in this study. As we can see from Fig. 5, the temperature rises almost linearly due to conductive heat transfer in the first stage. In the temperature range of 350°C – 400°C, a temperature plateau appears, indicating there exist endothermic reactions in this stage. Then the temperature increases sharply and exceeds the furnace temperature as a result of a subsequent exothermic reaction. Finally the center temperature drops and becomes stable, attaining thermal equilibrium with the furnace.

Torrefaction alters the composition and properties of biomass mostly by breaking down the reactive hemicellulose and decomposing cellulose thus reducing hygroscopicity.

However, for the pyrolysis of centimeter-scale pine wood particles, marked difference was not observed on the center temperature profile even though wood particles lost a lot of weight after severe torrefaction. Unlike fine particles which could be heated uniformly to the furnace temperature instantly, centimeter-scale wood particles are thermally thick. During pyrolysis of thermally thick particles, temperature is controlled by the energy variation in the control volume through thermal conduction, gas flow convection and heat generation from pyrolysis reactions. After torrefaction, wood particles become more porous and the structures of hemicellulose and cellulose are damaged, which might lead to the decrease of overall thermal conductivity and a lower heat transfer rate. On the other hand, the specific heat capacity of wood may also drop since torrefaction is in favor of char formation and char has a lower heat capacity than virgin wood, thus wood would be heated up faster. These two aspects explain why there is little difference in the center temperature profile during the first stage where temperature increases mainly because of thermal conduction. As seen in Fig. 5, temperature increases sharply at the end of pyrolysis while the mass profile stays almost constant, thus the exothermic reactions are not contributed by the lignin decomposition. Instead, the exothermic conversion of intermediate solid to char is responsible for the center temperature peak [23]. The fact that center temperature peak is not significantly affected by torrefaction implies that the char formation process during pyrolysis is not significantly affected by torrefaction.

To explain the thermal and gravimetric behaviors of wood during pyrolysis process, a lot of investigations of the reaction kinetics were conducted [24–27]. One component reaction scheme models pyrolysis as a process of converting wood to char, gas and tar. In multi-component models, the pyrolysis process is generally characterized by devolatilization of

wood components, hemicellulose, cellulose and lignin. Park developed a multi-step model which accounts for the endo/exothermic thermal behavior observed in the experiments [23]. In this model, wood decompose to gas, tar and intermediate solid when heated up, then tar experiences secondary decompositions into gas and char and intermediate solids crack into char. The phase transformation of solid from the amorphous state to the crystalline state is generally associated with an energy release[28,29], which could possibly result in an increase of temperature. Thus we suspect that the conversion of intermediate solid to char is actually the change of carbon solid from amorphous structure containing high free energy to a stable state of low free energy, nevertheless, such a guess requires further experiment and thermodynamic analysis.

3.3 Pyrolysis yield

The product yield is highly related to the torrefaction processes, as we can see from Table 3, where the yields of three pyrolysis products, liquid, char and gas, are listed. At the temperature of 225°C and 250°C, impact of torrefaction on pyrolysis products yield is almost negligible, which is in agreement with the results demonstrated in previous sections. Nevertheless, pyrolysis of pine wood torrefied at 275°C and 300°C implies that the total liquid yield drops and the yield of char rises with the increase of torrefaction temperature and time. Specifically, Table 3 shows that the liquid yield changes between 53.12% and 38.01% under different torrefaction conditions, and the char yield varies between 22.07% and 32.46%. Gas yield is also enhanced as the torrefaction severity increases. This agrees with [10]and [30], who indicated that several organic condensable volatiles such as acetic acid, furfural and formic acid were formed, resulting in the decrease of condensable components during fast pyrolysis experiments. Besides, the carbonization of wood during

torrefaction attributed to the increasing char yield. Pyrolysis of centimeter-scale pine wood particles reveals that the product yields remain almost the same for wood torrefied at 225°C and 250°C, but there exists a significant change when feedstock is torrefied at 275°C and 300°C. To find similarity between different torrefied conditions, it's worthwhile to compare the char yield based on the dried wood. In this case, char yield changes slightly from 22.07 (using raw materials) to 24.71% (using torrefied wood at 300°C for 35 min), implying the effect of torrefaction on the overall char yield based on dried wood is not significant, and such a char yield is mostly determined by the pyrolysis conditions.

3.4 Pyrolysis products characterization and quantification

To further understand the effect of torrefaction on centimeter-scale pine wood pyrolysis, the compositions of bio-oil were characterized by GC/MS and about 70 chemical components are identified by searching the NIST library[21]. The changes of functional group compositions in bio-oil at different torrefaction conditions are shown in Fig. 6 where chemicals are classified into 9 categories, namely ketones, acids, guaiacols, levoglucose, aldehydes, phenols, furans, catechol and others. Table 4 provides additional details about the major compounds. Of all the chemical functional groups, ketones contribute to the largest amount of chemicals in the bio-oil, ranging from 30 to 36 area%, followed by acids and guaiacols. As shown in Fig. 6 and Table 4, the differences of chemicals content between various conditions are generally small, and it seems that torrefaction mainly alters the quantities of same bio-oil components instead of creating new chemical species such as hydrocarbons which are important for transportation fuels. However, the amount of acids especially that of acetic acid, is obviously decreased after wood was torrefied under 275°C and 300°C, indicating torrefaction is helpful in reducing the acidity of bio-oil. Besides,

phenols from pyrolysis of torrefied pine wood increases to 6.08 area% compared with a value of 4.14 area% when there's no torrefaction impact. The amount of guaiacols also decreases with increase of torrefaction intensity. Fig. 6 and Table 4 also imply that torrefying pine wood at 225°C and 250°C has little influence on the pyrolysis products.

Both Meng[17] and Ren[18] stated that pyrolysis of torrefied biomass gave quality-improved products and recommended torrefaction as a potential pretreatment for bio-oil production. However, this study with centimeter-scale pine wood particles shows that the effect of torrefaction on the product of pyrolysis is small. The reason accounting for the difference between the work of Meng[17], Ren[18] and ours may come from the size of biomass particles used as feedstock. There will be temperature gradient inside a particle during heating process and this phenomenon will be enhanced when the particle size becomes larger. As can be seen from Fig. 2 when wood is torrefied at 275°C, the center temperature is lower than 250°C for the first 10 min, then it increases gradually to 275°C, which means wood is actually heated at low temperature for a long time because of the slow heating processes. Since we already showed that torrefaction at low temperatures such as 225°C and 250°C has little effect on pyrolysis of centimeter-scale wood particles, the slow heating at 275°C or 300°C may not benefit the wood as expected.

Torrefaction can modify the composition and structure of biomass and produces torrefied wood with less hemicelluloses and more cellulose and lignin residues. Torrefied wood generally has an increased carbon content and decreased oxygen content, and this is easy to understand considering the fact that wood will become char if torrefied for infinite time. Even though this study also implies that torrefaction can be used as a pretreatment of

biomass for bio-oil production since the content of acid does decrease, we should also realize that the improvement of bio-oil quality is achieved at the sacrifice of bio-oil yield.

3. Conclusions

Pyrolysis of torrefied wood provides potential for higher quality bio-oil synthesis. In this paper, the effect of torrefaction on pyrolysis of centimeter-scale pine wood was studied experimentally. Weight loss of pine wood after torrefaction experiences little change at 225°C and 250°C but increases significantly at 275°C and 300°C, indicating that severe decomposition occurs at high torrefaction temperature. Exothermic reactions start to occur when wood is torrefied at 275°C and 300°C, and this may be related with char formation and transformation. Pine wood exhibits a lower weight loss rate and a higher leftover char fraction during the pyrolysis process after wood is torrefied at 275°C and 300°C, and the effect of torrefaction on center temperature profile is not significant which may be because of the changes in wood properties after torrefaction. Besides, the conversion time of large particle pyrolysis was not remarkably affected by torrefaction; instead, it is related to the size of the biomass particle. Product yields are highly related to the torrefaction processes, and liquid yield decreases with increasing torrefaction intensity while char yield increases. Based on GC/MS analysis, the chemical composition of bio-oil produced from pyrolysis of torrefied wood shows a decrease of acid content, but overall the effect of torrefaction was not remarkable when large biomass particles are used for pyrolysis, and new species are not detected. It appears that the mechanism of torrefaction processes needs to be further studied with regards to hemicellulose, cellulose and lignin. Other techniques such as catalytic

pyrolysis need to be investigated to optimize pyrolysis product from centimeter-scale wood particles.

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Fig. 3. Solid mass fraction profiles of wood samples during pyrolysis processes. Wood were torrefied at 225°, 250°C, 275°C and 300°C for 15 min (a), 25 min (b) and 35 min (c).

Fig. 4. Conversion time of pyrolysis for wood samples torrefied under various conditions.

Conversion time is defined as the time when 95% of the total volatile matters are released.

Fig. 5. Center temperature profiles of wood samples during pyrolysis processes. Wood were torrefied at 225°, 250°C, 275°C and 300°C for 15 min (a), 25 min (b) and 35 min (c).

Fig. 6. Variation of function groups in bio-oils produced from pyrolysis of torrefied wood.

Table 1

Proximate and elemental analysis of pine wood sample (wt. %, on dry basis^a).

Proximate analysis	
Volatile matters	84.65 ± 1.64
Fixed carbon	15.22 ± 1.64
Ash	0.13 ± 0.00
Elemental analysis	
C	47.17 ± 0.05
H	6.07 ± 0.01
N	0.13 ± 0.00
O ^b	46.63 ± 0.06

^aError is calculated from two analysis data.

^bCalculated by difference.

Table 2

Weight loss of pine wood under various torrefaction conditions (wt. %, on dry basis^a).

Torrefaction conditions	225°C	250°C	275°C	300°C
15 min	0.72±0.02	1.45±0.05	3.99±0.15	9.82±0.60
25 min	1.39±0.05	3.06±0.07	8.11±0.25	19.65±0.41
35 min	1.75±0.09	4.26±0.15	11.46±0.13	23.88±0.43

^a Error is calculated from four experiments.

Table 3

Product yields from pyrolysis of torrefied wood. Char yield based on dried wood is also calculated and listed in the bracket.

Run #	Torrefaction Conditions		Products Yield (wt. % Based on Torrefied Wood)		
	Temperature (°C)	Time (min)	Liquid	Char	Gas
1	Raw biomass		53.12	22.07	24.81
2	225	15	54.09	22.41 (22.25)	23.50
3	225	25	53.57	22.38 (22.07)	24.05
4	225	35	53.26	22.23 (21.84)	24.51
5	250	15	53.57	22.52 (22.19)	23.91
6	250	25	52.95	22.96 (22.26)	24.75
7	250	35	52.18	23.18 (22.19)	24.46
8	275	15	51.58	23.12 (22.20)	25.30
9	275	25	48.92	25.28 (23.23)	25.80
10	275	35	47.64	26.34 (23.32)	26.02
11	300	15	50.70	24.72 (22.29)	24.58
12	300	25	43.63	29.64 (23.82)	26.73
13	300	35	38.01	32.46 (24.71)	29.53

Table 4

Main species in bio-oil obtained from pyrolysis of pine wood particles as determined by GC/MS (% area).

Compounds	Raw	225°C			250°C			275°C			300°C		
	Biomass	15min	25min	35min	15min	25min	35min	15min	25min	35min	15min	25min	35min
2-Amino-1,3-Propanediol	1.57	1.25	1.75	1.59	1.72	1.67	1.76	1.62	1.56	1.49	1.5	1.51	1.34
2,3-Butanedione	3.37	2.69	2.84	2.18	2.88	2.68	4.11	2.71	2.41	2.78	2.51	2.61	2.36
Acetic acid	13.46	14.23	13.86	13.22	13.12	12.98	12.86	13.74	12.44	11.71	11.83	11.17	10.70
2-Propanone, 1-hydroxy-	11.06	10.26	10.63	10.18	10.60	11.29	11.64	11.19	10.54	10.91	12.00	12.50	10.83
Acetic acid, methyl ester	3.64	3.34	3.74	3.71	3.75	3.75	4.06	3.82	3.54	3.41	3.70	3.72	3.12
Succindialdehyde	2.28	2.09	2.24	2.33	2.15	2.15	2.35	2.24	2.10	2.21	2.11	2.23	2.38
Pyruvic acid, methyl ester	2.93	2.67	3.00	2.81	2.94	2.92	3.10	3.11	2.79	2.75	3.05	2.51	2.57
1H-Imidazole,4,5-dimethyl-	3.28	2.90	3.38	3.07	3.22	3.08	3.32	3.26	3.08	3.34	2.86	3.00	3.04
Butanal,2-ethyl-	2.19	2.17	2.24	2.32	2.21	2.24	2.15	2.44	2.29	2.23	2.29	2.44	2.19
2-Propanone, 1-(acetyloxy)-	1.21	1.13	1.21	1.22	1.13	1.07	1.17	1.37	1.12	1.14	1.33	1.22	1.12
2(5H)-Furanone	1.81	1.19	1.33	1.77	1.73	1.74	1.8	1.83	1.97	1.84	1.79	1.08	1.77
2-Hydroxy-2-cyclopenten-1-one	3.09	2.85	3.11	3.13	3.13	3.03	3.23	3.24	3.24	3.17	3.05	3.09	3.09
Furfural, 5-methyl-	1.49	1.64	1.55	1.52	1.38	1.59	1.56	1.71	1.82	1.61	1.76	1.78	1.88
Corylone	1.91	1.82	1.82	1.95	1.95	1.93	2.02	2.08	1.96	2.29	2.04	2.33	2.47
Phenol, 2-methyl-	0.94	1.11	0.87	1.11	1.06	1.00	1.01	1.09	1.13	1.27	1.16	1.15	1.53
Phenol, 3-methyl-	1.29	1.61	1.32	1.16	1.31	1.39	1.41	1.37	1.35	1.76	1.50	1.76	1.79
Phenol, 2-methoxy-	2.69	2.80	2.72	2.65	2.75	2.88	2.99	2.90	2.67	3.22	2.95	3.24	3.00
Cyclopropyl carbinol	2.08	2.03	1.93	2.19	2.05	2.14	2.02	2.18	2.98	2.78	1.86	1.92	1.85
4-Methyl-2-oxo-pentaneitrile	1.84	1.72	1.74	1.66	1.86	1.92	2.16	1.88	2.18	2.25	2.03	2.19	2.06
Creosol	4.05	4.13	3.90	3.89	5.21	4.18	4.34	4.29	4.05	4.77	4.35	4.81	4.55
2,3-Anhydro-d-mannosan	1.45	1.42	1.56	2.18	1.60	1.88	2.40	1.79	1.60	1.59	1.67	1.94	2.11
Phenol, 4-ethyl-2-methoxy-	1.54	1.53	1.23	1.55	1.47	1.39	1.51	1.51	1.37	1.69	1.28	1.51	1.88
2-Mehoxy-4-vinylphenol	1.49	1.47	1.53	1.69	1.53	1.69	1.47	1.53	1.20	1.27	1.11	1.05	0.81
Phenol, 2-methoxy-4-propenyl-	2.35	2.21	2.19	2.15	2.27	2.12	2.00	1.88	1.36	1.29	0.98	0.74	0.59
1,6-anhydro-β-D-Glucose	5.23	6.80	6.57	6.44	5.81	6.86	5.69	5.24	7.25	7.42	6.65	5.90	9.15

Fig. 1. Schematic of the experiment apparatus.

Fig. 2. Center temperature profiles of pine wood particle during torrefaction processes.
Torrefaction temperatures are 225°C, 250°C, 275°C and 300°C.

Figure

Fig. 3. Solid mass fraction profiles of wood samples during pyrolysis processes. Wood were torrefied at 225°, 250°C, 275°C and 300°C for 15 min (a), 25 min (b) and 35 min (c).

Fig. 4. Conversion time of pyrolysis for wood samples torrefied under various conditions.

Conversion time is defined as the time when 95% of the total volatile matters are released.

Fig. 5. Center temperature profiles of wood samples during pyrolysis processes. Wood were torrefied at 225°, 250°C, 275°C and 300°C for 15 min (a), 25 min (b) and 35 min (c).

Figure

Fig. 6. Variation of function groups in bio-oils produced from pyrolysis of torrefied wood.