*Sindh Univ. Res. Jour. (Sci. Ser.) Vol. 48 **(4D)** 09-16 (2016)*

SINDH UNIVERSITY RESEARCH JOURNAL (SCIENCE SERIES)

Fast Pyrolysis of Rubber Wood Sawdust via a Fluidized Bed Pyrolyzer: The Effect of Fluidization Gas Velocity

M. A. F. MAZLAN*, Y. UEMURA, S. YUSUP

University Technology PETRONAS, Malaysia

Received 28rd August 2016 and Revised 17th October 2016

Abstract: Rubber wood sawdust was pyrolyzed in a fluidized bed reactor at 500 °C with nitrogen as a fluidization gas and silica sand as a fluidizing bed material. The first part of the study is to determine minimum fluidization velocity (U_{mf}) of sand, char, and binary mixture (char and sand) based on experimental and calculation methods. The next objective is to study the effect of fluidization gas velocity (U_g) on the yield and distribution of pyrolysis products. At higher gas velocity, the yield of bio-oil increased, whereas non-condensable gas decreased. To examine physicochemical properties of pyrolysis products, the third part involves analyses of pyrolysis products based on the highest bio-oil yield occurred at U_g of 5.46 cm/s. Bio-char product had significantly higher carbon composition and calorific value than original biomass feedstock and bio-oil fractions. Fractional condensation was incorporated to condense pyrolysis vapours into six fractions of bio-oil. Bio-oil products contained high percentage of oxygen and hydrogen, signifying high water content which decreased the calorific value. However, via a fractional condensation setup, composition of water was reduced at the later part of condensers. From a GC-FID quantitative analysis, major chemical compounds in bio-oil were acetic acid and phenol.

Keywords: fast pyrolysis, fluidized bed pyrolyzer, fluidization gas velocity, fractional condensation, rubber wood.

1. INTRODUCTION

The prospect of energy generation and chemical derivation based on biomass utilization is feasible in Malaysia due to the availability and lavishness of numerous residues from agricultural, plantation, and forestry industries. However, to prevent another issue of food against fuel, non-edible biomass such as wood and municipal solid waste as well as agriculture wastes for instance rice husk, palm kernel shell, bagasse, and corn husk are used to convert biomass into valuable products via several thermal, chemical, and biochemical methods (Bardhan *et al*., 2015). Ordinarily the waste has no or little economic values and often causes disposal problems. In most cases, remaining parts after logging and deforestation activities are left in the jungle (Osman *et al*., 2014). One of the major plantation and forest trees in South East Asia is rubber tree or otherwise scientifically known as *Hevea brasiliensis* (MTIB, 2012). In this study, rubber wood sawdust (RWS) residue from sawmilling industry is selected as a feedstock due to its abundance and cost-free.

Many research articles have reported on pyrolysis process which provides fundamentals and guidelines for further enhancements. Pyrolysis could be categorized into slow, intermediate, fast, and flash pyrolysis type. The classification is generally defined by heating rate, temperature, and vapor residence time. In the last 25 years, pyrolysis at higher heating rate and very short vapor residence time has gained much attention as the process could increase bio-oil yield up to 50 wt.% by reducing the possibility of secondary cracking of pyrolysis vapor occurred in reactor (Bridgwater, 2012; Jahirul *et al*., 2012). Fast pyrolysis could be described as a heating process of organic materials at a medium temperature between 450 to 550 °C and in a short retention time of a few seconds of vapour product, under the absence of oxygen or air. Thus, the material does not combust because no oxygen is present. However, the three main biomass pseudo-components of cellulose, hemi-cellulose, and lignin that formed the material are thermo-chemically decomposed into charcoal and volatiles. Some of these volatiles could be condensed into liquid, called pyrolytic oil or bio-oil. All that is left is carbon lattice of solid charred materials, called bio-char. The incondensable volatiles and gas are termed as pyrolysis gas or non-condensable gas (Jahirul *et al*., 2012; Yaman, 2006).

The core of pyrolysis process is the reactor. There are several reactor designs which could be applied into pyrolysis reaction such as fixed bed, fluidized bed, rotating cone, entrained flow, and vacuum reactor (Basu, 2013; Butler, 2011). In this research work, a fluidized bed reactor type was used to perform fast pyrolysis of rubber wood sawdust. A fluidized bed pyrolyzer is a combination of fluidization and pyrolysis processes. Fluidization could be defined as a process

*Corresponding author: Mohammad Amir Firdaus Mazlan email: amir11@hotmail.com

* Centre for Biofuel and Biochemical Research (CBBR), Universiti Teknologi PETRONAS

which involves a fluidizing medium; either gas or liquid vertically pass in a fluidized bed which consisted of solid particles via a fluid distributor of either porous or perforated plate. Thus, the particles are changed from a fixed solid condition to a dynamic fluid-like form (Basu, 2013; Yang, 2003). Fluidized bed reactor has been found to be effective for converting biomass waste into useful and profitable bioenergy and biochemical products. Some of the advantages are high heat and mass transfer rate, uniform particle mixing, and ability to operate the reactor in continuous state (Mohan *et al*., 2006). Nevertheless, to fluidize biomass materials is challenging because of irregular sizes, shapes, and densities. By adding inert particles such as sand, it could improve fluidization and heating of biomass particles, by performing as a proficient heat and mass transfer medium in the reactor. Also, a gas distributor filled with ceramic beads is used in this study to ensure uniform distribution of fluidizing gas. These concepts are applied in some engineering processes, such as pyrolysis, gasification, and combustion (Yang, 2003).

Unlike crude oil, distillation of bio-oil to separate water and light fractions of chemical compound is difficult because some of bio-oil components are highly reactive. Fractional condensation of pyrolysis vapour in a pyrolysis system is a promising downstream process to separate bio-oil constituents into different fractions. By using fractional condensation setup instead of only a single condensation unit, pyrolysis vapour from reactor passes through successive condensers operated at different temperatures (Chen *et al*., 2010; Butler, 2011). This design creates the opportunity to produce several fractions of bio-oil with different compositions, which could be utilized for further diverse applications.

A number of research articles have been published on fast pyrolysis process using fluidized bed reactor, which offer references for advance studies. However, there is a lack of understandings on the effect of fluidization or superficial gas velocity (U_g) during pyrolysis reaction. In this paper, fast pyrolysis of rubber wood sawdust (RWS) is performed by using a fluidized bed reactor at 500 °C with nitrogen as a fluidization gas and sand as a fluidizing bed material. The impact of fluidization gas velocity on the yield and distribution of pyrolysis products is investigated. Numerous fluidization experimental works have been carried out to define minimum fluidization velocity (U_{mf}) of a particular particle (Ali *et al*., 2013; Amutio *et al*., 2013). Nevertheless, there is a limited number of works on the behaviours of a binary mixture fluidization involving biomass. It is difficult to select fluidized bed configurations especially for binary mixture differing in both density and particle size. So, it is important to determine the minimum fluidization velocity of binary mixture consisting of RWS char and sand in this research work. Therefore, the objective of the study is to conduct fast pyrolysis experiments of rubber wood sawdust using a fluidized bed pyrolyzer and study the effect of fluidization gas velocity on the products yield as well as to characterize physicochemical properties of pyrolysis products.

2. MATERIALS AND METHODS

2.1 Feedstock preparation

Rubber wood sawdust (RWS) was collected from a sawmill in Perak, Malaysia. The biomass material was dried in a drying oven (Memmert, 100-800 model) for 24 h at 105 °C to minimize the free moisture in feedstock which could affect the performance of pyrolysis reaction (Mohan *et al*., 2006). Then, the biomass was sieved by a sieve shaker (CISA) to the size range of 0.15 to 0.50 mm. By referring to the author's previous research review, smaller particle size favors higher rate of fast pyrolysis reaction (Mazlan *et al*., 2014). However, very small size range is difficult to handle and could cause light biomass particles to be blown out of reactor during fluidization and experience incomplete pyrolysis reaction.

In fluidized bed pyrolyzer operation, silica sand collected from the Morib Beach in Selangor was used as a fluidization medium. The sand underwent a few steps of preparation before ready to be used as a fluidizing bed medium. First, the sand was washed with distilled water for three times to remove salinity and any foreign material effectively. Next, it was dried in a drying oven at 105 °C until moisture content is less than 1 wt.%. After that, the sand underwent a calcination process at 700°C for 3h in an electric furnace (ThermWise) to remove any organic material. Finally, was screened to the size between 0.15 and 0.25 mm.

2.2 Experimental setup

Fig. 1 illustrates a schematic diagram of the fluidized bed pyrolyzer used to carry out fast pyrolysis of RWS in this study. The experimental setup is a continuous feed system to decompose biomass by thermo-chemical reaction comprising of four core parts:

1) a feeding system consisting of a reservoir and screw feeder to feed biomass
2) a fluidized bed reactor for decomposition of biomass
3) a char separation section involving of two cyclones to trap fine char particles
4) a series of six condensers consisting of three stages of fractional condensation using three different mediums operated at three different temperatures:

a) tap water at room temperature (28 °C), for 1st condenser;
b) chilled water at 5 °C, for 2nd condenser; and
c) ethylene glycol at -10 °C for 3rd, 4th, 5th, and 6th condensers.

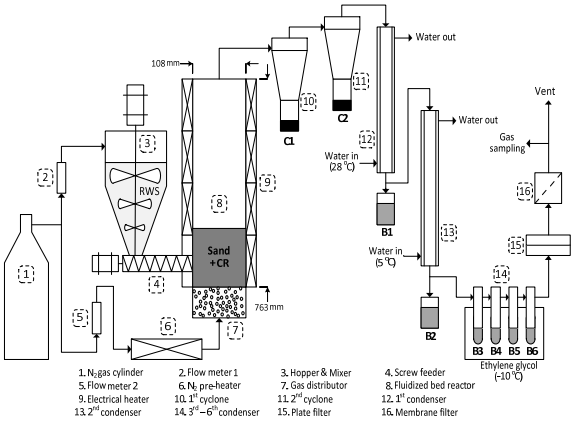


Fig. 1: Schematic diagram of the fluidized bed pyrolyzer system

2.3 Pyrolysis procedure

In each experimental run, a prescribed amount of 0.5 kg of RWS feedstock was put into the hopper and 1.2 kg of silica sand was put into the reactor. Nitrogen gas flow rate of 1 L-NTP/min was set at flow meter 1 to prevent backflow of biomass inside the hopper. The wind box was filled with ceramic beads and a distributor made of stainless steel net with an opening of 50 µm were installed at the bottom of the fluidized bed reactor to distribute carrier gas uniformly crossing the sand bed. Nitrogen gas was used as a fluidization gas and pre-heated at 500 °C. Flow rate of fluidizing gas was set at flow meter 2 to control the fluidization or superficial gas velocity parameter (3.64, 4.55, and 5.46 cm/s). A screw feeder with length and diameter of 400 and 26 mm, respectively was equipped with a water jacket at room temperature (28°C) to prevent carbonization of biomass feedstock prior entering the reactor. After the desired pyrolysis temperature (500 °C) was acquired and stable, the screw feeder was switched on to start biomass feeding into the reactor at a rate of 25 g/min. Duration of the experiment was held at the selected gas velocity for 30 min to ensure pyrolysis reaction has completed. The calculated overall power consumption for each fast pyrolysis process was 4.8 kWh.

The fast pyrolysis reaction produced bio-char, bio-oil, and non-condensable gas. Most of char particles were accumulated inside the reactor and a few amounts were blown out of the reactor and then trapped inside the first and second cyclones, denoted as CR, C1, and C2, respectively. Most of pyrolysis vapors were condensed into bio-oil by condensers and collected inside the collectors. The six fractions of bio-oils were denoted as B1, B2, B3, B4, B5, and B6 according to the sequence of condenser number, correspondingly. The yield of non-condensable gas (NCG) was calculated by using a mass balance equation (Mazlan *et al*., 2015):

$$\text{Bio-char [wt.\%]} + \text{bio-oil [wt.\%]} + \text{NCG [wt.\%]} = 100 \quad (1)$$

2.4 Pyrolysis products analysis

To determine the properties of biomass feedstock and pyrolysis products, the second part involving analyses of pyrolysis products from the highest fluidization gas velocity experiment (5.46 cm/s) was accomplished. Elemental analysis was carried out by using a CHN analyzer (Perkin Elmer 2400). Oxygen content was determined by difference of C, H, and N values. Calorific value was measured by a bomb calorimeter (IKA C6000 Isoperibol). Water content of bio-oil was analysed by a volumetric Karl Fischer titrator (Mettler Toledo V30) with CombiTitrant 5 Keto (Merck) and CombiSolvent Keto (Merck) were employed as the titrant and solvent, respectively. All of the aforementioned analyses were repeated at least twice to verify the reproducibility and then averaged.

3. RESULTS AND DISCUSSION

3.1 Fluidization study

In any fluidization process, it is essential to determine minimum fluidization velocity (U_{mf}) of a particular material. In this study, it is the velocity of N_2 fluidization gas at which the particle bed of sand, RWS, and char materials start to expand and move upward from a fixed bed position due to the gas inflow is higher than the gravitational force downward. However, for pyrolysis in a fluidized bed reactor, it is difficult to estimate the U_{mf} since a mixture of biomass, char, catalyst or fluidizing bed materials are involved. Most research articles incorporated data of bed material only in the calculation by assuming it is the dominant factor in a fluidization process (Amutio *et al*., 2013; Heo *et al*., 2010). In addition, it is difficult to observe fluidization process during high temperature of pyrolysis operation. The minimum fluidization velocity is calculated based on the correlation between the Reynolds and Archimedes numbers given by the Ergun equation. Wen and Yu (1966) suggested a simplified form of the Reynolds equation, consisting of two constants (K_1 and K_2), termed as two-constant correlation. Later, Paudel and Feng (2013) proposed a new correlation which includes the mass percentage.

$$U_{mf} = (\mu_g \, Re_{mf}) / (d_p \rho_g) \quad (2)$$

$$Re_{mf} = (K_1^{\,2} + K_2 Ar)^{0.5} - K_1 \quad (3)$$

$$Re_{mf} = \{30.28^2 + [0.046\,(1 - x_c) + 0.108\,x_c]\,Ar\}^{0.5} - 30.28 \quad (4)$$

$$Ar = g d_p^{\,3} \rho_g (\rho_p - \rho_g) / \mu_g^{\,2} \quad (5)$$

For this research work, a modified solution was used to calculate U_{mf} of the binary mixture (sand and char). Binary mixture of sand and RWS biomass was not considered because upon biomass feed entered the reactor, it started to decompose into char in a few seconds. Effective density (ρ_e) and effective diameter

(d_e) of char/sand mixture were calculated by the equations reported by Goosens *et al*. (1971), which could be applied in Reynolds-Archimedes correlations. Therefore, the binary mixture is assumed as a new single constituent.

$$1/\rho_e = w_c/\rho_c + w_s/\rho_s \quad (6)$$

$$d_e = d_c d_s \left[(w_c \rho_s + w_s \rho_c) / (w_c \rho_s d_s + w_s \rho_c d_c)\right] \quad (7)$$

The result of U_{mf} from calculation method was compared to the actual U_{mf} determined via a cold flow fluidized bed model with similar dimension and condition excluding the heating. **(Fig. 2)** shows a comparison of U_{mf} between the char, sand, and binary mixture (sand and char) based on calculation method and actual experimental run in determining the U_{mf}. Values of U_{mf} for the three particle types between calculation and experimental are closed, hence proving that the calculation method is a competent technique to determine minimum fluidization velocity at high temperature. It is worth noting that the U_{mf} of sand, char, and binary mixture from experimental run are higher than equation calculation. The reason could be in real life fluidization situation, extra force or velocity is required to break the inter-molecular force between particles.

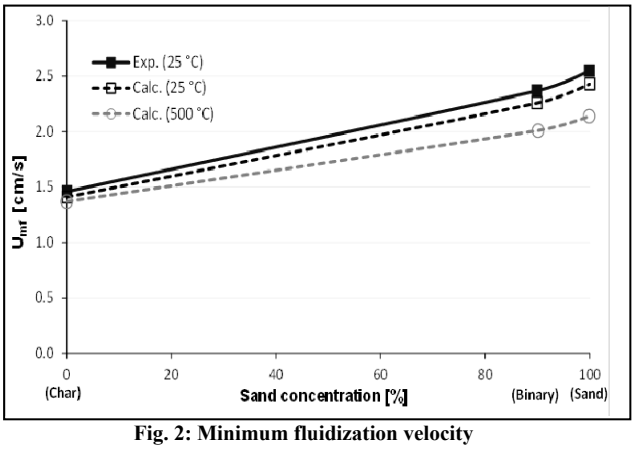


Fig. 2: Minimum fluidization velocity

When the upward velocity of gas exceeds the free-fall terminal velocity of particles, the gas will carry the particles upward and eventually out of the chamber. Terminal velocity (U_t) of the binary mixture based on calculation method at 500 °C is 131 cm/s and was calculated according to the Stokes Law as follows (Bourgeis and Grenier, 1968):

$$U_t = (Ar/18)(\mu_g/d_p\rho_g) \quad (8)$$

Minimum fluidization and terminal velocity provide the minimum and maximum boundary points in selecting superficial gas velocity (U_g). Therefore, three U_g were selected (3.64, 4.55, and 5.46 cm/s) to determine the effect of fluidization gas velocity in fast pyrolysis of RWS using the bubbling fluidized bed pyrolyzer.

3.2 Mass yield

Fig. 3 displays the effect of fluidization gas velocity (U_g) on the mass yield of RWS fast pyrolysis products. At higher gas velocity, the yield of bio-oil increased, whereas non-condensable gas decreased. The reason is at higher U_g, residence time of pyrolysis vapors was reduced. So, reaction rate for primary decomposition of biomass is higher, hence producing more bio-oil. At low U_g, the possibility of secondary reactions, such as bio-oil cracking and char repolymerization increases and more gas was formed due to longer vapor residence time in the reactor (Heo *et al*., 2010). However, a very high fluidization velocity could really have negative impacts on the solid mixing and heat transfer efficacies. The ability to control volatiles residence time without major effects on liquid product yield is important in scaling up fluidized bed reactor to commercial sizes.

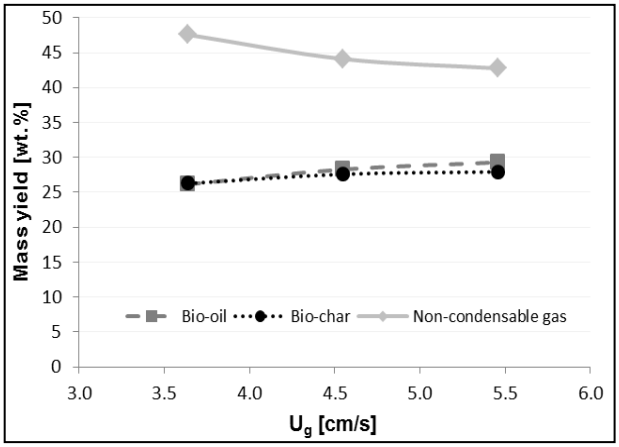


Fig. 3: Yield of pyrolysis product

The mass distribution of bio-char and bio-oil at each collecting location are given in Table 1. In this pyrolyzer unit, two successive cyclones were used to remove fine char particles from pyrolysis vapours which could further enhance secondary cracking of bio-oil vapor and cause solid impurities in bio-oil product. Although the total bio-char yield from Fig. 3 increased when U_g was higher, but based on Table 1, the amount of char formed inside the reactor, CR reduced when U_g was increased. The reason is at higher fluidization gas velocity, more fine char particles were blown out of the reactor and accumulated inside the first and second cyclones. C1 and C2 had finer particle size (less than 0.1 mm) as they were able to elutriate from fluidized bed reactor while CR, which was mixed up with the sand bed, had a bigger size range. In the case of bio-oil fractions, higher amount of bio-oil was collected for B1 and B2 operated at lower fluidization gas velocity. As U_g was increased, more bio-oil accumulated at the later

part of condensers because residence time of pyrolysis vapor was reduced.

Table 1: Distribution of pyrolysis product

Product	Location	Mass [g]		
		3.64 cm/s	4.55 cm/s	5.46 cm/s
Bio-char	CR	113.9	110.6	108.5
	C1	10.3	16.9	20.3
	C2	2.2	5.0	6.4
Bio-oil	B1	23.5	21.8	21.9
	B2	59.4	65.9	63.2
	B3	18.0	19.4	17.4
	B4	14.8	14.6	21.9
	B5	7.0	7.6	8.5
	B6	3.5	3.8	6.0

3.3 Fractional condensation

Elemental and calorific value analyses of the RWS feedstock and its pyrolysis products from the highest fluidization gas velocity experiment are summarized in Table 2. Due to difficulty in taking homogenous sample from CR, char sample was analysed from the cyclones. The char product has significantly higher carbon composition and calorific value (CV) than original feedstock and bio-oil fractions. Kim *et al*. (2013) has reported that higher carbon content could contribute to higher CV. Bio-oils produced in this study contain higher percentage of oxygen and hydrogen when compared to the initial feedstock and char, implying high water content in the bio-oil, as further supported by Fig. 4. As reported by other literatures, the presence of high water content could decrease the calorific value of bio-oil product (Ali *et al*., 2013; Amutio *et al*., 2013). However, bio-oils which were collected in condensers 1, 5, and 6 contained significantly higher percentages of carbon and CV than bio-oils fractions in B2, B3, and B4, signifying the advantages of using a fractional condensation setup.

Table 2: Elemental and calorific value analyses

Sample	Elemental composition [wt.%]				Calorific value
	C	H	N	O	[MJ/kg]
Raw RWS	46.6	7.1	0.3	44.7	19.4
RWS char	77.2	2.6	0.4	15.2	29.1
B1	35.9	10.3	0.3	53.5	13.3
B2	22.7	9.8	0.3	67.2	8.9
B3	24.1	10.0	0.1	65.8	9.3
B4	29.8	9.2	0.2	60.8	10.3
B5	36.5	7.6	0.1	55.8	14.1
B6	40.9	6.3	0.1	52.7	16.7

Fig. 4 illustrates the amount of bio-oil and water in bio-oil as well as the percentage of water content in each fraction of bio-oil. Overall, bio-oil fraction from pot 1, B1 was a viscous tar, consisting of heavy organic compounds. B2 and B3 were mostly aqueous because more water vapours were condensed while B4, B5, and B6 were mainly heavier organics. Although the mass of bio-oil is the highest at B2, but the value is largely constituted of water. Unlike crude oil, distillation of bio-oil to separate water and organic fractions is difficult because some of bio-oil components are highly reactive (Westerhof *et al*., 2011). A fractional condensation setup is an improvement of this pyrolyzer design, which condenses pyrolysis vapours to various bio-oil fractions at the order of saturated vapour pressure. By applying fractional condensation setup, composition of water in the bio-oil was reduced because most of water was condensed in the second and third condensers. Separation of water is a crucial step as the presence of water in bio-oils could lower the energy content and flame temperature of bio-oil for potential fuel application (Demirbas, 2000).

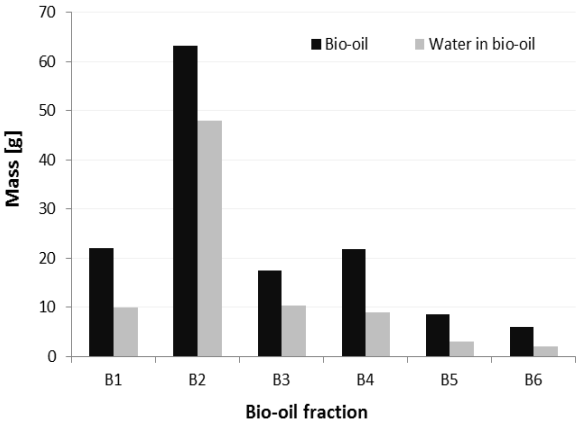


Fig. 4: Water content of bio-oil

Bio-oil is a very complex mixture of carboxylic acids, water, aromatic hydrocarbons, phenolics, aldehydes, ketones, alcohols, esters and furans. **Fig. 5** shows the distribution of the two major chemical compounds, which are acetic acid and phenol in the six fractions of bio-oil. The data was obtained from quantitative analysis by using a GC-FID. One of the factors affecting the distribution of chemical components in bio-oil is miscibility. Acetic acid was the highest organic in the second condenser, B2 because acetic acid is very miscible in water. The same tendency was observed for acetic acid in B3. To be brief, acetic acid is dominant in all bio-oil fractions which have high water content. On the other hand, phenol compound has an opposite trend and was found high in organic bio-oils, B1, B4, B5, and B6. The reason could be that phenol is less soluble with water. Fractional

condensation is a good method for preliminary separation of phenol. High amount of phenol in bio-oil is interesting because derivation of it could be used as an alternative to petroleum-based phenol. It is an important industrial commodity as a precursor to various materials. Likewise, high amount of acetic acid indicates the suitability of bio-oil to be considered for value-added chemicals.

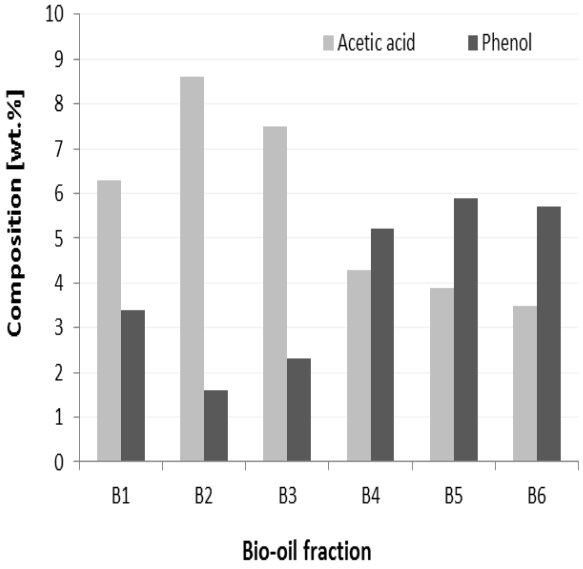


Fig. 5: Major composition of bio-oil

5. CONCLUSION

Fast pyrolysis of rubber wood sawdust was carried out at fluidization gas velocity of 3.64, 4.55, and 5.46 cm/s to investigate the effect of fluidization gas velocity on the yield and distribution of pyrolysis products. As the U_g was increased, bio-oil yield increased, but the yield of non-condensable gas decreased. One of the main purposes for fast pyrolysis is to obtain a higher yield of bio-oil. In this case, higher U_g is recommended for fast pyrolysis of RWS within the experimental conditions in this study.

One of the important indices for economic viability of pyrolysis process is calorific value. However, the presence of water in bio-oil significantly decreased the energy value. By applying fractional condensation setup, water content of bio-oil was reduced in certain fractions. Moreover, preliminary separation of major components in bio-oil such as acetic acid and phenol is feasible with fractional condensation step.

ACKNOWLEDGMENTS

This research was carried out with the financial support of the Mitsubishi Corporation Trust Fund of Japan and Long-term Research Grant Scheme MOE of Malaysia.

NOMENCLATURE

ρ_e	**effective density of binary mixture [kg/m^3]**
ρ_c	**density of char [kg/m^3]**
ρ_s	**density of sand [kg/m^3]**
ρ_g	**density of gas [kg/m^3]**
ρ_p	**density of particle [kg/m^3]**
w_c	**mass ratio of char [-]**
w_s	**mass ratio of sand [-]**
d_e	**effective mean diameter of binary mixture [m]**
d_c	**mean diameter of char [m]**
d_s	**mean diameter of sand [m]**
d_p	**mean diameter of particle [m]**
U_g	**fluidization gas velocity [m/s]**
U_{mf}	**minimum fluidization velocity [m/s]**
U_t	**terminal velocity [m/s]**
μ_g	**viscosity of gas [kg/s.m]**
Re_{mf}	**Reynolds number at minimum fluidization [-]**
Ar	**Archimedes number [-]**
x_c	**mass percentage of char [-]**
g	**gravitational acceleration [m/s^2]**

REFERENCES:

Ali N., Y. Uemura, H. Afif, N. Osman, W N. Omar, T. Tsutsui, (2013) Effect of operating conditions and fractional condensation on pyrolytic products, Journal of the Japan Institute of Energy 92 1014-1020.

Amutio M., G. Lopez, J. Alvarez, M. Olazar, J. Bilbao, (2013) Flash pyrolysis of forestry residues from the Portuguese Central Inland Region within the framework of the BioREFINA-Ter project, Bioresource Technology 129 512-518.

Bardhan S. K.., S. Gupta, M. E. Gorman, M. A. Haider, (2015) Biorenewable chemicals: Feedstocks, technologies and the conflict with food production, Renewable and Sustainable Energy Reviews 51 506-520.

Basu P., (2013). Biomass gasification, pyrolysis and torrefaction: Practical design and theory, 2nd ed. Academic Press Canada

Bourgeis P., P. Grenier, (1968) Ratio of terminal velocity to minimum fluidization velocity, The Canadian Journal of Chemical Engineering 46 325-338.

Bridgwater A. V., (2012) Review of fast pyrolysis of biomass and product upgrading, Biomass & Bioenergy 38 68-94.

Butler E., (2011) A review of recent laboratory research and commercial developments in fast pyrolysis and upgrading, Renewable & Sustainable Energy Reviews 15 4171-4186.

Chen T., C. Deng, R. Liu, (2010) Effect of selective condensation on the characterization of bio-oil from pine sawdust fast pyrolysis using a fluidized-bed reactor, Energy Fuel 24 6616-6623.

Demirbas A., (2000) Mechanisms of liquefaction and pyrolysis reactions of biomass, Energy Conversion and Management 41 633-646.

Goosens W.R.A., G.L. Dumont, G.L. Spaepen, (1971) Fluidization of binary mixture in the laminar flow region, The Chemical Engineering Progress Symposium Series 116 38-45.

He. H. S., H. J. Park, C. Ryu, D. J. Suh, J. H. Yim, S. S. Kim, (2010) Bio-oil production from fast pyrolysis of waste furniture sawdust in a fluidized bed, Bioresource Technology 101, 91-96.

Jahirul M. I., M. G. Rasul, A. A. Chowdhury, N. Ashwath , (2012) Biofuels production through biomass pyrolysis A technological review, Energy 5 4952-5001.

Jung S. H., S. J. Kim, J. S. Kim, (2012) Characteristics of products from fast pyrolysis of fractions of waste square timber and ordinary plywood using a fluidized bed reactor, Bioresource Technology 114 670-676.

Kim S W., B S. Koo, J S. Lee, S. Choi, G. R. Kim, J W. Ryu, (2013) Bio-oil from the pyrolysis of palm and Jatropha wastes in a fluidized bed, Fuel Processing Technology 108 118-124.

Kunii D., (1991) Levenspiel O, Fluidization Engineering, Elsevier.

Mazlan M.A.F., N. Osman, S. Yusup, (2014) Review on Pyrolysis of Hardwood Residue to Biofuel, Applied Mechanics and Materials 625 714-717.

Mazlan MAF., Y. Uemura, N. Osman, S. Yusup, (2015) Fast pyrolysis of hardwood residues using a fixed bed drop-type pyrolyzer, Energy Conversion and Management 98 208-214.

Mohan D., C. U. Pittman, P. H. Steele, (2006) Pyrolysis of wood/biomass for bio-oil: A critical review, Energy Fuels 20, 848-890.

MTIB, Malaysian Timber Statistics (2012) 2009-2011, Malaysian Timber Industry Board.

Osman, N. B., H. T. Othman, R. A. Karim, M. A. F. Mazlan, (2014) Biomass in Malaysia: Forestry based residues, International Journal of Biomass and Renewables 3 7-14.

Paudel B., Z. G. Feng, (2013) Prediction of minimum fluidization velocity for binary mixtures of biomass and inert particles, Powder Technology 237 134-140.

Sukiran C. M., N. K. A. Bakar, (2009) Bio-oils from pyrolysis of oil palm empty fruit bunches, American Journal of Applied Sciences 6 869-875.

Wen C Y., Y H. Yu, (1966) A generalized method for predicting the minimum fluidization velocity, AIChE Journal 12 610-612.

Westerhof R J M., D W F. Brilman, M. Garcia-Perez, Z. Wang, (2011) Oudenhoven SRG, van Swaaij WPM, Kersten SRA, Fractional condensation of biomass pyrolysis vapors, Energy Fuel 5 1817-1829.

Yaman S., (2006) Pyrolysis of biomass to produce fuels and chemical feedstocks, Energy Conversion and Management 45 651-671.

Yang W C., (2003) Handbook of Fluidization and Fluid-Particle Systems, Marcel Dekker. CRC press.