Pyrolysis of Tobacco Rob: Effect of Particle Size on Kinetic Study and Fuel Gas Yield and Composition

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During pyrolysis of tobacco rob (TR), the operating parameters such as the temperature, the heating rate, residence time, and particle size affect the process and result of the pyrolysis. Some of these parameters have been closely considered, but the particle size of TR is often ignored. In this study, the size of TR particle was considered as a major factor in determining the mass loss in thermogravimetric analysis (TGA) and product yield and composition at different reactor temperatures in the fixed-bed reactor. The TGA results showed that the conversion rate increased and the activation energy decreased with a decrease in particle size. The experiments demonstrated that fuel gas yield increased with a decrease in particle size, while char and tar yield decreased. Smaller particle sizes resulted in higher H_2 and CO contents. Minimizing the size of raw materials is an alternative method to improve the gas quality of TR pyrolysis. The increase of gas yield was attributed to the decomposition of char and tar vapor as temperature increased. Moreover, the performances of the shredder for the breakage of the TR, such as the effect of the rotor velocity and hydraulic pressure on product size distribution was investigated. The results showed that with hydraulic pressure increasing, size distribution of product was finer. When hydraulic pressure was constant, the products size distribution was coarser with increasing rotor velocity.

Keywords: Pyrolysis; Kinetic; Tobacco rob; Particle size

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INTRODUCTION

Taking into account the problems of greenhouse effect together with the decrease of fossil resources, biomass has been considered to be a future renewable resource with a high potential for energy production (Nath and Das 2003; Demirbas 2006). Thermochemical conversion of biomass to produce liquid and gaseous fuels is one of the most attractive technologies in terms of energy and environment. Among the thermochemical processes, pyrolysis is a promising tool for providing bio-oil that could be used as fuel or chemical feedstock (Mahinpey *et al.* 2009; Wang *et al.* 1997). The pyrolysis of biomass is a very old energy technology that is again becoming attractive among various systems for the use of biomass as a source of energy (Scott and Piskorz 1984; Zaror *et al.* 1985).

Tobacco plants were widely cultivated in China as an important cigarette material. The tobacco production has been 500 to 550 million tons in China each year.

However, tobacco rob (TR) accounted for more than 60% of the total tobacco plants production; this could not be used for cigarette production, and the cost was great to deal with them. Thus, TR often has been treated by burning as agricultural wastes. This leads to serious environmental problems and an enormous waste of resources. So, the recycling of this waste and the exploitation for potential bioenergy would be indispensable. Thus, this study primarily focused on this feedstock and its experimental results.

Thermogravimetric analysis (TGA) could be a useful tool to study the thermal behaviour of materials. The rate of mass loss as a function of temperature and time was measured and provided a means to estimate the kinetic parameters in the thermal decomposition reaction. The kinetic study of biomass pyrolysis was of relevant importance because it constituted the initial step of the combustion and gasification processes. These data were crucial for efficient modelling, design, and operation of pyrolysis process and related thermochemical conversion systems (Sonobe and Worasuwannarak 2008; Jauhiainen *et al.* 2004). Many TGA studies had been carried out for pyrolysis of various non-edible biomass sources in the past few decades and established significant information on the pyrolysis behaviour and its kinetics (Park *et al.* 2009; Guo and Lua 2009). The influence of particle size on pyrolysis for olive solid waste biomass under nitrogen and oxidative atmospheres was studied by Chouchene *et al.* (2010). It was concluded that under oxidative atmosphere, the samples of less than 0.5 mm particle size are the most reactive ones. High char quantity with low ash content was observed with the particle size of 2 to 2.8 mm. In another study, Demirbas (2004) examined the effect of temperature and particle size of various biomasses on biochar yield and reactivity. The biochar yield increased with increasing particle size of the sample.

Pyrolysis of TR had been studied by Yang *et al.* (2011) in order to evaluate the influence of operating parameters (*i.e.* temperature, heating rate, and different catalysts). However, one important operating parameter that is often ignored is the particle size. The particle mass size distribution and particle mass concentration are important parameters for the design and optimization of biomass gasifier (Gustafsson *et al.* 2011). Thus, the objective of this study was to investigate the effects of biomass particle size on kinetic study and yield and composition of fuel gas product using two different methods based on TGA and fixed-bed reactor. The aim was to gather experimental evidences of particle size effect for TR pyrolysis for which there was still a shortage of comprehensive data, and to investigate the relationship between the particle size effect and pyrolysis product composition.

EXPERIMENTAL

Methods
Materials and milling procedure

The tobacco rob (TR) samples used in this study were collected from tobacco waste, which was from a farm in Jishou City, Hunan Province, China. The samples were dried under the sun for a period of 7 days to reduce the moisture content and then were separated into three different size fractions by sieving: the fractions 0 to 90 μm in size,

fractions 90 to 180 µm, and fractions 180 to 380 µm. In order to study the kinetics of the process, the particle size has been usually chosen in these ranges by many researchers (Li *et al.* 2004; Sensöz *et al.* 2000; Rapagna and Latif 1997). Moreover, less than 2 mm particles size biomass has been used mainly for pyrolysis of biomass. The ultimate and proximate analyses and the heating value of the sample are shown in Table. 1.

Table 1. Ultimate Analysis and Proximate Analysis of TR

Ultimate analysis (wt.%)		Proximate analysis (wt.%)	
C	43.33	Moisture content	10.82
H	6.596	Volatile matter	68.34
O[a]	38.86	Fixed carbon	19.30
N	0.758	Ash	1.54
S	0.096	Low heating value (MJ/kg)	20.67
[a] By difference			

The lab-scale shredder for TR breakage in the tests consisted of compaction and shredding chambers. A vertical hopper was positioned on the housing to receive a consecutive inflow of materials. A pusher was positioned at the top of the hopper, connected to the hydraulic piston. The pusher and the hopper constitute the compaction chamber.

In the experiments, it was ensured that the shredder was properly choked and fed. Choke feeding the shredder means that the inlet bin is entirely filled with material, to ensure a smooth and stable operation. At the start of the breakage, the feed reaches the compaction chamber, compressed by the pusher, and then the compressed materials are pushed into the shredding chamber. The breakage mechanism is based on the pulling, shearing, and meshing effects between the rotating blades and the comb-shaped shear blades. In the shredding chamber, the compressed materials are meshed by the rotating blades and the shear blades, which overlap the pulling and compressive shearing processes by the rotating blades, resulting in the formation of fine particles. The collected fragment products were sieved in a commercial mechanical sieve shaker for 5 min, and the product size distribution were estimated.

Thermogravimetric analysis

Thermogravimetric analysis of the TR sample was carried out with a TA Instrument system (Diamond TG/DTA, PerkinElmer Instruments). A sample mass of 10 ± 1.0 mg was used for the thermogravimetric analysis in each experiment. Nitrogen was used as the purge gas for thermal cracking reactions. The flow rate was measured by a volumetric flow meter and was maintained at 40 mL/min. The heating rate was controlled at a rate 10 ℃/min. The TGA experiments were performed in non-isothermal condition from room temperature to 900 ℃ by placing the TR sample in the TGA pan varying the particle size of the sample. Three particle diameter ranges were used in this study, the fractions smaller than 90 µm, between 90 and 180 µm, and between 180 and 380 µm. All experiments were repeated two to three times and reproducible results were successfully achieved.

Apparatus and procedures of pyrolysis

Pyrolysis tests were carried out in a lab-scale fixed-bed reactor, and the apparatus is shown schematically in Fig. 1. The hearth of reactor was made of quartz tube and was externally heated by an electrical ring furnace, which was covered with an insulation layer outside. The effective length of the reactor was 1200 mm with an inner diameter of 60 mm. The quartz tube was divided into heating zone, with normal temperature zones 1 and 2 along the axial direction shown in Fig. 1. The furnace was heated at a rate 10 ℃/min to desired final temperature and kept constant. The type K thermocouple was used to measure the temperature profile in the heating zone of hearth. A filter in series was used as de-dusting units for fuel gas cleaning. A condenser in series was used as cooling units for fuel gas cooling and tar capture. The fuel gas from the reactor entered the following de-dusting and cooling units in sequence.
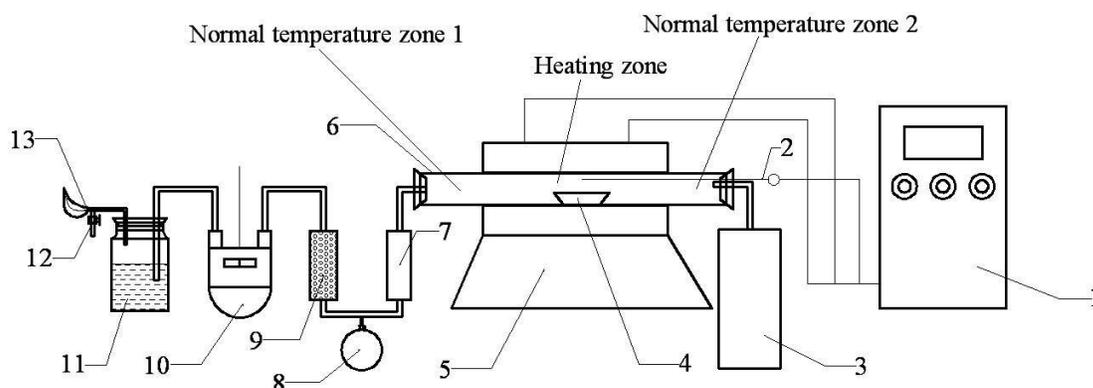
Fig. 1. Experimental apparatus. (1) Temperature controller; (2) thermocouple; (3) nitrogen gas tank; (4) porcelain boat; (5) electric furnace; (6) quartz tube reactor; (7) condenser; (8) tar collector; (9) filter; (10) flow meter; (11) water sealed bottle; (12) to gas collector bag; (13) exhaust gas burner.

A 2 g sample was put into a porcelain boat which was placed in normal temperature zone 1 before test. In each test the electrical heater was turned on firstly. When desired temperature was achieved in the heating zone, the porcelain boat was pushed into the heating zone. After set pyrolysis time, the porcelain boat was pushed into normal temperature zone 2 and test is finished. Nitrogen was used as carrier gas and the total volume of product gas was determined by a N_2 balance. Nitrogen gas (flow rate of 100 mL/min) was introduced for 40 min to keep anoxic atmosphere and kept constant during experiment. With the total volume of gas produced and volumetric concentration of each species, the volume of each component was obtained; using the ideal gas state equation and the mass of TR feed, the specific yield of gas was obtained.

The dry, clean, and cool fuel gas was sampled by a gas sampling bag. And the gas compositions were analyzed by GC 9800T with a thermal conductivity detector (TCD) and FID detectors. The oil produced as a result of the pyrolysis was collected in the condenser. The mass of oil was obtained as the difference in masses of the condensers before and after pyrolysis test. The char allowed to cool under nitrogen was collected at the end of each experiment and weighed. The varied factors were pyrolysis temperature and particle size, the temperature range chosen was 600 to 900 ℃, whereas three particle

diameter ranges were used, the fractions smaller than 90 µm, between 90 and 180 µm, and between 180 and 380 µm. In this study, each experiment was repeated at least three times to ensure data reliability. The data reported in this study are average value of three times, and data variability was within 5%.

RESULTS AND DISCUSSION

Pyrolysis Tests in TGA
Pyrolysis at different particle sizes

      Thermal decomposition behaviours of TR pyrolysis at three different particle sizes under flowing nitrogen were obtained, and results can be seen in Fig. 2. At temperatures lower than 200 ℃, the small change of conversion in the samples was attributed to vaporisation of moisture that was cohered on the surface of the samples (Thangalazhy-Gopakumar *et al.* 2011). The TR samples started to decompose and release volatile matter around 250 ℃. The TG curves of the TG showed only two major weight loss stages between 250 and 350 ℃, and 350 and 800 ℃.
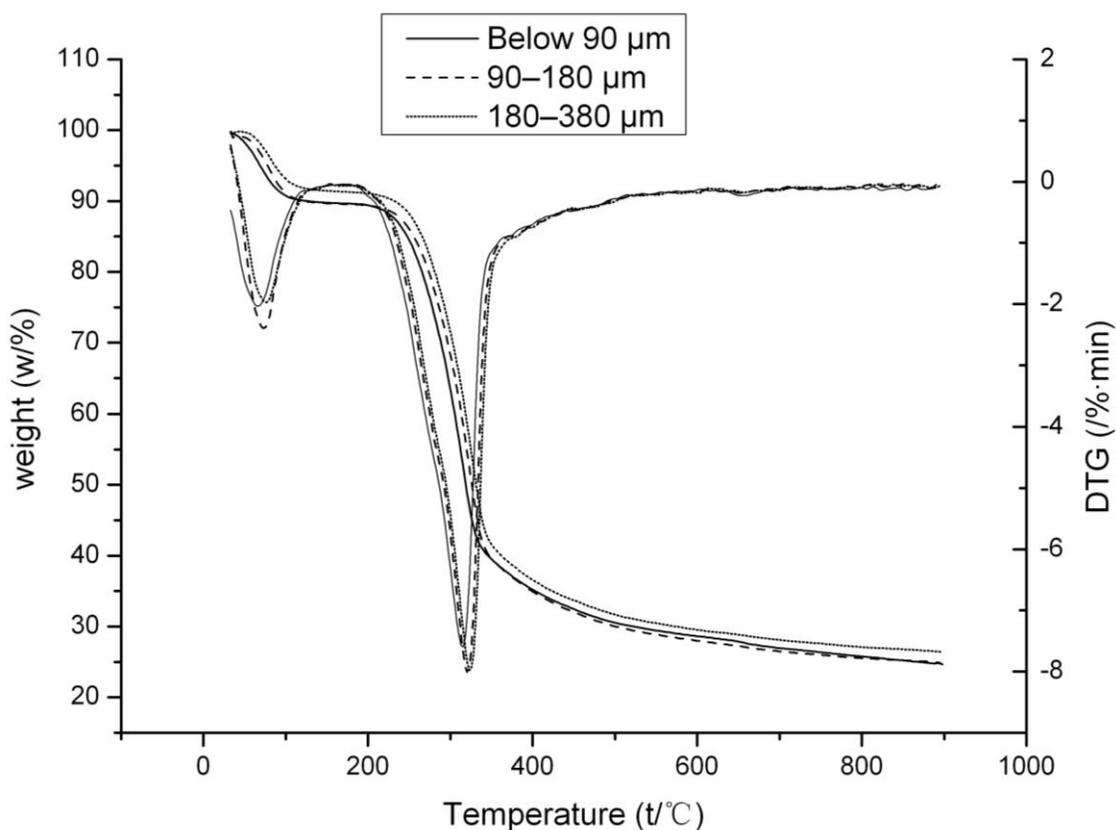
Fig. 2. Thermogravimetric behavior of TR at different particle sizes

      It was clear that the slope of the curve changed between the two temperature intervals. The slope between 250 and 350 ℃ was higher than that between 350 and 800 ℃. The conversions at different particle sizes exhibited similar patterns. Since the

samples contained mainly cellulose, hemicellulose and lignin, it was known that the hemicellulose started to decompose at around 225 to 325 ℃, and the cellulose was found to decompose between 325 and 375 ℃. Lignin had a broad decomposition temperature range at temperatures higher than 250 to 500 ℃ (Di Blasi and Lanzetta 1997; Ferdous *et al.* 2002). Decomposition at 500 ℃ or higher progressed slowly due to the remaining lignin or char, similar to that reported by Fisher (Fisher *et al.* 2003).

As can be seen in Fig. 2, it was observed at temperatures below 400 ℃ that the TG curve shifted slightly to the right with increasing particle size, and the DTG curve presented that smaller particle size tended to slightly promote thermal degradation processes towards lower temperature. With increasing particle size, the maximum rate of mass loss increased from 7.83%/min to 8.06%/min. These results could be attributed to two reasons. One is the influence of particle size on the heat transfer since the pyrolysis process mainly occurs in the surface of TR. Larger particles contain greater heat transfer resistance, and hence the actual temperature inside the particle is lower, which leads to the occurrence of a devolatilization process (Lv *et al.* 2004). Subsequently, incomplete pyrolysis results in a large amount of residual char. The other possible reason could be that the pyrolysis process of smaller particle was mainly controlled by reaction kinetics; as the particle size increased, the process was mainly controlled by gas diffusion, since the resultant product gas inside the particle had more difficulty to diffusing out (Lv *et al.* 2004).

Kinetics parameters

Kinetic models were studied for TR pyrolysis to obtain the kinetic parameters including activation energy and pre-exponential factor. The rate of reaction for the decomposition of a solid depended on the temperature and the amount of substance (Orfao *et al.* 1999). Thus rate equation for the kinetics analysis could be expressed as:

$$\frac{dX}{dt} = k \cdot f(X) \tag{1}$$

where k is the rate constant, $f(X)$ represents a hypothetical model of reaction mechanism, and X is the conversion ratio of biomass feedstock:

$$X = (W_0 - W_t)/(W_0 - W_f) \tag{2}$$

where W_0, W_t, and W_f are the initial mass of the sample, the mass of pyrolysis sample, and the final residual mass, respectively. The reaction rate constant k was expressed by the Arrhenius equation,

$$k = A\exp(-E/RT) \tag{3}$$

where A is pre-exponential factor, E is activation energy, R is the universal gas constant, and T is temperature. Besides, the reaction model in Eq. (1) could be expressed as,

$$f(X) = (1 - X)^n \tag{4}$$

where n is the order of reaction. In many applications, the pyrolysis of biomass was assumed to be a first-order reaction (*i.e.*, n = 1). Therefore, under a constant heating rate β (= dT/dt), Eq. 1 could be rearranged to:

$$\frac{dX}{dT} = \frac{A}{\beta} \cdot \exp\left(-\frac{E}{RT}\right) \cdot (1-X) \tag{5}$$

By the Doyle integral method (Starink 2003), Eq. 5 could be integrated to:

$$\text{(6)} \quad \ln[-\ln(1-X)] = \ln\frac{AR}{\beta E} - 5.3308 - 1.0516\frac{E}{RT}$$

For most values of activation energy and for the temperature range of pyrolysis, the term of $\ln(AR/\beta E)$ could be regarded as a constant (Guo and Lua 2001). Thus, a straight line might be obtained from a plot of $\ln[-\ln(1-X)]$ versus $1/T$. T was the average value of temperatures at which the thermogravimetric data best fit a straight line done by linear regression. From the linear regression of Eq. 6, the activation energy and the pre-exponential factor could be calculated by the slope and the intercept of the line, respectively.

The variation of activation energy as a function of the particle size, calculated using Eq. 6, is presented in Table. 2. It could be seen that all the regression results had nearly extreme coefficients of determination, R^2 (from 0.9806 to 0.9953). Therefore, the assumption that pyrolysis of biomass underwent a first-order reaction should be proper.

Table 2. Kinetic Analysis of TR Pyrolysis at Different Particle Sizes

	Temperature (℃)	Conversion (%)	E (kJ/mol)	A (1/s)	$R2$
180–380 μm	248-348	17.57~79.49	58.25	5.0×10^{10}	0.9836
	348-806	79.49~99.19	11.64	8.5×10^{5}	0.9937
90–180 μm	242-345	14.81~78.16	57.51	4.4×10^{10}	0.9856
	345-785	78.16~98.89	11.41	7.9×10^{5}	0.9953
Below 90 μm	238-345	15.99~77.61	53.29	1.6×10^{10}	0.9806
	345-825	77.61~98.88	10.85	6.5×10^{5}	0.9903
R^2: coefficient of determination					

From Table 2, it can be seen that TR pyrolysis exhibited typical, multi-step reaction characteristics. In the first-step reaction, the activation energy differed with different particle sizes and temperature ranges, and ranged from 53.29 to 58.25 kJ/mol. The pre-exponential factors varied in the same manner and ranged from 1.6×1010 to 5.0×1010 1/s. The activation energy and pre-exponential factor for smaller particle size was lower than that for larger particle size. The smaller particle significantly increased the rate of reaction, reducing the temperature required to a given percentage conversion by approximately 5 to 10 ℃. During the second-step reaction, the activation energy and pre-exponential factor ranged from 10.85 to 11.64 kJ/mol and 6.5×105 to 8.5×105, respectively. The variation trend was similar to that of the first-step reaction. For both of these steps, the turning points of conversion for TR pyrolysis was about 78 wt.%. Main decomposition occurred at the conversion from about 15% to 80%. When the conversion increased above 80%, the activation energy and pre-exponential factor declined rapidly, which probably attributed to greater presence of residual char (Park *et al.* 2009). The activation energy values obtained here were smaller than those from pine tree, saw dust, and *Arundo donax*. Kim *et al.* (2010) showed that the apparent activation energy

increased 145 to 302 kJ/mol with increasing pyrolysis conversion. Wang *et al.* (2008) reported the ranges of 142 to 168 and 158 to 250 kJ/mol for cellulose and hemicelluloses, respectively. Jeguirim and Trouve (2009) reported the activation energies for cellulose and hemicelluloses to be in the range of 90 to 140 and 110 kJ/mol.

Pyrolysis Experiment in Fixed-bar Reactor

Effect of Particle size on pyrolysis product yields

Figure 3 shows the effect of particle size on dry gas yield at different reactor temperatures. Figure 4 shows the percentage by weight of the sample that remained in the porcelain boat in the form of char, together with tar that adhered to the walls of the condenser, as a function of particle size at different reactor temperatures.
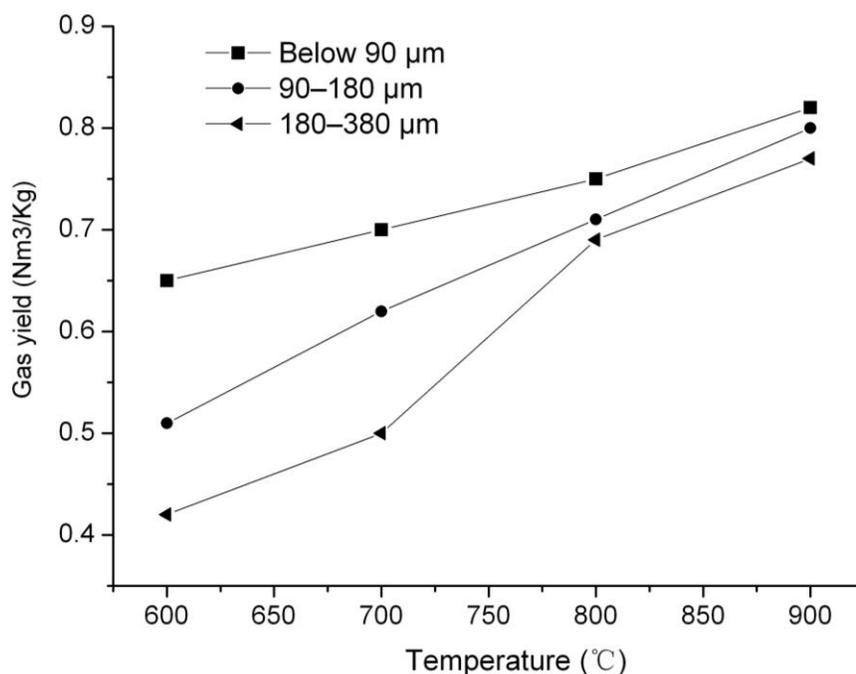
Fig. 3. Dry gas yield of TR pyrolysis as a function of particle sizes at different hearth temperatures

It can be seen from Figs. 3 and 4, the dry gas yield and the production of char and tar were primarily influenced by the operating temperature. By changing the temperature from 600 to 900 ℃, the gas yield increased significantly, while the char and tar decreased sharply for all particle size. The increase of gas yield could be attributed mainly to the decomposition of char and the tar vapor as temperature increased (Yang *et al.* 2011), since more char and tar could be converted into gas through Boudouard reactions and thermal cracking reaction, respectively.

Moreover, there was a tendency for the gas yield to decrease with increasing particle size. The effect of particle size on gas yield can be taken into account from two opposite aspects: one is that smaller particle size, due to larger surface area, improves heat and mass transfer and therefore has faster heating rates, producing more light gases and less char and condensate (Cui *et al.* 2006); another aspect is that the increase of

Lignocellulose

particle size can prolong the residence time of volatile matter in particle, which is helpful to enhancing secondary reaction (thermal cracking) of tar in particle, increasing the gas yield (Seebourg *et al.* 1997). From the tendency of gas yield decreasing with particle size shown in Fig. 3, it can be concluded that the effect of the former is much more pronounced than that of the latter.
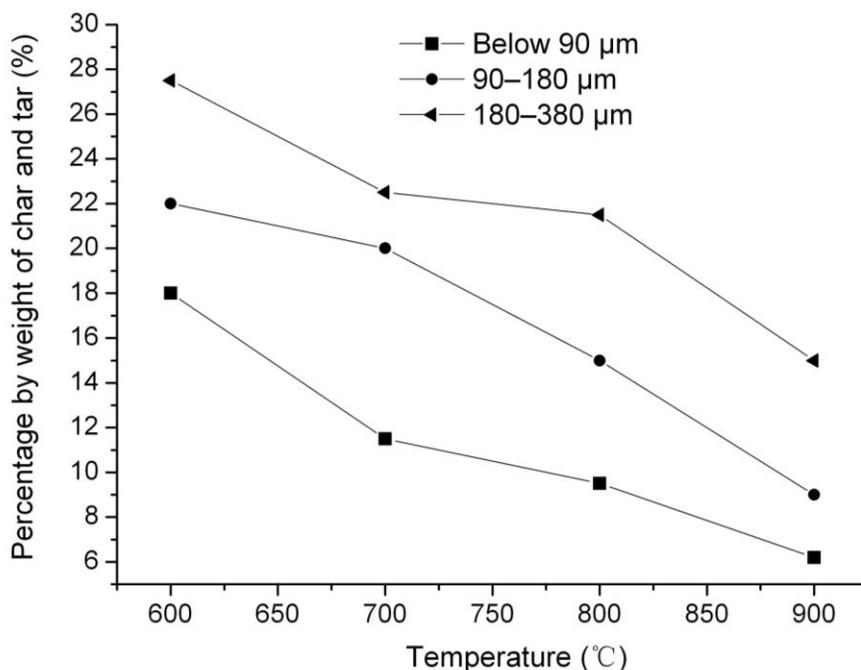
Fig. 4. Percentage by weight of char and tar as a function of particle size and hearth temperature

Other workers have also shown a significant increase in oil-char yield with increasing particle size. For example, Nasir and Paul (1998) investigated that as the particle size was increased from < 0.5 to the 6.0 to 10.0 mm size range there was a 59% increase in oil yield. Shen *et al.* (2009) suggested that the smaller sized particles had a greater surface area per unit mass such that more oil was retained on the surface of the shale which subsequently underwent secondary decomposition resulting in lower oil yields. Their work investigated the pyrolysis of three size ranges, 1.0 to 2.0, 2.0 to 3.35, and 4.75 to 5.61 mm and found that the 1.0 to 2.0 mm size range retained more gas than the 4.75 to 5.61 mm range. They also suggested that the increased secondary reactions of smaller particles may be related to the void fraction of the packed bed in the pyrolysis retort. The smaller shale particles are packed more efficiently, causing a reduction in the void volume, which makes it more difficult for the oil to move through the shale, increasing residence times of the hydrocarbons in the hot zone and consequently increasing secondary reactions and thereby reducing oil yield. Encinar *et al.* (1996) found increased gas yield for particle sizes of two agriculture residues between 0.4 and 2 mm and suggested that this was due to the formation of larger pores caused by particle cracking in the larger particles.

Effect of particle size on fuel gas composition

In regard to the gas composition, the gas component distribution profile from pyrolysis at 900 ℃ is presented in Table 3 as a function of particle size. The main components were H_2, CO, CO_2, and small quantities of low molecular weight hydrocarbons, such as CH_4, C_2H_4, and C_2H_6. Pyrolysis product yields and composition were dependent on the sample particle size. This finding can be explained as follows: for the biomass with smaller particle size, the pyrolysis processes are under kinetic control; while for the biomass with bigger particle size, the pyrolysis processes mainly happen in the surface of biomass powder, affected by the heat and mass transfer. Also, the larger the particle, the greater is the heat transfer resistance, and hence the lower is the actual temperature inside the particle at which the devolatilization process takes place, which causes incomplete pyrolysis, resulting in a large amount of residual char (Di Blasi 1996).

Table 3. Pyrolysis Gas Composition of Pine Sawdust and Tobacco Rob as a Function of Particle Size at 900 ℃

Sample	Pine sawdust			Tobacco rob		
Particle size/d (μm)	$d < 90$	$90 < d < 180$	$180 < d < 380$	$d < 90$	$90 < d < 180$	$180 < d < 380$
H_2	22.35	20.12	17.58	25.68	23.51	21.98
CO	32.13	28.01	25.97	27.36	24.89	22.53
CO_2	24.98	29.71	34.49	33.95	37.27	40.36
CH_4	9.71	10.23	8.67	11.02	13.10	12.72
C_2H_4	0.96	0.88	0.75	1.18	0.96	1.64
C_2H_6	0.42	0.33	0.39	0.81	0.27	0.77

For TR samples, the volume percentages of the main gas components showed increasing trends when the particle size was varied from 180–380 μm to 0–90 μm. The volume percentage of H_2 increased steadily from 21.98 to 25.68% and CO content increased from 22.53 to 27.36%. The yield of CH_4 increased first from 12.72 to 13.10% with a decrease in particle size; however, it decreased again to 11.02% as the particle size continuously decreased. C_2H_4 and C_2H_6 contents were relatively small, and the influence of particle size was insignificant. Only CO_2 decreased with decreasing particle size.

For pine sawdust samples, different gas compositions behaved differently as particle size decreased: the contents of H_2 and CO show increasing trend, from 17.58 to 22.35% and from 25.97 to 32.13%, respectively. And for CO_2 the content decreased significantly, from 34.49 to 24.98%. Meanwhile the variations of the others gas components (CH_4, C_2H_4 and C_2H_6) with particle size were not in a monotonic trend.

In general, the content of H_2 and CO showed increased trends with decreasing particle size, which might be attributed to enhanced pyrolysis reaction, as described by the following equation (Dai *et al.* 2000):

$$\text{Biomass} \rightarrow \text{char} + \text{tar} + H_2O + \text{gas} (H_2, CO, CO_2, CH_4, C_nH_m) \tag{7}$$
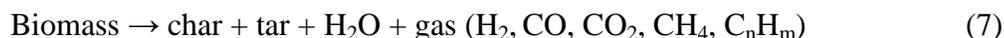
For CO_2 the content decreased, which could be explained by this: decreasing particle size improves Boudouard reactions:

$$C + CO_2 \rightarrow 2CO \tag{8}$$

Effect of pressure and rotor velocity on particle size distribution

The tests were carried out at different hydraulic pressure, namely 60, 70, and 80 kg/cm^2, respectively. At contstant hydraulic pressure, the products obtained with three different rotor velocities (1000, 1200, 1500 rpm/min) were analyzed. The rotor velocity was varied by means of changing the diameter of pulley conical disc. It is important to note that except for the rotor velocity and hydraulic pressure, all other parameters were constant. The evolution of the proportion of the fine fraction (the mass fraction of the fine product) in the product with various rotor velocity and hydraulic pressure is shown in Fig. 5.
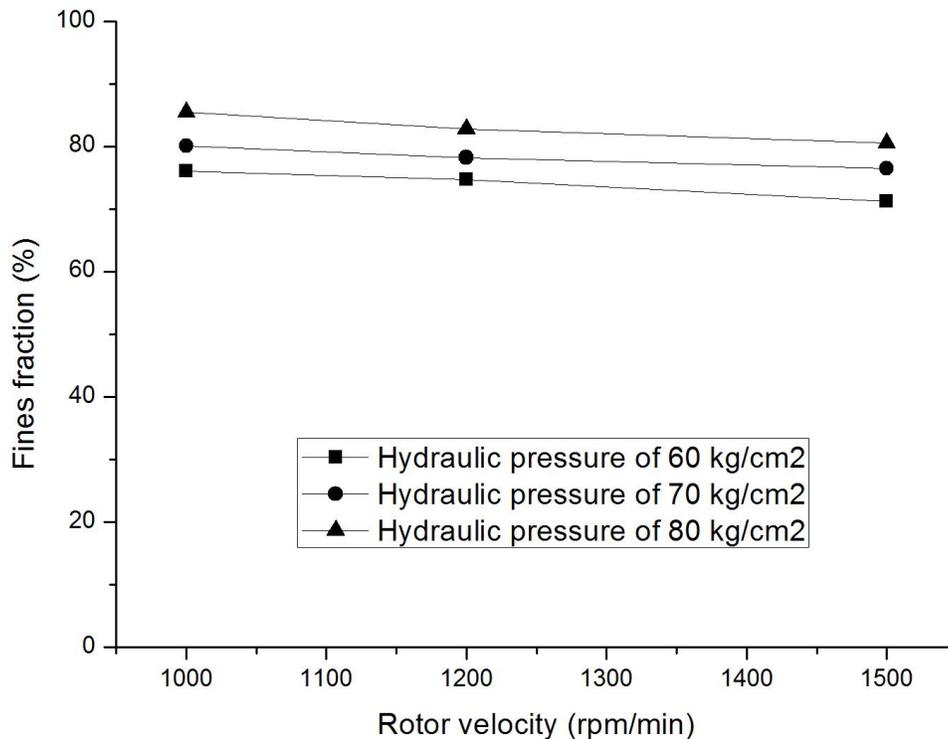
Fig. 5. Proportion of the fine fraction (d < 90 μm) in the product as a function of rotor velocity and hydraulic pressure

It can also be seen from Fig. 5, the higher hydraulic pressure leads to an increase of proportion of fine fraction in the product. As the rotor velocity is 1000 rpm/min, the passing is 85% (90 μm screen) with the pressure being 80 kg/cm^2; for the pressure of 60 kg/cm^2, the value is 76%. The explanation is that when the materials is crushed at higher pressure, the plastic deformation is smaller with the stress distribution being much closer to pure shear, and under the conditions, the product's size mainly depend on the distance between the rotating blades and comb-shaped shear blades, which leads to the increase of proportion of the fine fraction in the product. As rotor velocity is constant, with the increase of hydraulic pressure, the energy consumption is increased and more fine products are produced. As fixed hydraulic pressure, with higher rotor velocity leads to the increase of energy consumption and decrease of coarser product size distribution.

CONCLUSIONS

1. Pyrolytic behaviours of TR at different particle sizes were studied in TGA. Decreasing temperature of the primary decomposition of TR was attributed to a decrease in particle size. The effect of temperature and particle size on product yield and composition from TR pyrolysis was also studied in the fixed-bed reactor. Higher temperature resulted in higher yield and quality of fuel gas. Smaller particles produced more gaseous products, less tar and char, but a reduction in the effect of TR particles size with increasing temperature was observed. Moreover, smaller particles produced more H_2 and CO. It was demonstrated that minimizing the size of raw materials was more favorable for gas quality and yield.Meanwhile,

2. A lab-scale shredder consisting of compaction and shredding chambers was designed. The effect of the rotor velocity and hydraulic pressure on product size distribution was investigated. The experimental results showed that the rotor velocity and hydraulic pressure obviously affect the performances of the shredder. As rotor velocity was constant, with the increase of hydraulic pressure, more fine products were produced. As fixed hydraulic pressure, higher rotor velocity leaded to the decrease coarser product size distribution.

ACKNOWLEDGMENTS

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