

# Experimental Study on Impact of Heating Temperature and Heating Rate during Carbonization of Woody Biomass

Haizhen Huang\*, Zhenwei Jiao, Zhenyang Shu and Yaoguo Zeng

Thermal energy department, Jilin university, Changchun, China

\*Corresponding author

**Abstract**—Carbonization is the thermal treatment technique performed in an inert atmosphere, which aims to improve the fuel properties. In this study, the selected woody biomass of koraiensis bark (KB) was carbonized under three heating levels (5°C/min, 10°C/min, 20°C/min) at heating temperature from 200°C to 600°C. The yields of fixed carbon, charcoal yield rate, energy yield rate, mass energy density and quality of charcoal were analyzed. Considering all the evaluation indexes, KB carbonized at 450°C under heating rate of 10°C/min matched each index best under the preset experimental conditions.

**Keywords**- biomass; carbonization; heating rate; heating temperature; energy yield

## I. INTRODUCTION

China has become the second largest energy consumer in the world, it is necessary to ensure rational utilization of energy and protect environment. Biomass energy shows a promising prospect among different renewable energies resources [1-2]. Many technologies have been proposed including biomass briquetting or pelletizing, biochar, torrefaction, gasification or hydrothermal processing etc. Carbonization is a process with a thermal treatment in an inert atmosphere while producing charcoal from biomass pellets, which improves the thermochemical properties of biomass in heating value, energy density and combustion efficiency[3-9]. It provides the possibility of biomass energy utilization and extension, especially in rural area in China.

In order to control the yield and quality of carbonized biomass effectively, the sound understanding of the carbonization process is therefore very necessary. In this paper, the impact of final heating temperature and heating rate on carbonization process of woody biomass was investigated.

## II. EXPERIMENTAL METHODS

### A. Materials and Samples

The selected biomass material is koraiensis bark (KB), which is an abundant biomass resources in China. The cylindrical biomass pellet samples prepared for carbonization process were made via a self-heating hydraulic mold machine at the mold temperature of 180°C and mold pressure of 25MPa under which conditions the pellets could meet the requirements of carbonization. Each sample was 25mm in diameter, 10g in mass and about 1.04-1.12g/cm<sup>3</sup> in mass density.

### B. Experimental Device

The proximate analysis and calorific values of samples were performed by automatic industrial analyzer (SDTGA-3000) and automatic calorimeter (SDACM-3000) respectively. Carbonization of samples were conducted in the experimental device shown in Figure I. A cylindrical electric oven with 130mm interior diameter and 3kW rated power was used to heat the samples during carbonization process. Both the heating rate and the chamber temperature were controlled by an PID controller (Yuguang AI518P).

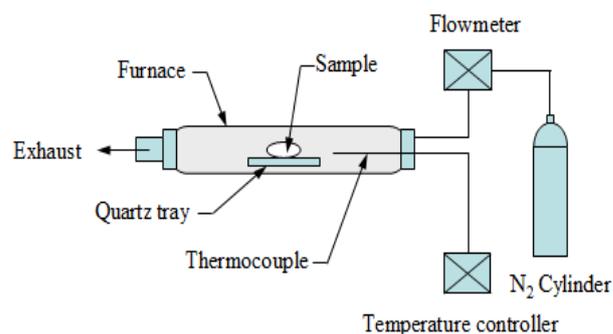


FIGURE I. SCHEMATIC DIAGRAM OF EXPERIMENTAL DEVICE OF CARBONIZATION PROCESS

### C. Experiments

The experiment was conducted under inert atmosphere of nitrogen gas. First put the sample into the middle part of the furnace chamber, then pure nitrogen gas flowed through at the flow rate of 3L/min in order to purge the chamber before carbonization process and continuously flowed through during the process. When samples were heated at heating rate of 5°C/min, 10°C/min, 20°C/min to the preset final temperature, after keeping the final temperature for 30min, heating process would be stopped, but the nitrogen gas continued flowing through until the chamber temperature declined to 100°C. Then after the sample's temperature declined to room temperature, it would be sealed in a plastic bag with desiccant to get ready for the thermal property test and analysis. The naming rule of each examined sample was defined. For example, a sample heated to final temperature of 200°C at 5°C/min heating rate is KB-200-5.

### III. RESULTS AND DISCUSSION

$$\eta_e = \eta_m(Q_2/Q_1) \times 100\% \quad (2)$$

#### A. Definition of Quality Index of Carbonization Process

Biomass is mainly composed of hemicellulose, cellulose and lignin [10]. All of the three components will conduct thermal degradation and yield different gaseous products while being heated under inert atmosphere. That process is pyrolysis, the gaseous products are volatile, the remained part of biomass is charcoal. Parameters used to described the quality indexes of charcoal includes proximate analysis, high calorific value (HCV), charcoal yield rate (CYR), energy yield rate (EYR) and mass energy density (MED), which are defined as follows:

$$\eta_m = (m_2/m_1) \times 100\% \quad (1)$$

$$\eta_d = \eta_e / \eta_m \quad (3)$$

$\eta_m$ — charcoal yield rate, %;  $\eta_e$ — energy yield rate, %;  $\eta_d$ — mass energy density;  $m_1, m_2$ —mass of samples before and after carbonization, g;  $Q_1, Q_2$ —high calorific value (HCV) before and after carbonization on dry basis, MJ/kg.

Table I shows the proximate analysis on dry basis, high calorific values, charcoal yield rate, energy yield rate and mass energy density of samples carbonized at various conditions.

#### B. Analysis of Impact Factors on Charcoal Quality

##### 1) Impact of final heating temperature

TABLE I. PROXIMATE ANALYSIS AND YIELDS OF KB CHARCOAL AT VARIOUS CONDITIONS

Samples	Volatile (%)	Ash (%)	Fixed carbon (%)	HCV (MJ/kg)	CYR (%)	EYR (%)	MED
RAW KB	76.47	6.26	17.27	20.24	100	100	1
KB-200-5	70.03	6.65	18.33	20.52	90.5	91.71	1.01
KB-250-5	68.31	7.65	21.1	20.85	85.91	88.46	1.03
KB-300-5	52.23	11.83	32.61	22.66	68.17	76.28	1.12
KB-350-5	41.52	14.87	41.01	23.02	58.3	66.27	1.14
KB-400-5	30.11	17.62	48.58	23.18	50.44	57.74	1.14
KB-450-5	24.86	19.39	53.47	23.45	46.11	53.40	1.16
KB-500-5	20.59	20.19	55.69	23.9	43.14	50.92	1.18
KB-550-5	20.05	20.42	56.33	23.9	41.54	49.03	1.18
KB-600-5	14.96	22.04	60.77	24.02	38.15	45.25	1.19
KB-200-10	69.43	7.05	19.46	20.67	88.41	90.24	1.02
KB-250-10	63.6	8.65	23.87	21.04	81.95	85.15	1.04
KB-300-10	51.09	12.13	33.45	22.44	67.64	74.96	1.11
KB-350-10	44.49	13.78	37.99	22.95	60.19	68.22	1.13
KB-400-10	35.51	15.89	43.81	23.41	51.89	59.99	1.16
KB-450-10	30.24	17.35	47.84	23.77	48.63	57.08	1.17
KB-500-10	24.37	18.75	51.71	23.69	43.68	51.10	1.17
KB-550-10	21.41	19.41	53.52	23.81	41.6	48.91	1.18
KB-600-10	18.08	20.52	56.61	23.61	40.19	46.86	1.17
KB-200-20	67.13	7.72	21.3	20.37	86.12	86.63	1.01
KB-250-20	57.42	10.23	28.23	20.59	76.32	77.60	1.02
KB-300-20	46.68	13.26	36.59	22.45	61.26	67.92	1.11
KB-350-20	41	14.66	40.45	22.49	60.29	66.96	1.11
KB-400-20	30.31	17.33	47.8	22.54	49.62	55.23	1.11
KB-450-20	28.26	17.22	49.48	22.95	46.15	52.30	1.13
KB-500-20	24.12	18.69	51.56	23.36	43.58	50.27	1.15
KB-550-20	20.55	19.75	54.47	23.85	40.01	47.12	1.18
KB-600-20	19.8	19.66	54.24	23.94	39.07	46.19	1.18

Figure II shows the yields of different products during the carbonization process of KB at different final heating temperature respectively after holding time of 30 min.

Figure II (a) shows the yields at different temperature in the range from 200°C to 600°C at heating rate of 5°C/min. The yield of the FC increased with the increase in the heating temperature range from 18.63% to 60.77%. It showed a faster increase before heating temperature of 400°C than after 400°C. This is mainly because most volatile within the KS released quickly under 400°C, thus made the mass percentage of FC yield increased quickly. It became harder to be released for the rest of volatile, so that FC yield increased a bit slowly after final heating temperature of 400°C. The HCV showed an increasing trend within the preset temperature range from 20.85MJ/kg to 22.66MJ/kg with characteristics of a peak increase between 250°C and 300°C. The reason for this rapid change of HCV is mainly because the sharp decrease of volatile from 68.31% to 52.23% in this temperature range, while FC increased from 21.1% to 32.61%. The HCV increased from 20.52 MJ/kg to 24.02 MJ/kg within the the heating temperature range. Both CYR and EYR showed a downward trend within the preset temperature range. Before final heating temperature of 250°C, both CYR and EYR showed similar downward trends and values. At the final heating temperature range of 250°C to 600°C, it still remained the similar downward trends but with a difference between values. CYR decreased from 90.5% to 38.15%, EYR decreased from 91.71% to 45.25% within the preset temperature range.

Figure II (b) and (c) shows the yields at different temperature in the range of 200-600°C at heating rate of 10°C/min and 20°C/min respectively. The results showed similar trends like at heating rate of 5°C/min with different characteristic values. At the heating rate of 10°C/min, the yield of the FC increased from 19.46% to 56.61% within the heating temperature range. The HCV with a peak increase between 250°C and 300°C changed from 21.04 MJ/kg to 22.44 MJ/kg, the volatile changed from 63.6% to 51.09% , while FC increased from 23.87% to 33.45%. The HCV increased from 20.67 MJ/kg to 23.61 MJ/kg within entire heating temperature range, while CYR decreased from 88.41% to 40.19%, EYR decreased from 90.24% to 46.86%. At heating rate of 20°C/min, the yield of FC increased within entire heating temperature range from 21.3% to 54.24%. The HCV changed from 20.59 MJ/kg to 22.45 MJ/kg with a peak increase between 250°C and 300°C, along with the volatile changed from 57.42% to 46.68% , while FC increased from 28.23% to 36.59%. The HCV increased from 20.37MJ/kg to 22.94MJ/kg within entire heating temperature range, while CYR decreased from 86.12% to 39.07%, EYR decreased from 86.63% to 44.26%.

### 2) Impact of heating rate

FIGURE III shows the yields of products during the carbonization process of KB at different heating rate of 5°C/min, 10 °C/min and 20°C/min respectively after holding time of 30 min.

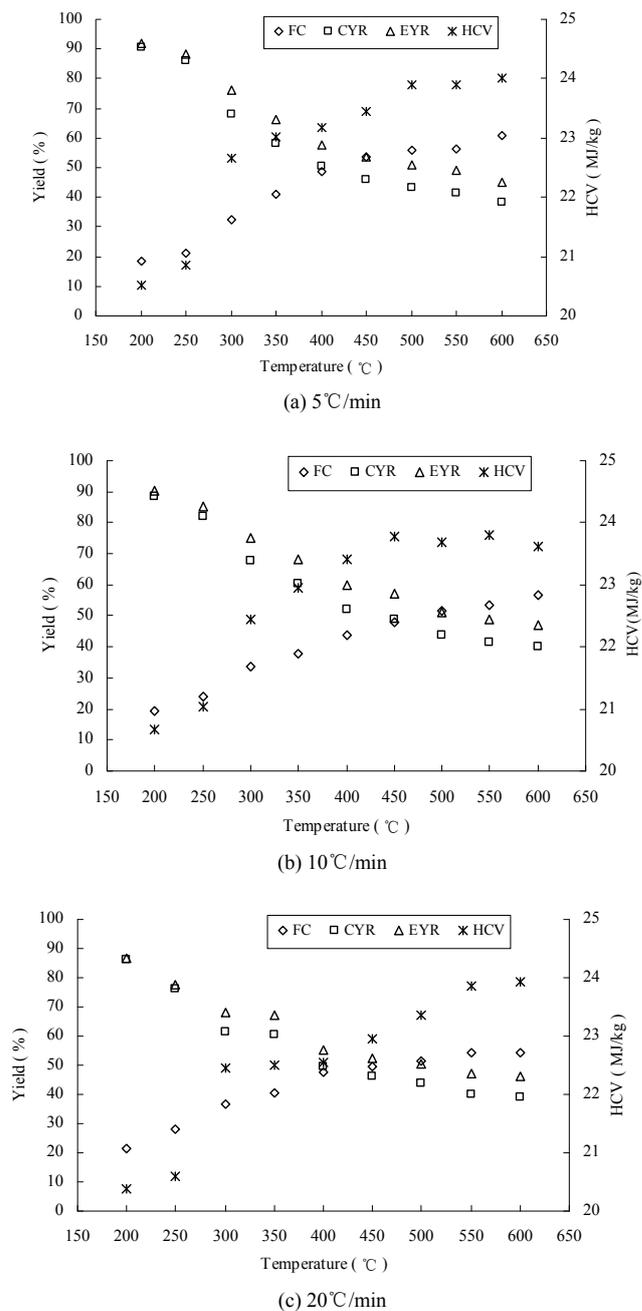


FIGURE II. YIELDS UNDER VARIOUS FINAL HEATING TEMPERATURE

FIGURE III (a) shows the yield of FC at different heating rate. The yield of FC showed an increasing trend at entire preset heating temperature range, but increased faster before 450°C than after 450°C. The reason is that more volatile released before 450°C made it harder to be released afterwards. It showed the same increasing sequence before 300°C under each heating rate, with the biggest value difference at final heating temperature of 250°C. Because at the beginning, volatile within KB began to be released while heated, the faster the temperature increased, the more volatile would be

released under lower temperature range of 300°C. So the yield of FC would be increased while volatile released. The more volatile was released, the faster the yield of FC would increase. The yield of FC increased fastest at heating rate of 20°C/min before 300°C. It changed from 21.3% to 36.59% while volatile changed from 67.13% to 46.68%. After final heating temperature of 300°C, the sequence of increasing rate of FC began to change. Within the temperature range of 300°C to 500°C, the yield of FC at heating rate of 5°C/min became the fastest one. This is mainly because more volatile at higher heating rate was released than at higher heating rate. Even if at the same final heating temperature, it was more difficult for the rest volatile at higher heating rate to be released. So the yield of FC at 20°C/min became the lowest one at the heating temperature of 500°C till 600°C, and the yield of FC at 5°C/min became the fastest one after heating temperature of 350°C till 600°C.

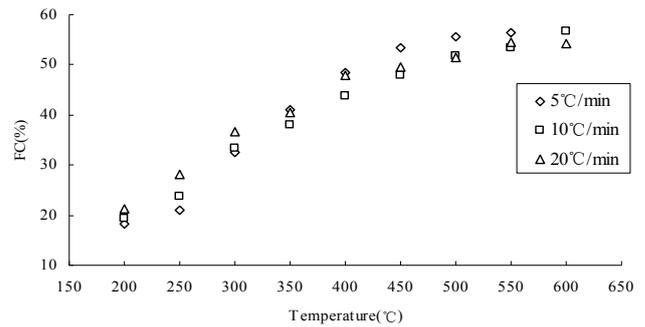
FIGURE III (b) shows the MED at different heating rate. It showed an increasing trend at entire temperature range with a rapid increase between 250°C and 300°C. It showed larger value difference from 350°C to 450°C between each heating rate. In that temperature range, heating rate of 10°C/min increased fastest, then 5°C/min and 20°C/min in sequence which meant the charcoal at 10°C/min heating rate had the largest energy density per unit mass.

FIGURE III (c) shows the CYR at different heating rate. Within entire heating range, the CYR showed a downward trend because of the release of volatile, with larger value difference between 250°C to 300°C. Then from 350°C to 600°C, it showed little value difference between each heating rate.

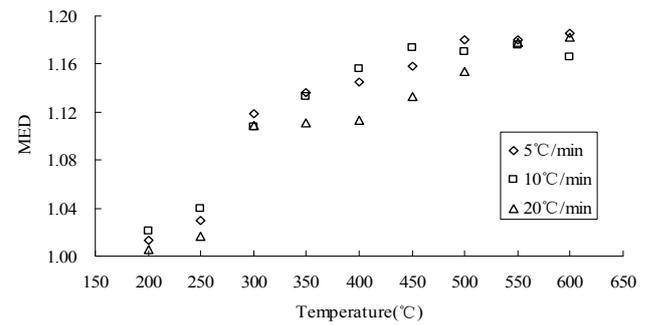
FIGURE III (d) shows the EYR at different heating rate. It showed the similar downward trend with CYR. Within entire heating range, the EYR showed a downward trend with larger value difference between 250°C to 300°C. Then from 350°C to 600°C, it also showed little value difference between each heating rate.

C. Analysis of Optimum Carbonization Conditions

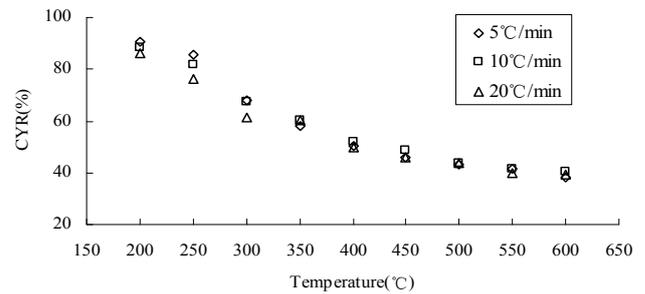
From the analysis of impact factors on carbonization aforementioned, both final heating temperature and heating rate have impact on the process. Set MED as the most important evaluation index, then EYR, CYR and FC in sequence, and compare the proximate analysis with typical soft coal, FIGURE IV shows the change of each index at different final heating temperature under 10°C/min heating rate, then carbonization process at 450°C final heating was the best result, which meant in comprehensive consideration, sample KB-450-10 matched each index best under the preset experimental conditions.



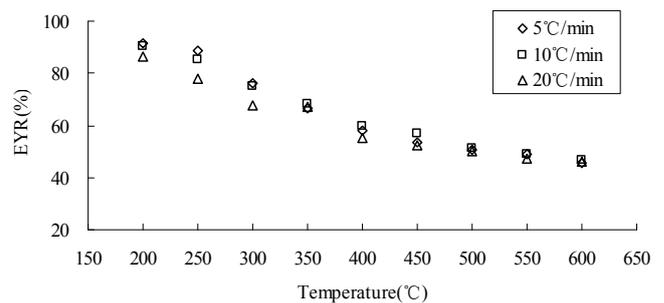
(a) fixed carbon



(b) mass energy density



(c) charcoal yield rate



(d) energy yield rate

FIGURE III. YIELDS UNDER DIFFERENT HEATING RATE

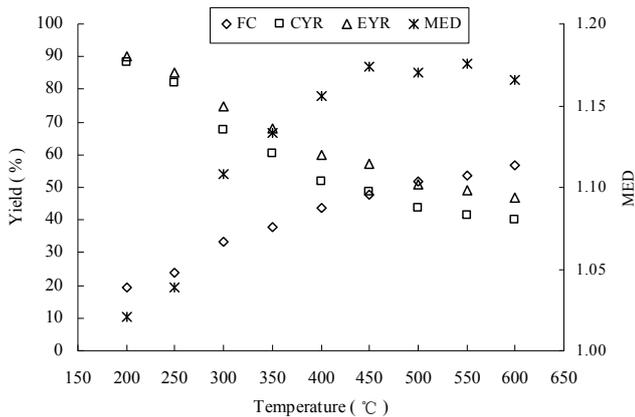


FIGURE IV. CHANGE OF INDEX AT 10°C/min HEATING RATE

#### IV. CONCLUSION

From the analysis of impact factors on carbonization aforementioned, both final heating temperature and heating rate have impact on the process. Both FC and MED increased with the increase of final heating temperature, but showed different increasing rate at different heating rate. Both CYR and EYR decreased with the increase of final heating temperature, but showed larger difference in value at lower final heating temperature. Set MED the most important evaluation index, then EYR, CYR and FC in sequence, then carbonization process at 450°C final heating was the best result, which meant sample KB-450-10 showed the similar thermochemical properties with typical soft coal, and matched each indicator best in a comprehensive consideration under the preset experimental conditions.

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