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Effects of particle aspect ratio on pyrolysis and gasification of anisotropic wood cylinder

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HIGHLIGHTS

- Effects of wood aspect ratio (length/diameter) on pyrolysis and gasification are discussed.
- X-ray computed tomography is used to visualize the 3D anisotropic structure of chars with various aspect ratios.
- The total tar yield from pyrolysis decreases with an increasing aspect ratio.
- Char reactivity during gasification increases with a decreasing aspect ratio.
- Role of anisotropic structure of woody biomass is relevant to aspect ratio.

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ABSTRACT

In this study, the effects of particle aspect ratio (length/diameter) of a wood cylinder on pyrolysis and gasification characteristics were experimentally investigated. X-ray computed tomography was used to visualize the structure of char with different aspect ratios. Small and uniform pores were observed near the surface, whereas the size and shape of majority of the middle pores were large and random. Regardless of the aspect ratio, the pores generally aligned along the axial direction of wood cylinders. In the pyrolysis process, the total tar yield was found to decrease with an increasing aspect ratio. This was due to the tar being transported predominantly through the axial pores; therefore, wood cylinders with a high aspect ratio provided a long residence time for intraparticle tar decomposition, resulting in a lower tar yield. An Arrhenius plot of char reactivity during gasification revealed an aspect ratio effect in the internal-diffusion controlled zone (zone II), which did not appear in the kinetically controlled zone (zone I). Char reactivity increased with a decreasing aspect ratio in zone II. The gasifying agent primarily penetrated into the char through the top and bottom surface of the wood cylinder as a result of the pores aligned along the axial direction. The role of anisotropic structure of woody biomass was relevant to its aspect ratio.

1. Introduction

The use of woody biomass as fuel has attracted attention as a renewable energy resource. Woody biomass has the potential to suppress long term CO_2 emissions owing to its carbon neutrality [1]. Gasification is an efficient technology for extracting energy from solid fuels, such as coal and biomass [2,3]. The gasification process basically consists of pyrolysis or devolatilization and char gasification. However, there are two major issues that need to be considered to improve gasifier efficiency; (i) the tar problem and (ii) slow char conversion. During the pyrolysis process, tar formation and condensation cause operational issues in gasifiers such as blockages in pipelines, gas coolers, engines, and turbines. Char reactivity is also a key factor, because char gasification is the slower process in gasification than pyrolysis and volatiles gasification [4,5].

Due to the nature of woody biomass materials, their pore structure and physical properties are anisotropic. For example, gas permeability along wood grains is 10^3 higher than it is across wood grains [6]. Many studies [7–13] have investigated tar formation and char gasification using fine particles, and the relationship between pyrolysis conditions and tar yield has been summarized in some review papers [14,15]. However, anisotropic properties seem to have been neglected. The actual biomass feedstock of wood chips and wood pellets, which are generally used in commer-

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cial applications such as combustors and gasifiers, are relatively large in size. For example, wood chips vary in size from 10 × 10 × 5 mm to 15 × 15 × 8 mm for small woodchip boilers [16]. Therefore, the anisotropic structure is likely to play an important role in the intra-particle gas transport during both, pyrolysis and gasification process.

Previously, we studied the intra-particle reactions and anisotropic structure in biomass pyrolysis and gasification processes [17–20]. X-ray computed tomography (CT) was used to visualize the intra-particle anisotropic structure [17]. Study of the role of char anisotropic structure in gasification found that char gasification mainly progressed in the pore direction under the diffusion controlled region [17]. This observation provides a useful hint for improving the reactivity of char with anisotropic structure. Wood particles with different aspect ratios (length/diameter) are thus expected to exhibit differing char reactivities during gasification owing to anisotropic structures. However, little effort has been made to study the effect of aspect ratio on char gasification or intra-particle tar decomposition. The effect of particle aspect ratio on pyrolysis and gasification of woody biomass has been studied to some degree [21,22], but the anisotropic structure of woody biomass was not focused.

In this study, the anisotropic structures of chars with different aspect ratios are first visualized by X-ray CT, and the effect of the particle aspect ratio on pyrolysis and gasification is subsequently discussed with regard to the anisotropic structure.

2. Experimental

2.1. Wood samples

Wood samples used in this study are Japanese cypress wood cylinders with three differing aspect ratios. The wood grain is in the axial direction of cylinder. Proximate and ultimate analyses of the Japanese cypress wood (trunk) appear in Table 1. Information on wood cylinders with three aspect ratios (D8 × L2, D6 × L3.6, and D4 × L8) together with photographs is shown in Table 2 and Fig. 1, respectively. All samples had the same mass and volume, with an initial weight of 48 mg and initial volume of 101 mm^3.

2.2. Pyrolysis and gasification experiment

Pyrolysis and gasification experiments were conducted in a thermobalance. The experimental apparatus and details of the experimental procedure have been described in our previous paper [17]. The wood sample was dried at 383 K for 10 min prior to pyrolysis. The pyrolysis was subsequently performed at a constant heating rate of 30 K/s in argon atmosphere with a 0.8 L/min flow rate. In this study, the heating rate was fixed. The effect of heating rate on pyrolysis products and char reactivity has been discussed in our previous studies [17,18,20]. The pyrolysis pressure was maintained at 0.1 MPa. The final temperature of the pyrolysis was 1423 K with a holding time of 5 min. Following pyrolysis, the temperature was changed from the final pyrolysis temperature to a desired gasification temperature under flowing argon. The gasification temperature was varied in the range of 723–1423 K. When the desired temperature was reached, isothermal gasification was initiated by switching the gas line to a 20% oxygen/argon mixture with a 1 L/min flow rate. When investigating the pyrolysis characteristic, tar was defined as the condensable compounds attached to the filter in the ice-cold trap and inside the downstream tube. Details of tar yield determination have been similarly described in our previous paper [17].

Table 1
Proximate and ultimate analyses of Japanese cypress wood (trunk).

Proximate analysis (wt%)	
Volatile matter	78.7
Fixed carbon	13.2
Ash	0.2
Moisture	7.9
Ultimate analysis (wt%, daf)	
C	51.5
H	6.2
O	42.2
N	0.1
S	–

2.3. Intra-particle temperature measurement

The temperature history within the wood cylinders during pyrolysis was measured at the center of the particle using a *K*-type thermocouple with a diameter of 0.5 mm. The thermocouple was inserted through a hole drilled into the center of the wood cylinder (at a depth of 1 mm, 1.8 mm, and 4 mm for D8 × L2, D6 × L3.6, and D4 × L8 char, respectively). Temperature data was acquired at intervals of 200 ms using a data logger (MEMORY HiLOGGER 8430, Hioki Corp.) over the entire pyrolysis process. Details of the intra-particle temperature measurement have been previously described [20].

2.4. X-ray CT analysis

X-ray CT (Xradia VersaXRM-500) was used to investigate the intra-particle structures of the D8 × L2 and D4 × L8 char samples. An advantage of X-ray CT analysis is its ability to visualize the intra-particle char structure without destroying the char sample. A series of cross-sectional images with a diameter of 2 mm and a resolution of 2 μm was obtained. The region of 3D image reconstruction is a 2 × 2 mm cylinder (height × diameter). The visualized regions for X-ray CT analysis are shown in Fig. 2. The visualized region for D8 × L2 char covers the center of the particle, while that of D4 × L8 char covers the upper-center and wall side of the particle.

2.5. Char reactivity measurement

The char conversion (X) and gasification rates (R) were calculated using Eqs. (1) and (2), respectively

$$X = 1 - \frac{m}{m_0} \quad (1)$$

$$R = \frac{\mathrm{d}X}{\mathrm{d}t} = -\frac{1}{m_0}\frac{\mathrm{d}m}{\mathrm{d}t} \quad (2)$$

where m is the mass of char at time t, m_0 is the initial mass of the char at the beginning of gasification. Noted that the sample ash content was neglected due to a very low amount of ash in Japanese cypress wood (Table 1). In the present study, the char reactivity, R_i, is defined as the initial gasification rate at $X = 0$ under a 20% oxygen/80% argon atmosphere.

3. Results and discussion

3.1. Temperature history

Fig. 3 shows temperature histories measured at the center of wood cylinders with various aspect ratios during pyrolysis. For all aspect ratios, initially the temperature increased gradually, with a decreasing slope of temperature observed due to the endother-