



Research paper

Production of liquid fuel from plastic waste using integrated pyrolysis method with refinery distillation bubble cap plate column

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ABSTRACT

The objective of this paper is to optimise the liquid product of pyrolysis from as much as 500 g of polypropylene (PP) plastic waste, using a fixed bed type reactor in a vacuum condition (-3 mm H₂O), to minimise the oxygen entering the reactor. The vapour flows through the 4-tray distillation bubble cap plate column for fractionation by utilising heat from the reactor. Process conditions at 500–650 °C and of 580 °C optimum liquid oil yield is 88 wt.%, comprising of kerosene in tray I with a volume of 350 ml, gasoline in tray II and III with a volume of 228 ml, and tray IV had no condensate. Gas yield is 5 wt.% and the rest is char. At the conditions between 500 °C and 560 °C, gasoline yield in 6–67 wt.% comprises of kerosene and gasoline. However, at process conditions between 600 °C and 650 °C yields of 64–83 wt.% comprising of diesel oil was obtained at tray I and II, while kerosene and gasoline were obtained in the next tray. The characteristics of fuel obtained from plastic such as density, viscosity, octane–cetane number, ash content and calorific value have similar properties with those of fossil fuels.

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1. Introduction

Until now, utilisation of plastic materials in modern human life is increasingly widespread and cannot be avoided, and this results in plastic production globally increasing annually from various industries and households (Lopez et al., 2017), and experiences progression and innovation (Koç, 2013). Plastic materials have advantages such as its light weight, transparency, strong and cheap manufacturing process. Used plastics will be discharged into an environment that ends in the land fill or ocean. Based on data, Indonesia ranks second in the world of contributors of plastic waste ending up in the sea which reached 187.2 million tons after China's 262.9 million tons (Jambeck et al., 2015).

The process of plastic degradation in nature is divided into several categories i.e. physical, biological, and chemical processes. The physical degradation processes in nature occur through pressure, humidity and heat from the sun. Based on their chemical compounds, in plastics composed of hydrocarbon chain polymers derived from petroleum refining, the bonds between the hydrocarbon monomers are so strong, making the degradation process difficult at ambient temperature (32 °C). As a result, it is very difficult to be biologically degraded by enzymes and bacteria, therefore, takes a very long time for the degradation process (Yuliansyah et al., 2015).

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Several alternatives have therefore been developed to conduct an efficient process of recycling plastic waste, and such methods include through physical and chemical processes. Physical methods are commonly referred to as “three R” i.e. reduction, reuse and recycling (Moinuddin et al., 2012). This method is inappropriate because plastic waste returns to the environment and will later on end up as waste plastic. In addition, it requires high labour costs for the separation process, thereby reducing the sustainability of the process (Anuar et al., 2016). However, the chemical process through the pyrolysis method is a more efficient and economical method of recycling, because it can restore the energy contained in plastic (Zadgaonkar, 2006).

Pyrolysis is a decomposition process of long-chain hydrocarbon (polymer) molecules into smaller sizes (monomer) with the use of high heat (450–800 °C) (Arena and Mastellone, 2006), in a shorter duration and a condition with the absence of oxygen (Anuar et al., 2016), generating products in form of carbon, as residues and volatile hydrocarbons which can be condensate as fuel and non-condensable as gaseous fuel (Lee, 2006). The reaction of this polymer is a weak bond chain and is damaged by increasing temperature, followed by the formation of the free radical propagation stage. These free radicals will then separate again to form smaller ones which produce more stable compounds (Scheirs, 2006). These smaller free radicals produce stable compounds in the form of paraffin compounds, isoparaffins, olefins, naphthenes and aromatics (Tadmor, 2006) with the general reaction mechanism for plastics thermal degradation as explained by Lee (2006).

Pyrolysis of waste plastics PP has been investigated by many researchers who discovered liquid pyrolysis products to be similar

to crude oil (Wong et al., 2017). However, its products show the presence of ash and wax from raw materials, which reduces the quality (Miskolczi and Ateş, 2015), and the result of condensate analysis using Gas chromatography (GC-MS-FID) consisting of C₇–C₃₀ with a maximum peak in C₉ (Kassargy et al., 2017). An analysis of the derived gases and oils indicated that pyrolysis gave a mainly aliphatic composition consisting of a couple of hydrocarbons (alkanes and alkenes).

The liquid fuel obtained from the pyrolysis process cannot be directly used as fuel, due to the presence of impurities (ash) and wax from the feedstock (Mburu et al., 2016), hence, the pyrolysis product is used in reducing the ash and wax content in fuel products. The purification of the pyrolysis products was conducted using distillation bubble cap tray column which reduces the ash and wax content in fuel products. Moreover, used for separate the pyrolysis product has based on different boiling points. This review therefore focuses on the effect of temperature on the pyrolysis results which have been integrated with the bubble cap distillation column. This is carried out by utilising the heat from the reactor to separate the liquid product in a vacuum condition which minimises the oxygen entering the reactor. However, in vacuum conditions, organic vapour leaves the reactor faster, thereby reducing vapour residence time and shifting evaporation to lower temperature areas, thus reducing the average vapour temperature. This establishes a more favourable mass transfer condition, and obtains the highest liquid yield (MaXiaolong et al., 2017). The obtained liquid product is analysed of physical characteristics to determine the specific type of product and compare fuel oil with the fossil.

2. Materials and methods

2.1. Materials

Samples were sorted according to resin codes developed by the Society of Plastic Industries. The raw materials utilised in this study were derived from Polypropylene (PP) type plastic Density (ρ) = 1.30–1.58 g/cc; Crystalline melting temperature (TM) = 168–175 °C such as plastic bottle waste gathered from scavengers around Keputih Sukolilo Surabaya, Indonesia. Dirt was washed off the plastic waste, after which it was then cut into small pieces, with sizes of 1×3 cm with the use of enumerator machines, to significantly reduce the volume of the sample chamber in the reactor.

2.2. Apparatus and experimental procedures

This study employed a fixed bed type reactor, made of stainless steel (2). The reactor heating process reaches a maximum temperature of 750 °C (3), in a space that has been isolated to reduce the heat emanating from the system (1). This reactor can work either as a thermal or catalytic pyrolysis process. The temperature is measured and regulated in an electric heating source, using the Integral Proposal (PI) method with Off-Set 2 °C as a process variable controller. The heating rate is 15.46 K/min, including the slow pyrolysis category. Temperatures varied at 500, 520, 540, 560, 580, 600, 620 and 650 °C under vacuum ($P_{\text{input}} = -7$ mm H₂O; $P_{\text{out}} = -10$ mm H₂O) to remove the air (oxygen) in the reactor.

The experiments were conducted with a prepared 500 g of plastic waste. The sample was then heated and melted in the reactor, producing organic vapour. The vapour flows through distillation of bubble cap column as a result of the heat from the reactor and vacuum pressure. Ash residue and wax carried by the vapour will go down to the reactor due to the condensate or resistance beneath the column plate. Whereas, un-condensed vapour flows through the riser (reverse current below the cap), moves down through the annular space (between the riser and the cap), and eventually

forms a liquid bubble (vapour mixture with condensate) through a series of available slots along the edge of the lid at the bottom. Condensed vapour is stored on a column plate which then flows into tray I (4) as an oil product. Vapours that are un-condensate in tray I, are inhibited under the column plate II through column I. Vapour having a higher boiling point will be condensed through column I, then collected in tray I. Whereas, the un-condensate vapour flows through the riser, moving down through space annular, and forms bubbles through a series of slots. The condensate then flows on the column plate II and is then stored in tray II. The same process is repeated for tray III. However, the vapour that does not condense in tray III is a volatile compound (low boiling point), condensed with the aid of a condenser using a water cooler (± 5 °C), leaving the condensed vapour to be accommodated in tray IV. Unconditioned vapour flows through a gas-washing bottle filled with H₂O₂ (10%, v/v) solution to absorb acidic and toxic compounds with the use of a vacuum pump, before being disposed of into the environment. The temperature of each condensate passing through the tray has been measured using a digital thermocouple Leybold series 666 209 (3).

The mass percentage of product composition could then be calculated for % conversion, % oil, % residue and % gas according to the formula given below (Mabood et al., 2010).

Conversion of thermal cracking:

$$\text{Conversion (wt.\%)} = \frac{\text{Mass of polypropylene (PP)} - \text{Mass of residue}}{\text{Mass of polypropylene (PP)}} \times 100\% \quad (1)$$

Liquid Yield:

$$\text{Oil (wt.\%)} = \frac{\text{Mass of oil}}{\text{Mass of polypropylene (PP)}} \times 100\% \quad (2)$$

Residue (Char) Yield:

$$\text{Residue (wt.\%)} = \frac{\text{Mass of residue}}{\text{Mass of polypropylene (PP)}} \times 100\% \quad (3)$$

Gas Yield:

$$\text{Gas (wt.\%)} = 100\% - (\text{Oil} + \text{Residue}) \quad (4)$$

The resulting fuel product is specifically based on density ($\rho_{60^\circ\text{C}}$), Specific Weight (Sg) and °API (Chemstations, 2004).

The °API Gravity is defined as:

$$^\circ\text{API}_{60^\circ\text{F}} = \frac{141.5}{S.g_{60^\circ\text{F}}} - 131.5 \quad (5)$$

Where, S.g: Specific gravity

$$S.g_{60^\circ\text{F}} = \frac{\rho_i}{\rho_{\text{H}_2\text{O}}}, \text{ at } 60^\circ\text{F} \quad (6)$$

Where, API : API gravity

$S.g_{60^\circ\text{F}}$: Specific gravity, 60 F/60 F

$\rho_{\text{H}_2\text{O}}$: Density of H₂O at 60 °F, g/ml

ρ_i : Density of component i at 60 °F, g/ml

3. Result and discussion

This study made use of a pyrolysis reactor integrated with bubble cap distillation column to pyrolyse plastic and separate liquid products, in order to reduce the energy requirement of the process. The vapour phase reactor will condense in each tray due to contact with the cold surface. The component with the heaviest oil will condense in tray I, and so on. The distillation in the study was carried out without reflux, because each tray served as a cold surface to condense the vapour, meaning that fractionation can

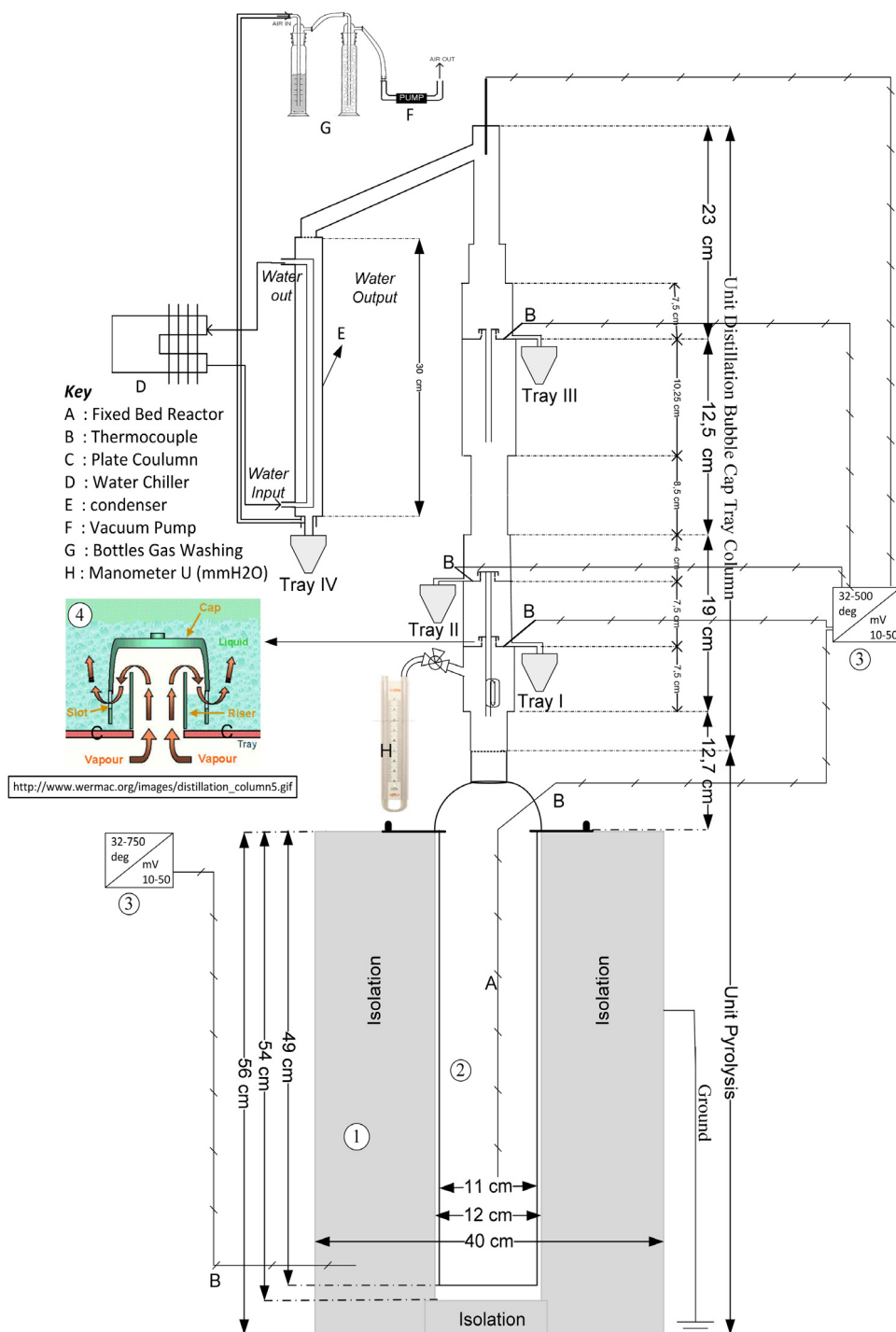


Fig. 1. Schematic of thermal cracking pyrolysis integrated with distillation bubble cap column.

occur in each tray. The maximum number of trays that can be operated by the bubble cap distillation column process is four. This is because there is no condensate in the fourth tray at optimum process conditions (580 °C), even though a condenser unit with cooling water (± 5 °C) has been added. (See Fig. 1.

3.1. Polypropylene conversion and liquid yield

The pyrolysis process of plastic waste generates fuel, offering an alternative to gas. But in general, the composition of pyrolysis liquid product may differ, depending on the composition of the feedstock and its process parameters (Yuliansyah et al., 2015).

The results of pyrolysis products (liquid, gas and char) were obtained within the range of 500–650 °C. From the degradation of polypropylene (PP), plastic waste pyrolysis was calculated using Eqs. (1)–(3), and the results are illustrated in Fig. 2. Also, the product of distillation bubble cap column of each tray (ml fuel oil /g PP plastic) is presented in Table 1.

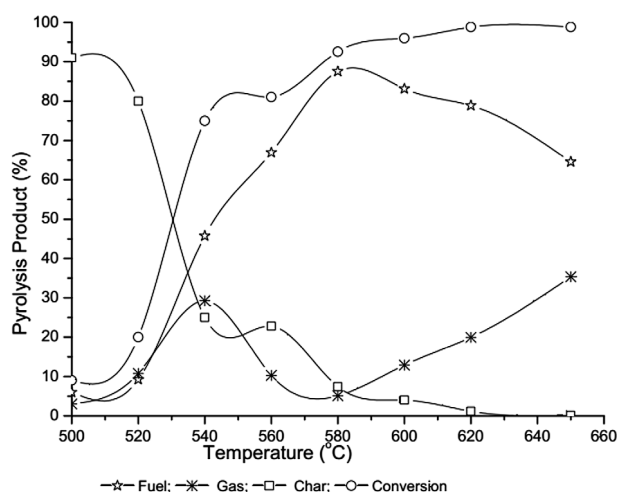
The quantity of gas and fuel oil yield has its conversion (wt.%) illustrated in Fig. 2 (—○—). There was an increase in the conversion of PP plastic waste from 9% (at 500 °C) to 99.87% (at 650 °C). Theoretically, the yield will increase alongside an increase in temperature due to the fact that the reaction rate is faster at high temperatures

Table 1

The product of distillation bubble cap column of each tray. Effect of temperature process.

Pyrolysis temperature (°C)	Product of distillation (ml Fuel/g PP)				Total product
	Tray I	Tray II	Tray III	Tray IV	
500	0.080	-	-	-	0.080
520	0.120	-	-	-	0.120
540	0.544	0.066	-	-	0.611
560	0.348	0.136	0.072	-	0.556
580	0.700	0.376	0.080	-	1.156
600	0.574	0.438	0.058	0.022	1.092
620	0.846	0.074	0.018	0.024	0.962
650	0.150	0.244	0.126	0.308	0.828

PP: Polypropylene; - : There e is no condensate

**Fig. 2.** The pyrolysis products (yield %wt) as a response of process temperature.

(Velghe et al., 2011). Therefore, as temperature increased, more heat was supplied to the polymer in order to weaken its chain structure, and this resulted in more polymer chains being cracked (Wong et al., 2017). However, to obtain liquid products such as fuel, optimum process conditions are required (Table 1). This research obtained optimum conditions for fuel oil at 580 °C (1156 ml fuel/g PP) or 578 ml fuel oil in 500 g PP. Under the optimum process conditions, PP polymers experience melting temperature (TM) at first, and then proceed to decomposition temperature (Td) conditions for the polymer bonds to form hydrocarbon compounds (monomers). These compounds then undergo degradation of thermal cracking recombination in order to form hydrocarbon products such as paraffins, olefins, naphtha and aromatic (PONA) (Anuar et al., 2016). Simultaneously, the combination of free radicals as a result of secondary reactions in stable hydrocarbon compounds also forms PONA compounds.

Process conditions above optimum, polymers experience cracking recombination and combination degradation to form hydrocarbon products such as PONA. Increasing temperature results in oligomeric cracking, i.e. in the primary reaction, there is a termination of imperfect polymer bonds (wax forming), and the secondary reactions of free radicals form short chain hydrocarbons (gas compounds are formed). As a result, the gas yield rises and yields fuel oil falls, as illustrated in Fig. 2. (—★— with —*—). Moreover, carbon residue rises together with the vapour due to heat and rising pressure in the reactor (ash content rises) (Barbarias et al., 2015). This is however responsible for the obtained low product quality in trays I to IV within the temperature range 620–650 °C. Condensate (fuel oil) cannot be used directly due to its high ash and wax content. The product came out looking brownish-black and

viscous, which is an indication that it needs to be recycled (Tables 4 and 5). (See Fig. 3.)

The vapour flows through the 4-tray distillation bubble cap plate column by utilising heat from the reactor, and this is due to the heat emanating from the reactor or vapour pressure which can condensate in the tray III at optimum conditions (580 °C). Whereas, at temperatures above the optimum conditions vapour can be condensate in tray IV, but a higher energy is required to obtain high ash and wax content (tray I and II), which will then require a cost to separate. In addition, various characteristics of the fuel obtained in accordance with the boiling point of each product are achieved. However, vapour which is left un-condensate in tray IV is processed using H₂O₂ 10% (v/v) in gas washing bottles to absorb acidic gas and CO₂ formed from pyrolysis before being discharged into the environment.

3.2. Physical properties and characteristics of oils

Fuel derived from pyrolysis is very similar to crude oil, and therefore cannot be directly used as fuel or other sources of energy, given that it must meet certain standard specifications to ensure the performance of the combustion engine. Plastic pyrolysis products are considered to be sources of hydrocarbons from petroleum in the form of naphtha products. As a result, the fuel characteristics of these products are modified to standard fuel products. It therefore needs to be refined, and this research made use of the distillation bubble cap plate column in doing so. As a result, a wide range of fuels obtained is expected to be used on an engine, in accordance with the characterisation of the fuel oil. The characterisation or specifications for standard fuels have been established by ASTM/IP or instrument tools that conform to ASTM standards.

3.2.1. Characterisation of oils by density

Density is one of the parameters indicating the characteristics of the product. A specific gravity was measured according to ASTM D 1298 standard at 60 °F. Table 2 shows fuel specification results of Distillation Bubble Cap Tray Column based on Specific Gravity, °API from Handbook of Petroleum Product Analysis (Speight, 2002).

Liquid fuel specification standard based on specific gravity or °API of Handbook of Petroleum Product Analysis is shown in Table 3. The obtained results demonstrated that the condensate fuel at different temperatures resulted in different types of fuel. The condensate fuel in tray I resulted in gasoline at temperatures of 500–560 °C, kerosene at temperatures of 580 °C and 600 °C, and diesel at temperatures of 620 °C and 650 °C. However, the condensate fuel on tray II yielded gasoline at temperatures of 540–620 °C and kerosene at the temperature of 650 °C. The condensate fuel on tray III resulted in gasoline at temperatures of 580–650 °C, and the condensate fuel on tray IV resulted in gasoline at temperatures of 600–650 °C.

Table 2

The fuel density of product through the distillation bubble cap column.

Pyrolysis temperature (°C)	Tray I			Tray II			Tray III			Tray IV		
	ρ_{60}	S.g ₆₀	°API	ρ_{60}	S.g ₆₀	°API	ρ_{60}	S.g ₆₀	°API	ρ_{60}	S.g ₆₀	°API
500	0.7512	0.7518	56.71	-	-	-	-	-	-	-	-	-
520	0.7520	0.7528	56.46	-	-	-	-	-	-	-	-	-
540	0.7512	0.7521	56.64	0.7457	0.7463	58.10	-	-	-	-	-	-
560	0.7608	0.7614	54.34	0.7248	0.7254	63.56	-	-	-	-	-	-
580	0.7756	0.7762	50.80	0.7457	0.7464	58.08	0.7121	0.7130	66.96	-	-	-
600	0.7789	0.7800	49.98	0.7453	0.7454	58.33	0.7163	0.7169	65.87	0.6910	0.6916	73.09
620	0.7853	0.7860	48.52	0.7221	0.7228	64.27	0.7252	0.7258	63.46	0.7184	0.7199	65.10
650	0.8241	0.8249	40.05	0.8082	0.8089	43.43	0.7707	0.7714	51.93	0.7383	0.7390	59.98

No. condensate












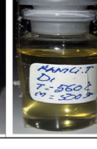
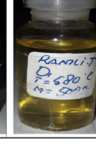



Tray	Temp. Process	500°C	520°C	540°C	560°C	580°C	600°C	620°C	650°C
Tray IV									
Tray III									
Tray II									
Tray I									

Fig. 3. Fuel products from plastic wastes integrated pyrolysis methods with distillation bubble plate column.**Table 3**

Specific gravity and API gravity of crude oil and selected products (Speight, 2002).

Material	S.G 60 °F/60 °F	API gravity, deg
Crude	0.65–1.06	87–2
Casinghead liquid	0.62–0.70	97–70
Gasoline	0.70–0.77	70–52
Kerosene	0.77–0.82	52–40
Lubricating oil	0.88–0.98	29–13
Residual and cracked residual	0.88–1.06	29–2

3.2.2. Characterisation of oils by kinematic viscosity

Viscosity is an important property of oil products which affects the handling or storage, pumping and burning (including the selection of burner types used) of these products. If the kinematic viscosity value is low, it will influence the oil fuel quality, giving it a low heating value (Lee, 2006).

Kinematic viscosity was measured according to ASTM D 445 standard at 40 °C. The values of the fuel kinematic viscosity of each tray are presented in Table 4.

It can be observed from Table 4 that the temperature pyrolysis and height of the column (tray) significantly affected the products' kinematic viscosity. The high process temperature pyrolysis accelerates the breaking of the polymer structural bonds. Moreover, under certain process conditions, the termination of the polymer

bonds is imperfect, and results in the vapour containing polymers due to the influence of pressure and temperature in the reactor. According to the presented data, the product has high kinematics viscosity at condensate tray I and II at temperatures of 620 °C and 650 °C. The results of the kinematic viscosity analysis shown in Table 4 indicate that fuel oil products obtained through the distillation bubble cap plate column possess similar properties with those of fossil fuels. It is in accordance with the characteristics of kerosene and gasoline in the process conditions of 500–600 °C, while above the temperature optimum is obtained by diesel, kerosene, and gasoline in the process conditions of 620–650 °C.

3.2.3. Characterisation of oils by ash content and wax

The ash content is the amount of impurities in the form of burning ash. During pyrolysis, there is a decomposition of plastic polymers which produces vapour and char. The ash content is carried by vapour, and this can diminish the quality of fuel products as regards the nature of fuel cleanliness which can have consequences on the performance combustion engines. Ash content from each tray is shown in Table 5.

From Table 5, it can be observed that ash acquisition content for tray I, met the standards at 500 °C and 520 °C, tray II met the standards at 540 °C and 600 °C, tray III met the standards at 580 °C and 600 °C, and tray IV met the requirements at 600–650 °C. This is due to the lack of oxygen entering the reactor (vacuum process conditions), and as a result, there is no oxidation reaction in

Table 4

The fuel kinematic viscosity (40 °C) of distillation bubble cap column product and standards parameter (ASTM Standards, 2008; Petroli Agip, 2000; Sharma et al., 2014).

Pyrolysis temperature (°C)	Kinematic viscosity at 40 °C (mm ² /s)				Standard Kinematic viscosity at 40 °C		
	Tray I	Tray II	Tray III	Tray IV	Gasoline (mm ² /s)	Kerosene (mm ² /s)	Diesel (mm ² /s)
500	0.652				1.3–2.4	1.4–3.0	1.9–5.5
520	1.006						
540	1.121	0.897					
560	1.578	0.960					
580	2.445	1.080	0.92				
600	2.850	1.236	1.11	0.450			
620	3.150	1.590	1.26	0.666			
650	4.140	1.860	1.46	1.044			

Table 5

The ash content of distillation bubble cap column product and standards parameter ASTM Standards, 2008.

Pyrolysis temperature (°C)	Ash content (% w/w)				Standard ash content, %wt	
	Tray I	Tray II	Tray III	Tray IV	Light Oil	Heavy Oil
500	0.01				0.015	0.15
520	0.01					
540	0.02	0.008				
560	0.02	0.011				
580	0.03	0.012	0.005			
600	0.32	0.014	0.005	0.011		
620	0.39	0.022	0.018	0.002		
650	0.39	0.026	0.025	0.022		

the reactor. The effect of pyrolysis temperature on the ash content of each product shows the tendency that an increase in pyrolysis temperature will lead to an increase in the ash content of each tray. This can be attributed to an increase in temperature and pressure which allows carbon from the pyrolysis process to carry vapour in column distillation (620–650 °C). Fuel is classified as low-quality when it contains ash and wax. The ash content from plastic degradation residues appears in form of carbon residue. However, it is very important for the ash content to not exceed the standard set, because if it does, it could damage the internal combustion engine piston when used as fuel. The high wax content is as a result of the imperfect breaking of the polymer structural bonds which is due to the high temperature. The of wax formation on the research at the temperature 620–650 °C. This is an effect of fuel oil clogs present in the capillary fuel pipe which transports fuel into the combustion engine.

3.2.4. Characterisation of oils by calorific value

One of the important properties of fuel is its calorific or heating value, which is defined as the energy given when the fuel mass unit is burned without sufficient air. The equipment employed in determining these calorific values was calorimeter 5E-C5500 Series Digital in accordance with ASTM D-4809. The calorific values of each tray as shown in Table 6 were similar to those reported by Silvarrey and Phan (2016) which were within the range of 44–48 MJ/kg. These values were also similar to heating values of conventional fuel/petroleum and fuel oil product from plastics pyrolysis reported by many studies which are within the range of 33.6–53.4 MJ/kg, depending on the original plastic polymer composition (Anuar et al., 2016). The production of liquid fuel from plastic waste using this method is therefore feasible to be applied.

3.2.5. Characterisation of oils by octane and cetane numbers

The octane number is a measure of a fuel's ability to resist 'knock.' The octane requirement of an engine varies with compression ratio, geometrical and mechanical considerations, and operating conditions. The higher the octane number, the greater the fuel's resistance to knocking or pinging during combustion. The anti-knock or octane quality as indicated by the Research and

Motor Octane numbers (RON and MON), is an essential property of fuel. Generally speaking, the anti-knock quality of a fuel in a given engine operating condition is defined by its octane index $OI = RON - KS$ where K is a constant for that condition, and S is the sensitivity ($RON - MON$). The higher the octane index, the better the anti-knock quality of the fuel. K is often assumed to be 0.5 so that $OI = (RON + MON)/2$ (Kalghatgi, 2001). Cetane number (CN) on the other hand, is an empirical parameter associated with the ignition delay time of diesel fuels (Cataluña and Da Silva, 2012). Octane and cetane numbers were measured using portable octane metre, Kohler K88600 instrument. Test results were equivalent to ASTM D2699 and D2700 for octane number of gasoline, and equivalent to ASTM D613 for cetane number of diesel fuel. Octane and cetane numbers from each tray and standards parameter are shown in Table 7.

Table 7 indicates that the octane number is significantly influenced by the temperature and tray position. The higher the pyrolysis temperature, the lower the octane number for each tray and the compounds become non-volatile (the lower the boiling point). This is due to the formation of branched, aromatic and polycyclic aromatic compounds (aromatic groups, naphtha and isoalkanes), whereas at high temperatures, non-volatile compounds such as long-chain olefins and n-paraffins are formed, and this increases the cetane number value (Blazso, 2006). High octane numbers are better for internal engine combustions, but aromatic groups cannot be tolerated by the environment due to the fact that it is difficult to degrade. As a result, the aromatic content (40%, v/v) which is the maximum limit in fuel oil was derived by using the method ASTM D 1319 (Petroli Agip, 2000).

4. Conclusion

A study has been conducted to investigate the effects of temperature and optimise liquid products through refinery distillation bubble cap plate column. There are differences in liquid fuel characterisation yielded on each tray depending on the pyrolysis temperature. The type of fuel is based on an analysis of the characterisation of any condensate. Fuel condensate on tray I at temperatures of 500–560 °C, 580–600 °C, and 620–650 °C yielded

Table 6

Fuel calorific value of distillation bubble cap column product and standards parameter of gasoline, diesel and kerosene (Mabood et al., 2010; Naima and Liazid, 2013).

Pyrolysis temperature (°C)	Calorific value (MJ/kg)				Standard Calorific value (MJ/kg)		
	Tray I	Tray II	Tray III	Tray IV	Gasoline (MJ/kg)	Kerosene (MJ/kg)	Diesel (MJ/kg)
500	47.205				45.6	46.5	43.5–55.7
520	46.289						
540	46.944	46.006					
560	46.441	46.503					
580	46.851	46.561	46.745				
600	46.823	47.205	46.312	46.347			
620	45.154	46.334	46.214	46.9			
650	44.945	46.319	46.316	47.231			

Table 7

Effect of pyrolysis temperature on octane and cetane numbers of each tray and standards parameter of gasoline, kerosene, and diesel (Scheirs, 2006).

	Pyrolysis temperature (°C)						Standards octane/cetane number	
	540 Tray I	560 Tray I	580 Tray I	600 Tray I	600 Tray II	650 Tray IV	Gasoline ASTM D 2699	Diesel ASTM D613
Gasoline								
RON	97.1	97.2	89.1	88.7	92.2	93.8	90.2 – 107.1	
MON	83.7	83.5	81.8	81.5	84.0	85.0	82.6 – 103.1	
(R+M)/2	90.4	90.3	85.4	85.1	88.1	89.4	87.3 – 105.1	
Diesel								
CN	1.70	0.00	45.50	45.50	48.00	48.70		Min. 30

liquid fuels with specifications of gasoline, kerosene, and a mixture of diesel and polymer PP (wax), respectively. Fuel condensate on tray II at temperatures of 540–620 °C and 650 °C yielded liquid fuels with specifications of gasoline and kerosene, respectively. Fuel condensate on tray III at temperatures of 580–650 °C yielded gasoline, and fuel condensate on tray IV at temperatures of 600–650 °C yielded gasoline. The characteristics of fuel obtained from plastic such as density, viscosity, octane–cetane number, ash content and calorific value have similar properties with those of fossil fuels. Based on the characteristic analysis, fuel oil from plastic waste through Integrated Pyrolysis Method with Refinery Distillation Bubble Cap Plate Column can be used directly for engine or transportation fuel for gasoline type and kerosene, while the diesel fuel is recycled again to meet specifications of fuel oil.

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