

Effect of Residence Time on Liquid Product Yield through a Designed Pyrolysis Reactor with Six Series-Connected Condensers

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Abstract

The objective of this study was to investigate the effect of residence time on the product yields of multilayer plastic (ML) waste through pyrolysis using a household reactor. The system employed six series-connected condensers operating without cooling water for heat transfer. The research focused on determining the optimal residence time within the range of 60–120 min, with a heating rate of 5–15°C/min. Liquefied petroleum gas (LPG) served as the primary fuel for the pyrolysis process, while non-condensable gases were recirculated into the burner as supplementary fuel. The study analyzed the characteristics and quantities of the resulting products: solid residue, liquid oil, and non-condensable gases. The results indicated that the proportion of non-condensable gases ranged from 27.1% to 47.1%, while the liquid yield condensed from four of the six condenser tubes varied between 46.5% and 59.1%. The pyrolysis of ML waste produced solid residue ranging from 6.8 % to 13.8 % of the total products. The residence time significantly influenced the liquid yield, with the maximum liquid product of 591 g per 1 kg of ML feedstock obtained at a residence time of 60 min. To characterize the liquid product as biofuel oil, its chemical composition was analyzed using distillation gas chromatography (DGC) and gas chromatography-mass spectrometry (GC/MS). The analysis revealed that the liquid product contained fuel oil components, including kerosene, diesel oil, benzene, and fuel oil. Additionally, the liquid product exhibited a high heating value of 10,691 cal/g. Furthermore, substituting pyrolysis gas for LPG significantly reduced LPG consumption. This study provides valuable insights into the development of community-based pyrolysis systems.

Keywords: Condensation, Fuel oil, Multilayer plastic, Pyrolysis

1. Introduction

Synthetic plastic is a high-molecular-weight hydrocarbon compound synthesized from small hydrocarbon molecules, known as monomers, which are connected into long-chain structures called polymers through the process of polymerization. Most hydrocarbon compounds used in plastic production are derived from petroleum, which undergoes cracking to break down larger hydrocarbon molecules into smaller compounds that serve as precursors in the production of plastic. The world's first synthetic plastic, Bakelite, was invented by Leo Baekeland in 1907, marking the inception of the plastic industry and its subsequent global expansion [1].

Today, plastic is an indispensable material, as it can be molded into a wide variety of forms, including packaging, containers, plastic bags, water bottles, furniture, and medical equipment. Its popularity stems from its lightweight nature, high flexibility, toughness, corrosion resistance, and relatively low cost. Additionally, plastic is available in both translucent and transparent forms. Thailand currently consumes a vast quantity of plastic, particularly in the form of packaging materials such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and polyethylene terephthalate (PET). However, plastic presents a significant environmental challenge, as its long decomposition time and increasing accumulation have

led to global concerns. Incineration of plastic waste releases harmful pollutants into the atmosphere, while landfill disposal risks contaminating marine environments.

The recycling process is employed to reintroduce waste plastic into new production cycles, thereby reducing the consumption of petroleum, the primary raw material in plastic production, and minimizing residual plastic waste. However, recycling involves several steps—such as sorting, washing, and melting—which are less suitable for low-density polyethylene (LDPE) or mixed plastics [2], commonly known as multilayer plastics. Consequently, these types of plastics persist in the environment. Research has facilitated the development of various plastic disposal techniques, particularly those that convert waste into energy. These methods include pyrolysis, incineration, gasification, and liquefaction. Pyrolysis, a thermal decomposition process conducted at high temperatures in the absence of oxygen [3], breaks down plastic waste through chemical and thermal reactions. This process yields solid residue such as carbon black, non-condensable gases (some of which are flammable), and liquid fuels [4–6].

Catalysts are employed in high-temperature pyrolysis of plastic waste, in the absence of oxygen, to break down long-chain polymers into simpler molecules, typically within a temperature range of 300–900°C [7],[8]. The

vapors produced during pyrolysis are condensed into liquid products. The primary products of this process include gases, liquid pyrolysis oil (crude oil), and solid residue. Pyrolysis oil, a hydrocarbon compound with a high boiling point, is chemically similar to crude oil [5]. Co-pyrolysis with other materials, such as coal or lignite, can enhance the yield and quality of the products. The quantity and composition of the pyrolysis products depend on several factors. A study conducted on the pyrolysis of plastic types, such as bottles, yogurt cups, and polystyrene packaging (5–8 mm in size, 50 g in quantity), was performed in a laboratory setting using a round-bottom flask. The pyrolysis temperature ranged from 200°C to 441°C, with clay as a catalyst. The results demonstrated that temperature significantly influenced product yields. For instance, pyrolysis of high-density plastic at 300°C produced an 87.1% liquid yield. However, when the temperature increased to 441°C, the liquid yield decreased [4].

The pyrolysis of polystyrene plastic is typically conducted at 400°C [9], while polyethylene terephthalate (PET) undergoes pyrolysis at around 500°C [10]. In general, the residence time during pyrolysis ranges from 60 to 150 min, and achieving complete plastic decomposition requires an appropriate residence time. However, prolonged durations can lead to secondary cracking of the pyrolysis vapors, resulting in a higher proportion of gas relative to liquid [11]. The size of the plastic also influences heat transfer rates during the pyrolysis process. Additionally, factors such as the type of plastic, pressure, condensation rate, heating rate, and reactor type significantly affect the product yield. Most laboratory pyrolysis research is conducted using batch reactors, which process raw materials in a single batch and often use catalysts to improve product quality. Pyrolysis is primarily employed to convert plastic waste into liquid fuel, which can then be refined to enhance its quality or blended with other fuels for specific applications, resulting in the production of fuel oil. The liquid product typically contains alkanes, phenols, benzenes, and ketones [12]. Research on the pyrolysis of single-use and mixed plastics has shown that polyethylene and polypropylene, as feedstock, yield 44.2% paraffins and 44.7% olefins, respectively [13]. The heating value of polyethylene and polypropylene is approximately 9,553–10,270 cal/g [14], which is comparable to that of crude oil. Refining pyrolysis oil is essential to produce valuable fuels such as benzene, kerosene, naphtha, and diesel [12].

This research focused on the plastic pyrolysis process without the use of a catalyst to produce liquid fuel. A household-scale pyrolysis reactor with a 50 L capacity was employed for the experiments. The objective was to investigate the pyrolysis of ML plastic waste, which is non-recyclable and has limited value as feedstock, for liquid fuel production. The pyrolysis system incorporated a series of condensers to condense the pyrolysis vapor into liquid fuel without requiring cooling water or other cooling agents. Residence time ranging from 60–120 min was explored, using liquefied petroleum gas (LPG) as the

heat source and non-condensable gases recirculation system into the burner as an alternative energy source. Following the completion of the pyrolysis process, the quantities and properties of the resulting products were thoroughly analyzed.

2. Materials and Methods

2.1 Materials preparation

Plastic waste was collected from an open drum containing municipal solid waste, which primarily consisted of 40% organic waste, 25% plastic, 8% paper, and small amounts of metal, glass, and garden waste. The composition of the municipal solid waste was analyzed using the quartering method, based on the ASTM D5231-92 standard. Plastic waste thoroughly cleaned with water to remove any contaminants. The cleaned feedstock was then used for liquid fuel production via the pyrolysis process. The sorted plastic consisted of multilayer plastic packaging, which included various layers and types of plastics such as candy wrappers (20%), foil pouches (80%). Different types of plastics were used together without any distinction based on brand. For the 1 kg pyrolysis experiment, the plastics were cut into pieces approximately 4 × 4 cm in size (Figure 1).



Figure 1 ML packaging as feedstock with raw material size of 4 × 4 cm.

2.2 Pyrolysis reactor

The batch pyrolysis reactor, which introduced feedstock into the process at a single point, featured a 50-liter reactor tank made of carbon steel with a diameter of 35 cm, a height of 58 cm, and a thickness of 0.5 cm. The reactor was covered with a 0.2 cm thick steel plate, which had dimensions of 61 cm in width, 61 cm in length, and 71 cm in height. Ceramic fiber insulation was implemented throughout the interior. The system included a steel fractionation tube setup comprising six condensers arranged in series, each with a diameter of 10 cm and a length of 70 cm. The condenser tubes were installed in a three-tier configuration, with two tubes per tier placed parallel to each other. Each tube was equipped with valves at the ends for control (Figure 2). Condensation was achieved by allowing pyrolysis vapor to contact the inner surfaces of the tubes, without the use of cooling agents in the condensation system. The vapor condensed into a liquid product based on the boiling point temperature of the product entering the condenser tubes. The reactor was heated by a burner fueled with liquefied petroleum gas (LPG), and a system was installed to

measure the fuel flow rate. Additionally, a gas feeding system was integrated into the combustion chamber to utilize pyrolysis gas, derived from the thermal degradation of plastics, as a replacement for LPG. A pressure gauge and vacuum pump, operated by a 1/4 hp motor, were installed to create and maintain vacuum conditions. Temperature sensors (thermocouples) were placed at various points, including the outside reactor wall, the pyrolysis gas inlet, and the condenser tubes.

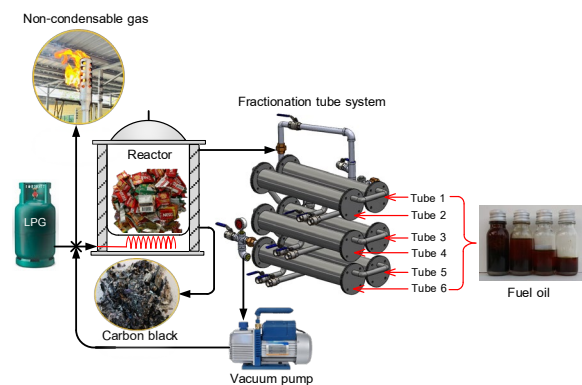


Figure 2 Pyrolysis reactor with conjunction to fractionating condenser tube.

2.3 Experimental investigation of pyrolysis

The liquid product was produced through the pyrolysis of plastic waste by feeding the feedstock into the reactor from the top and sealing the lid tightly with M16 hexagon-headed screws. Before each experiment, the vacuum condition was established to ensure proper operation of the vacuum pump system and to inspect the reactor for leaks. The fuel gas system was then activated to deliver gas to the burner. The temperature was maintained between 350–500 °C with a heating rate of 5–15 °C/min to induce the structural breakdown of the polymer into pyrolysis vapor. The pyrolysis vapor was subsequently directed into the condensation system.

The study investigated the impact of residence time at 60, 80, 100, and 120 min. The duration of the experiment for the residence time investigation was recorded from the initiation of the heating process. Following a 30 min heating period in the reactor, a flame was ignited in the exhaust gas pipe to combust some of the gas produced during pyrolysis. A comparison was made between reverse pyrolysis vapor (non-condensable gases) and fuel sourced from LPG (non-reverse pyrolysis vapor method), where only gas was used as fuel. For reverse pyrolysis vapor, the system was opened after gas flaring. Temperatures were recorded at 5 min intervals until the end of the process. Upon completion of the experiment, the valve for liquid oil collection was opened, and the yield percentage (%yield) was calculated. The percentage of non-condensable gases was calculated based on the percentages of liquid oil and solid residue. Quantities of liquid, solid, and non-condensable gases products were documented, along with data on LPG consumption during the pyrolysis

process. In order to ensure the reliability and precision of the results, the experiment was conducted three times.

2.4 Products analysis

Samples of liquid oil, solid residue, and non-condensable gases products were collected. The weights of the liquid and solid products were recorded to determine the yield percentage (%yield). Non-condensable gases were quantified using a standard formula. The properties of the solid residue were examined by analyzing their surface characteristics with an electron microscope and by identifying elements and compounds using Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM/EDX). The structure of the solid residue was analyzed using X-ray diffraction (XRD) with an Empyrean, PANalytical system (40 kV, 30 mA, wavelength 0.154 nm (CuK α), Scan range 2 θ 5–90°, Step size 0.026°, time/step: 70.125 sec) in the Netherlands.

The properties of the liquid oil were analyzed by elemental analysis (carbon, nitrogen, hydrogen, and sulfur) using a CHNS/O Analyzer, Flash 2000 by ThermoScientific in Italy. The chemical components and their proportions in the liquid oil were determined using Gas Chromatography-Mass Spectrometry (GC/MS) with a GC7890B / MSD 5977B system by Agilent Technologies in the USA. Samples were prepared by diluting 10 times with dichloromethane, filtering through a 0.22 μ m nylon membrane, and confirming the fuel composition using a Distillation-GC (DGC) apparatus. Thermal properties were also analyzed.

3. Results and Discussion

3.1 Effect of residence time on pyrolysis products

ML was used as feedstock in a 50-liter pyrolysis reactor. Pyrolysis vapor was generated through thermal decomposition and transferred from the reactor into a six-tube fractionated condensation unit to produce liquid product. The condenser tubes were labeled Tube 1 through Tube 6. The thermal decomposition temperature of ML materials was observed to range from 260°C to 440°C [15]. Direct measurement was used to determine the weight of the liquid oil. The weight of the non-condensable gases yield was calculated by subtracting the weight of the liquid oil product and solid residue from the weight of the loaded feedstock [16]. The calculation showed that the mean yield values from a minimum of three trials conducted with identical experimental setups fell within the experimental error range of less than $\pm 2\%$.

The effects of residence time, ranging from 60–120 min, were investigated using LPG gas as fuel, without recycling the pyrolysis gas back into the combustion system. The experiment identified three main types of products: solid residue, liquid oil, and non-condensable gases. The quantities of the products were as follows: non-condensable gases ranged from 27.1% to 47.1%, liquid oil from 46.5% to 59.1%, and solid residue from 6.8% to 13.8%. The product quantities are illustrated in **Figure 3**.

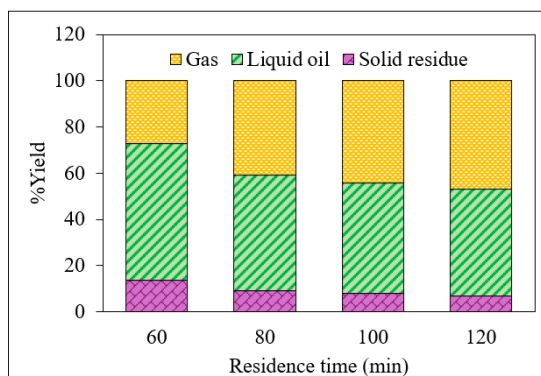


Figure 3 Pyrolysis products from pyrolysis of ML plastic waste.

The fractionating condenser tube successfully condensed the pyrolysis vapor through the condensation tubes, separating it into distinct liquid products. The experiment revealed that the pyrolysis vapor condensed into liquid products through four condensation tubes (Tubes 1–4). The liquid condensed through Tube 1 was highly viscous, appearing as a thick, dark black liquid similar to crude oil, and was produced in larger quantities compared to the other tubes. The liquid product from Tube 2 was brown, while the liquids from Tubes 3 and 4 were lighter shades of brown. The quantities of liquid products from all four tubes, influenced by the pyrolysis residence time, are depicted in **Figure 4**.

In the experiment conducted by Hariadi et al. [17], the pyrolysis of low-density polyethylene (LDPE) produced brown-colored liquid products. The composition of the liquid oil influenced its color [18]. The liquid oil yield was influenced by the plastic type, pyrolysis temperature, and residence time [7],[17]. The study demonstrated that residence time directly influenced the total quantity of liquid products. An increase in residence time inversely affected the total liquid quantity of liquid products, resulting in a decrease in the overall liquid yield. The experiment with a residence time of 60 min yielded the highest total liquid product, approximately 591 g. This result demonstrated a higher liquid yield compared to non-condensable gases and the lowest solid residue, consistent with the findings of Hariadi et al. [17]. The pyrolysis experiment on LDPE plastic revealed that the maximum liquid product yield was achieved at a residence time of 60 min [17]. However, increasing the residence time to 80 min decreased the total liquid product to 500 g, while the quantity of non-condensable gases increased. At residence time of 100 min and 120 min, the total liquid product decreased further to 478 g and 465 g, respectively. This was the result of the excess secondary reactions that occurred during extended pyrolysis times, which led to a decrease in the rate of polymer degradation into hydrocarbon bonds. Therefore, it was determined that pyrolysis with a residence time of 60 min was suitable to produce liquid oil.

The liquid products from Tubes 1-4, based on residence time, are shown in **Figure 5**. This trend corresponded with a decrease in the amount of solid residue as residence time increased. The solid obtained during the study appeared as glossy black solids.

At a residence time of 60 min, the solid residue amounted to 138 g. This decreased progressively to 91 g, 81 g, and 68 g at residence times of 80, 100, and 120 min, respectively (**Figure 6**). For the non-condensable gases, the experiment found that an increase in residence time correlated directly with an increase in the amount of gas product. At a residence time of 60 min, the amount of gas products was the lowest, approximately 271 g. As the residence time increased, the gas product quantity increased to 409 g, 441 g, and 467 g, respectively. The experimental results showed that the quantity of gas products was inversely related to the quantities of liquid and solid products; as the amount of gas products increased, the amounts of liquid and solid products decreased. This may be due to the prolonged heating time causing the pyrolysis vapor remaining in the reactor to continue receiving heat, resulting in rapid secondary cracking, which produced more non-condensable vapor instead of vapors that could condense into liquid. Additionally, uncontrolled heating rates caused the volatiles to rapidly crack into vapors [11], leading to an increased amount of non-condensable vapor and a decrease in the total liquid product.

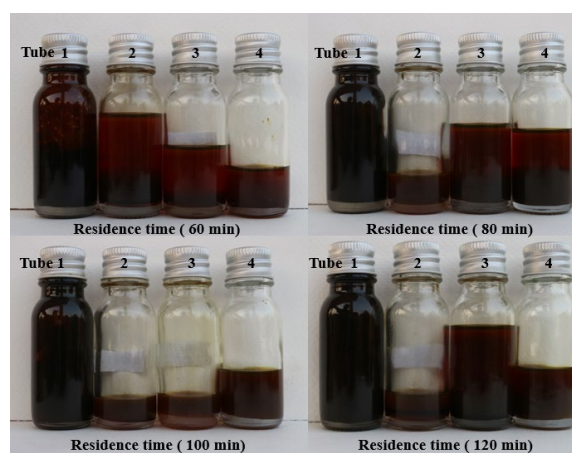


Figure 4 Liquid oil products from pyrolysis of ML plastic waste at different residence times.

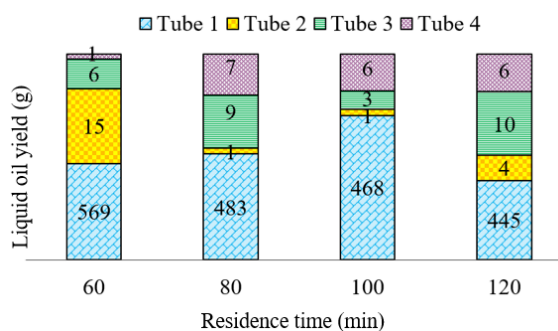


Figure 5 Liquid oil product from fractionating condenser tube.

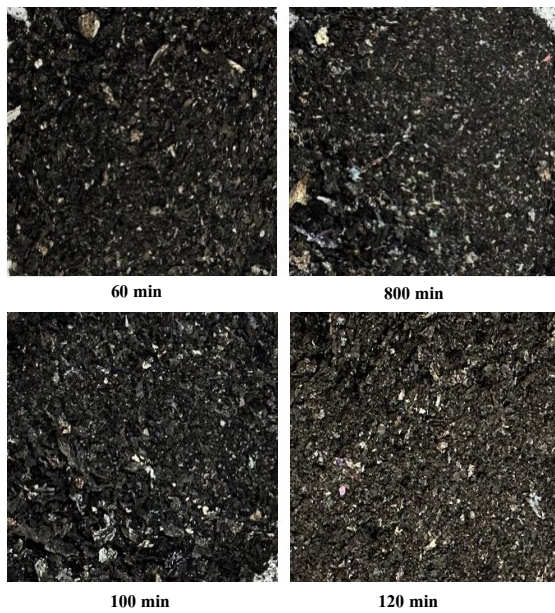


Figure 6 Solid residue from pyrolysis of ML plastic at different residence times.

3.2 Effects of residence time on temperature at measurement points

From recording temperatures during the pyrolysis process at residence time of 60–120 min, measurements at the outside reactor wall (T1), the pyrolysis gas outlet (T2), and the condensation tube at Tube 1 and Tube 2 (T3 and T4) revealed that the outside reactor wall temperature (T1) continuously increased at every studied time interval. The temperature increased rapidly after 25 min of residence time, consistent with the increased temperature of the pyrolysis gas outlet, which measured the temperature of the hot vapor flowing from the reactor. The residence time for the pyrolysis process affected the outside reactor wall temperature. At 60 min, the outside reactor wall temperature was approximately 191°C, which increased to 308°C, 318°C, and 319°C when the residence time was increased to 80, 100, and 120 min, respectively. This corresponded to the increasing temperatures of the pyrolysis gas outlet over time.

At 60 min of residence time, the pyrolysis gas outlet temperature was about 161°C, which increased to 185°C, 175°C, and 181°C as the time was increased to 80, 100, and 120 min, respectively. Regarding the temperature of Tube 1 (T3) of the condensation tube, at the beginning of the process, the temperature matched the ambient conditions. However, as time increased, the volatiles cracked into hot vapor or pyrolysis gas, causing the temperature of Tube 1 to rise. At 60 min, the temperature was approximately 67°C, and Tube 4 (T4) had a temperature of about 52°C, close to the temperatures at 80, 100, and 120 min, which were approximately 65°C, 49°C, and 52°C for Tube 3 (T3), respectively. T4, representing the temperature of Tube 2, decreased slightly to around 60°C, 43°C, and 45°C at residence time of 80, 100, and 120 min, respectively (Figure 7). The result was consistent with the experiments conducted by

Suryadimal et al [19]. The combustion of plastic waste was studied, and condensation was achieved using a three-level condenser. At 90 min, the surface temperature was recorded as 52.7°C [19]. At room temperature, the pyrolysis vapor condensed to form a liquid fraction.

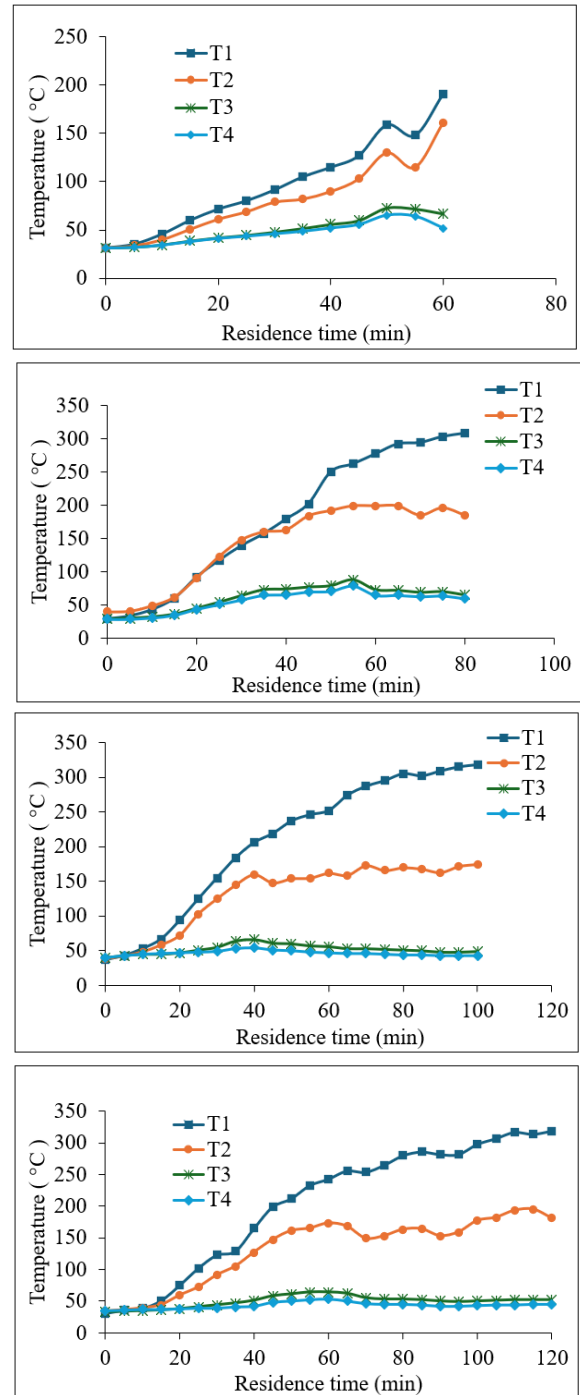


Figure 7 Temperatures recorded at different residence times (60–120 min).

3.3 Effect of pyrolysis gas recirculation

The maximum liquid product was produced at 60 min of residence time; consequently, this condition was selected to determine the properties and examine the

influence of pyrolysis gas recirculation. The pyrolysis process involved molecular breakdown when heat was applied to the polymer, resulting in hot vapor or pyrolysis gas when (LPG) was used as fuel. Fuel properties and flammability were exhibited by a portion of this vapor, which was unable to condense into liquid. Consequently, an experiment was conducted to incorporate the pyrolysis gas flow into the combustion system as a substitute for LPG gas. As the fuel pyrolysis gas was injected into the burner at a residence time of 60 min, the consumption of LPG was reduced from 0.9 kg to 0.6 kg in the pyrolysis gas recirculation experiment (**Figure 8**). The comparison based on residence time revealed an increase in LPG fuel gas consumption. Solid residue, liquid oil from the condensation tubes of the four tubes, and non-condensable gases were the products of the process. Pyrolysis vapor was generated during the primary decomposition and secondary cracking of the feedstock. This vapor contained low molecular weight gases that did not condense during the cooling process, collectively referred to as non-condensable gases. The non-condensable gases were identified as a mixture of various combustible gases, with their main components being CO, CO₂, H₂, CH₄, and linear hydrocarbons. It possessed a significant calorific value, and its flammable composition was utilized as fuel [4–6], [20]. Recirculating the pyrolysis gas into the burner as fuel resulted in a reduction of approximately 16.3% in the total liquid product when compared with the total liquid products at different residence times without using fuel pyrolysis gas in the burner. There was an increase in non-condensable gases, which might have been due to the heat entering the uncontrolled pyrolysis gas inlet; the gas flow rate depended on the raw material decomposition rate into fuel gas. This resulted in inconsistent and insufficient heat input into the process to fully break down the raw material into a condensable pyrolysis gas, leading to a decrease in the total liquid product. The reduced rate of heating due to the use of returned pyrolysis gas as fuel resulted in a decrease in the reactor temperature. The result corresponds to the study from Prurapark, et al. [21] which reported that the analysis of pyrolysis oil from HDPE as a raw material revealed a decrease in oil production due to pyrolysis at lower temperatures.

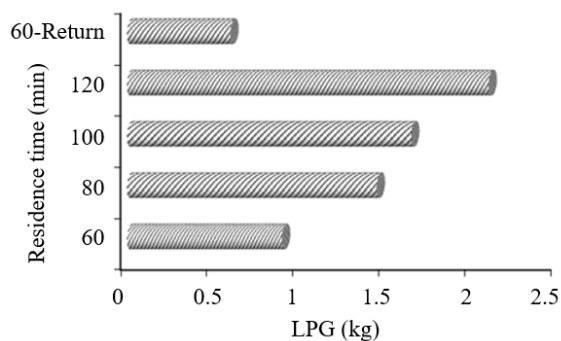


Figure 8 Quantity of LPG used as fuel gas in the pyrolysis process.

3.4 Analysis of solid residue

The surface morphology analysis of solids residue from the pyrolysis process at 60 min of residence time was compared with solids from the pyrolysis process that recirculated the non-condensable gases into the burner system. This was analyzed using a scanning electron microscope (SEM) at magnifications of 10,000x and 30,000x (**Figure 9**). It was found that the surface structure and shape were similar, with the external structure being small spherical particles of comparable size. Distinct spherical shapes were observed clustering together, all smaller than 2 μm . The external surface morphology of the solid from the pyrolysis of ML plastic displayed structural characteristics different from those of solid residue produced from polypropylene plastic through the pyrolysis process [22].

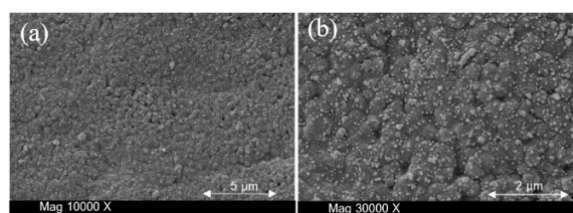


Figure 9 SEM images of solid residue at residence time of 60 min (a) using LPG fuel (b) recirculation of pyrolysis vapor into the burner.

The X-ray diffraction (XRD) technique was employed to analyze the crystalline structure of solid residue produced from the pyrolysis of mixed plastics with a residence time of 60 min. **Figure 10** illustrates the X-ray diffraction pattern. Rutile was the crystalline structure of titanium dioxide (TiO₂) observed at a peak angle of $2\theta = 27.53$, with a d-spacing of 3.23 and a full width at half maximum (FWHM) of 0.15. Furthermore, polyethylene (C₂H₄) compounds were identified at peak angles of $2\theta = 21.55$ and 23.90 , with d-spacings of 4.12 and 3.72, and FWHMs of 0.20 and 0.17, respectively. Additionally, the structures of magnetite (Fe₃O₄), quartz (SiO₂), and aluminum (Al) were identified.

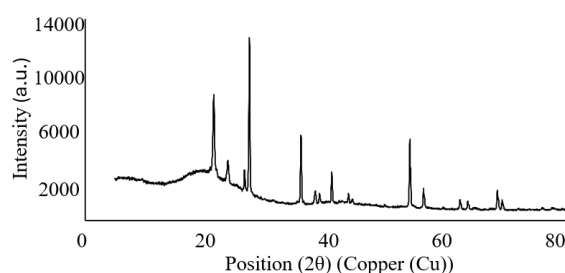


Figure 10 XRD pattern of solid residue from pyrolysis of ML plastic waste.

The SEM/EDX techniques were employed to analyze the crystalline structure of solid residue generated from the pyrolysis of ML plastic waste with a residence time of 60 min (Figure 11). The elemental composition found was carbon (C) 79.8%, oxygen (O) 11.0%, titanium (Ti) 6.5%, aluminum (Al) 1.4%, silicon (Si) 0.7%, calcium (Ca) 0.4%, and the smallest amount, iron (Fe), at 0.1% by weight, as illustrated in Table 1. These experimental results were consistent with the X-ray diffraction analysis, which identified compounds of TiO₂, SiO₂, Fe₃O₄, and Al in the crystalline structure. The pyrolysis of multilayer plastic waste produced solid residue that contained inorganic compounds, likely due to the presence of these compounds in the additives, fillers, or pigments used in the plastic materials. A combination of different polymers composes many multilayer plastics, with some layers potentially containing inorganic compounds. Pyrolysis may not fully degrade these inorganic compounds, leaving them as part of the solid residue product after the plastic material undergoes thermal decomposition.

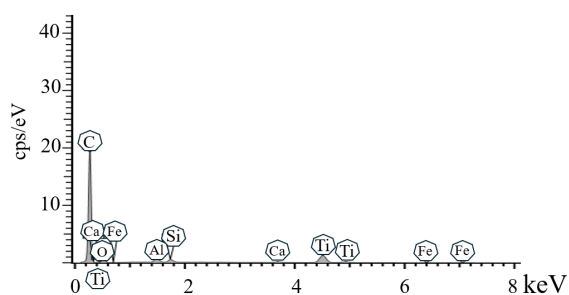


Figure 11 SEM/EDX analysis of solid residue particles.

Table 1 The elements in the solid residue particles by using SEM/EDX technique.

Element	Value (w%)
Carbon (C)	79.8
Oxygen (O)	11.0
Titanium (Ti)	6.5
Aluminum (Al)	1.4
Silicon (Si)	0.7
Calcium (Ca)	0.4
Iron (Fe)	0.1

3.5 Liquid oil properties

The analysis results of the liquid product sample from the experiment exhibited the highest total liquid product quantity at the experimental condition of 60 min of residence time. The liquid sample product from Tube 3 was analyzed by the CHNS/O Analyzer on a dry basis and ash-free, the oxygen content was calculated by subtracting the sum of the C, H, N, and S elements from 100%. The results revealed that the highest carbon component was 83.6%, followed by hydrogen and a small amount of nitrogen. Calculations

for oxygen quantity indicated approximately 2.9% by weight. The analysis results are shown in Table 2.

Table 2 CHNS/O Analyzer of liquid oil.

Element	Value (wt%, db)
Carbon (C)	83.6
Oxygen (O)	2.9
Nitrogen (N)	0.1
Hydrogen (Al)	13.1
Sulphur (S)	0.0

The results of the compositional and proportional analysis using Gas Chromatography-Mass Spectrometry (GC/MS) showed that the liquid sample condensed in Tube 3 (Figure 12) contained various chemical components as detailed in Table 3. The chemical composition of the liquid product was consistent with the study by Lakshmana et al. [23], which investigated the chemical composition of liquid from plastic waste and found components such as octadecane, heptadecane, and nonadecane [23].

Analysis of the quantity, proportions, and types of oil using Distillation Simulation Gas Chromatography (DGC), model GC7890A by Agilent, confirmed the fuel properties of the product. It was found that the liquid product obtained from the condensation of pyrolysis vapor was a fuel oil consisting of 38% gasoline, 22% kerosene, 27% diesel, and 13% fuel oil by weight, consistent with previous reports [12]. The high content of fuel oil, also known as residual oil, resulted in the brown color of the liquid. The diesel content of only 27% by weight may have been due to insufficient heating during the pyrolysis process to break down the pyrolysis vapor structure into diesel.

The obtained liquid fuel had a higher heating value (HHV) or gross heating value (GHV) of 10,691 cal/g and a net heating value (NHV) of 9,988 cal/g. The net heating value represents the net thermal energy per unit of liquid fuel by subtracting the heat loss required to evaporate water during combustion. The energy yield of the liquid product from the process was calculated using Eq. (1), and the energy yield of the product (%) was calculated using Eq. (2).

$$E_0 = \frac{HHV_0 \times W_0}{1000} \tag{1}$$

where:

E_0 = Energy of the liquid product (MJ)

W_0 = Quantity of the liquid product (g)

HHV_0 = Higher heating value of the product (MJ/kg)

$$EY = \frac{E_0}{E_{plastic\ waste}} \times 100 \tag{1}$$

where:

$E_{plastic\ waste}$ = Energy of the input (MJ)

EY = Energy yield of the product (%)

Based on the calculation, the energy yield of the liquid product was found to be 10,691 cal/g, resulting in an energy yield of 1.3 MJ.

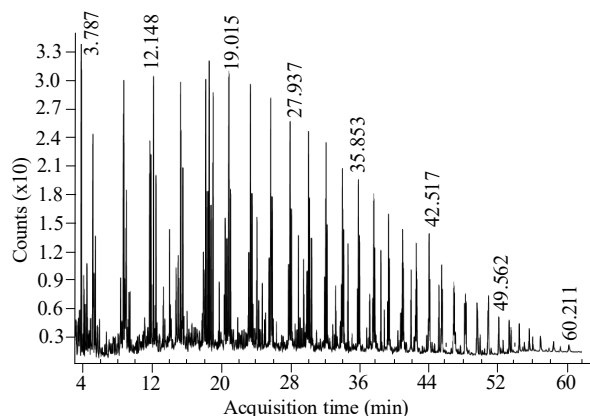


Figure 12 GC/MS test for liquid oil from pyrolysis ML plastic waste.

Table 3 The compound in liquid oil from pyrolysis ML plastic waste by GC/MS.

Compound name	Formula	Molecular weight
Oxirane, hexadecyl-	$C_{18}H_{36}O$	286.0
1,19-Eicosadiene	$C_{20}H_{38}$	278.2
(8Z)-14-Methyl-8-Hexadecen-1-ol	$C_{17}H_{34}O$	254.0
18-Nonadecen-1-ol	$C_{19}H_{38}O$	282.2
9-Octadecen-1-ol	$C_{18}H_{36}O$	268.2
Trans-2-Dodecen-1-ol, trifluoroacetate	$C_{14}H_{23}F_3O_2$	280.1
hydroxymethylcyclododecane	$C_{13}H_{26}O$	198.0
Cyclododecanemethanol	$C_{13}H_{26}O$	198.1
Heptadecanal	$C_{17}H_{34}O$	254.0
1-Octadecyne	$C_{18}H_{34}$	250.0
Oleyl alcohol, trifluoroacetate	$C_{20}H_{35}F_3O_2$	364.2
n-Tetracosanol-1	$C_{24}H_{50}O$	354.0
1-Heneicosanol	$C_{21}H_{44}O$	312.0
Behenic alcohol	$C_{22}H_{46}O$	326.0
n-Nonadecanol-1	$C_{19}H_{40}O$	284.3
1-Nonadecene	$C_{19}H_{38}$	266.0
Octacosanol	$C_{28}H_{58}O$	410.0
Dichloroacetic acid, heptadecyl ester	$C_{19}H_{36}Cl_2O_2$	366.2
Dodecane, 1-cyclopentyl-4-(3-cyclopentylpropyl)	$C_{25}H_{48}$	348.3

4. Conclusion

The study focused on the effect of residence time within the range of 60–120 min and a heating rate of 5–15°C/min on the production of liquid product from ML plastic waste using a household-scale pyrolysis reactor of 50 L capacity with a fractionating condenser tube. The

temperature was maintained between 350–500°C. It was found that the resulting products consisted of solid residue, liquid oil, and non-condensable gases. From the experiments, it was observed that the residence time of the process affected the quantity of the resulting products. At 60 min of residence time, the liquid yield was 569 g (59.1%) and increasing the residence time led to a decrease in liquid yield (46.5%), inversely proportional to the solid product yield. Increasing the residence time resulted in a decrease in solid yield and an increase in non-condensable gases. The solid residue increased from 6.8% at 60 min to 13.8% at 120 min. The total liquid product was reduced by approximately 16.3% as a result of the return of pyrolysis gas into the burner as fuel. The liquid products from the fractionation tubes, characterized by dark and light brown colors, were confirmed as biofuel through DGC and GC/MS analysis, showing components and properties consistent with biofuel oils, including benzene oil, gasoline, diesel, and stove oil. The liquid biofuel had a high heat value of 10,691 cal/g, and the solid products had chemical compositions matching those of the packaging materials used as feedstock. Studying the combustion of the recycling gas from the pyrolysis process in the burner resulted in a reduction in LPG fuel consumption, although there was a slight decrease in liquid fuel products. The heating value of pyrolysis oil is comparable to that of fuel oil, making it a suitable substitute for direct combustion as fuel in industrial plants, fuels to produce porcelain and ceramics, and energy source used for cremation without requiring quality improvement. If the liquid undergoes distillation to separate diesel and gasoline, followed by upgrading to meet quality and engine performance standards, it can be used as a replacement for or blended into vehicle fuels. The products from the pyrolysis process could serve as alternative fuels, reducing environmental impact during use and increasing the reserve of petroleum fuels for the future. This research serves as a guide for scaling up pyrolysis apparatuses to a community level.

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