Effect of HCl-Activated Natural Zeolite Catalyst Loading on Liquid Fuel Production from Waste Engine Oil Pyrolysis

Noversi Allolayuk[1], Alwathan Sofian*[2], Marcopolo Ginting [3], Sirajuddin [4], Muh. Irwan[5], Harjanto[6], Ramli Thahir[7], Abdul Muis[8], M. Taufik[9], Abdul Halim[10]
[1,2,3,4,5,6,7]*Department of Chemical Engineering, Politeknik Negeri Samarinda, Samarinda, Indonesia*
[8,9,10]*Department of Mechanical Engineering, Politeknik Negeri Samarinda, Samarinda , Indonesia*
Email address : ***alwatan@polnes.ac.id**

***Abstract*—The continuous increase in motor vehicle usage has led to a corresponding rise in lubricant oil consumption, resulting in a greater volume of used lubricating oil waste. Various treatment methods can be applied to process used lubricating oil waste, one of which is pyrolysis to convert the waste into liquid fuel. This study was conducted to determine the effect of activated natural zeolite as a catalyst in the conversion of used lubricating oil into liquid fuel. The used lubricating oil was subjected to pyrolysis for 120 minutes at a temperature of 350°C, using a feed volume of 500 mL. Catalyst weight variations of 0 g, 21.5 g, 43 g, 64.5 g, and 86 g were applied. The catalyst consisted of natural zeolite crushed and sieved to 100 mesh particle size. Prior to use, the zeolite was activated using 3 M HCl. The resulting liquid fuel products were evaluated in terms of yield percentage (%Yield), API gravity (°API), density, and viscosity. The pyrolysis process produced 287 mL, 332 mL, 387 mL, 441 mL, and 415 mL of liquid fuel, respectively. The maximum fuel yield was obtained with a catalyst weight of 64.5 g, producing 441 mL of liquid fuel with a yield of 88.2%, a density of 812.2 kg/m³, a viscosity of 2.48 cSt, and an API gravity of 42.56°. The API gravity value indicates that the liquid fuel product can be classified as kerosene.**

Keywords—activation, liquid fuel, waste engine oil, pyrolysis, natural zeolite.

I. INTRODUCTION

The number of motor vehicles in Indonesia continues to increase every year, resulting in a corresponding increase in the consumption of lubricating oil. According to the Central Bureau of Statistics (BPS), the number of motor vehicles increased steadily during 2018–2020 with an average annual growth rate of approximately 11.11% [1]. Based on this trend, the number of motor vehicles in East Kalimantan Province was projected to reach approximately 3.47 million units by 2023. The increasing use of lubricating oil consequently generates a larger amount of used engine oil, which is classified as hazardous and toxic waste (B3). Improper disposal of used engine oil may contaminate soil and groundwater because it contains various hazardous compounds and heavy metals. Therefore, proper management and recovery of used engine oil are important not only to minimize environmental pollution but also to utilize its remaining energy potential. Compared with fresh lubricating oil, used lubricating oil contains higher concentrations of metals such as aluminum (Al), iron (Fe), copper (Cu), manganese (Mn), and zinc (Zn) [2]. In addition, it contains hydrocarbon compounds, additive chemicals, corrosive acids, combustion residues, and other contaminants that accumulate during engine operation [3]. Owing to its relatively high hydrocarbon content, used engine oil still possesses considerable energy value and therefore has the potential to be converted into alternative liquid fuel instead of being disposed of as hazardous waste.

Among the available waste oil recovery technologies, pyrolytic distillation is considered one of the promising methods because it thermally decomposes long-chain hydrocarbons into lighter hydrocarbon fractions without requiring oxygen. The liquid products obtained from this process generally exhibit properties comparable to commercial fuels such as gasoline, kerosene, and diesel fuel. The application of catalysts during pyrolysis can improve the cracking reaction, increase liquid fuel yield, and reduce the formation of heavy hydrocarbon fractions. Natural zeolite has attracted considerable attention as a catalyst because of its low cost, natural abundance, and catalytic properties. Furthermore, acid activation using hydrochloric acid (HCl) removes impurities from the zeolite surface and enhances its catalytic activity by improving the accessibility of active sites. One approach to reducing the amount of used lubricating oil waste is to convert it into liquid fuel through a pyrolytic distillation process. This process produces a condensate product with properties like commercial liquid fuels such as gasoline, diesel, and kerosene. Previous studies reported that the liquid fuel yield obtained from used lubricating oil pyrolysis had not yet reached optimal levels. Therefore, this study investigates the conversion of used lubricating oil into liquid fuel using a pyrolysis process with varying amounts of natural zeolite catalyst activated by 3 M HCl [4,5].

Several researchers have investigated the catalytic pyrolysis of used lubricating oil using natural and synthetic zeolite catalysts [6]. The reported results demonstrated that zeolite catalysts promote the cracking of long-chain hydrocarbons into lighter fractions, thereby increasing liquid fuel yield and improving fuel characteristics compared with non-catalytic pyrolysis. Subsequent studies revealed that catalyst properties, including acidity, pore structure, and particle size, together with pyrolysis temperature, significantly influence hydrocarbon conversion, product distribution, and the physicochemical properties of the resulting liquid fuel [7]. More recently, further improvements in catalyst design and catalytic activity have been shown to enhance the production of diesel-like fuel from waste lubricating oil; however, catalyst performance remains strongly dependent on catalyst characteristics and operating

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conditions [8]. In addition, catalytic pyrolytic distillation has been reported to improve liquid fuel recovery and product quality, although the catalytic performance is still governed by catalyst-related parameters and process conditions [9]. Despite these advances, previous studies have mainly focused on catalyst type, catalyst modification, catalyst synthesis, or pyrolysis temperature, whereas the effect of different dosages of HCl-activated natural zeolite under identical operating conditions has received limited attention. Consequently, the optimum catalyst dosage required to maximize liquid fuel yield while maintaining acceptable fuel properties has not yet been clearly established, indicating the need for a systematic investigation of catalyst loading during the catalytic pyrolysis of used engine oil [10].

The novelty of this study lies in systematically evaluating the effect of different dosages of 3 M HCl-activated natural zeolite catalyst on the pyrolysis of used engine oil under identical operating conditions, thereby eliminating the influence of other operating variables. The produced liquid fuel was evaluated based on liquid fuel yield, density, viscosity according to SNI 8220:2017, and API gravity (°API) to determine the optimum catalyst dosage for producing high-yield liquid fuel with acceptable fuel quality.

The objective of this study was to investigate the effect of HCl-activated natural zeolite catalyst dosage on the pyrolysis of used engine oil for liquid fuel production. The results of this research are expected to provide an alternative approach for recovering hazardous waste into valuable fuel products while contributing to waste minimization and supporting resource recovery and circular economy practices.

II. METHODS

The used lubricating oil employed as the feedstock in this study was collected from vehicle repair workshops located around Samarinda State Polytechnic. Sample analyses were conducted at the Instrumentation Laboratory of the Department of Chemical Engineering, Samarinda State Polytechnic.

The equipment used in this research included a fixed-bed reactor, pyrolysis apparatus, condenser, connectors, water bath, oven, digital balance, graduated cylinder, thermometer, stopwatch, beaker, volumetric flask, spatula, density meter, Ostwald viscometer, filter paper, vacuum pump, Büchner funnel, two-neck Erlenmeyer flask, Petri dish, and aluminum foil. The main materials used were used lubricating oil, natural zeolite, 3 M hydrochloric acid (HCl), distilled water, and a pH indicator.

This study consisted of two main stages and several analytical parameters, namely the catalyst activation process, the pyrolytic distillation process, and the analyses of density, viscosity, yield, API gravity (°API), and GC–MS. The detailed experimental procedures and analytical methods are described as follows.

A. Activation Zeolite.

A total of 200 g of pretreated natural zeolite was immersed in 400 mL of 3 M HCl solution and allowed to stand for 2 hours. The activated zeolite was then separated by filtration using a vacuum pump and a Buchner funnel, followed by washing with distilled water until the filtrate reached a neutral pH of approximately 7. Subsequently, the zeolite was dried in an oven at 110°C for 2 hours before being used in the pyrolysis process.

B. Pyrolysis Process

The filtered used lubricating oil was mixed with activated natural zeolite at catalyst loadings of 0 g (without catalyst), 21.5 g, 43 g, 64.5 g, and 86 g. The mixtures were then introduced into the pyrolysis reactor. The pyrolysis process was carried out at a temperature of 350°C for 2 hours. Upon completion of the pyrolysis process, the liquid fuel product was collected and stored in an airtight container for further analysis.

C. Density Analysis

The oil sample to be analyzed was prepared and connected to the density meter using the appropriate measuring tube. The adapter and suction tube were installed on the density meter, and the instrument was switched on. The density measurement unit was selected from the instrument menu. The suction tube was immersed into the sample, and the plunger was fully depressed and then slowly released to draw the sample into the measuring chamber. The density value displayed on the density meter screen was recorded.

D. Viscosity Analysis

A 500 mL graduated cylinder was prepared, and an Ostwald viscometer together with a thermometer was placed inside. Distilled water was heated to 40°C and transferred into the graduated cylinder as a constant-temperature bath. The pyrolysis oil sample was introduced into the Ostwald viscometer. The flow time of the sample between the designated marks on the viscometer was measured using a stopwatch. The kinematic viscosity of the oil product was calculated using the following equation:

$$v\ produk = \frac{\rho\ Product \times t\ Product}{\rho\ Water \times t\ water} \times v\ air \qquad (1)$$

Where, ν is the kinematic viscosity, ρ is the density, and t is the flow time.

E. Yield Determination

The masses of the feedstock, liquid product, and residue were measured. The percentage yield was calculated using the following equation:

$$\%Yield = \frac{Mass\ of\ Product}{Mass\ of\ Feedstock} \times 100\% \qquad (2)$$

F. API Gravity Calculation

The density of the liquid fuel product was measured at 60°F. The specific gravity (SG 60°F) was determined by dividing the product density at 60°F by the density of water at 60°F. The API gravity was then calculated using the following equation:

$$°API = \frac{141{,}5}{Sg60°F} - 131{,}5 \qquad (3)$$

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Where, SG 60°F is the specific gravity of the product referenced to water at 60°F. Higher API gravity values indicate lighter fuel fractions, while lower values correspond to heavier petroleum products.

III. RESULTS AND DISCUSSION

This study was conducted to investigate the effect of varying the amount of natural zeolite catalyst, chemically activated with 3 M HCl, on the pyrolysis of used lubricating oil to produce liquid fuel. The catalyst used was natural zeolite that had been finely ground and activated using 3 M HCl to enhance its catalytic performance in chemical reactions. The activation process involves the removal of impurities from the zeolite pore surfaces and the enlargement of its surface area. As a result, the activated zeolite exhibits improved catalytic activity and efficiency [11]. Based on this premise, the effect of catalyst performance on several key parameters was evaluated, as discussed in the following sections:

A. Effect of Catalyst Performance on Liquid Fuel Yield nits

The performance of the zeolite catalyst can be evaluated through the yield of liquid fuel produced during the pyrolysis process. The results presented in Table 1 show that catalyst addition significantly increased the liquid product yield compared to the non-catalytic process.

Table 1. Analysis Results of Liquid Fuel Condensate Products

Catalyst Loading (g)	Yield (%)	Density (kg/m³)	Viscosity (cSt)	API Gravity (°API)
0.0	57.4	794.0	1.64	46.55
21.5	66.4	795.8	1.95	46.15
43.0	77.4	807.9	2.07	43.49
64.5	88.2	812.2	2.48	42.56
86.0	83.0	802.3	2.90	44.71

The relationship between catalyst loading and liquid fuel yield is presented in Figure 1.

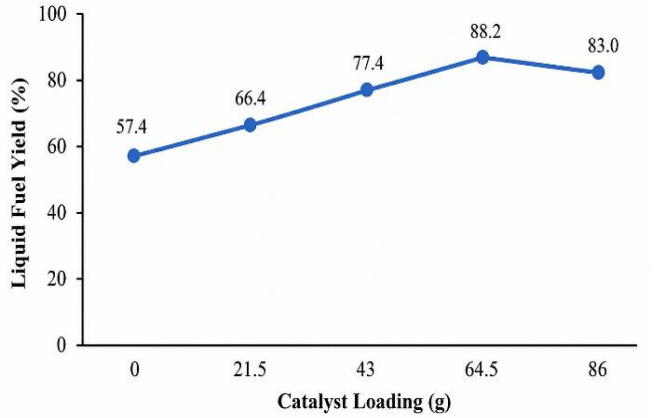

Fig. 1. Effect of Catalyst Addition on Liquid Fuel Yield

As shown in Figure 1, increasing the catalyst loading from 0 to 64.5 g resulted in a continuous increase in liquid fuel yield from 57.4% to 88.2%. This trend indicates that the zeolite catalyst effectively enhanced the cracking of long-chain hydrocarbons contained in waste engine oil into shorter hydrocarbon molecules that were more easily condensed into liquid products. The porous structure and acidic active sites of zeolite play an important role in promoting the breakdown of heavy hydrocarbons, thereby improving the conversion efficiency of the pyrolysis process.

However, when the catalyst loading was further increased to 86 g, the yield decreased to 83.0%. This finding suggests that the optimum catalyst loading was achieved at 64.5 g. Excessive catalyst addition may lead to pore blockage caused by coke deposition and accumulation of reaction residues on the catalyst surface, reducing the availability of active sites and consequently decreasing catalytic activity, the present findings are consistent with those reported [12], who observed that increasing catalyst dosage enhanced liquid product formation up to an optimum level. Beyond this optimum condition, catalyst deactivation occurred, resulting in a decline in liquid product yield. These results confirm that catalyst loading is one of the most important parameters affecting the efficiency of waste engine oil pyrolysis for liquid fuel production.

B. . Effect of Catalyst Addition on Density

The effect of catalyst loading on the density of the liquid fuel product is shown in Figure 2.

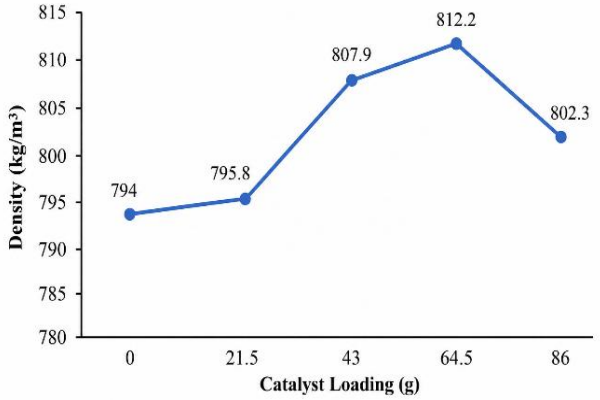

Fig. 2. Effect of Catalyst Addition on Product Density

Figure 2 shows that the density of the liquid fuel generally increased with increasing catalyst loading. The highest density value of 812.2 kg/m³ was obtained at a catalyst loading of 64.5 g, whereas the lowest density value of 794.0 kg/m³ was recorded in the absence of catalyst. The increase in density may be attributed to the formation of hydrocarbon fractions with characteristics like middle-distillate fuels. The presence of the catalyst promotes secondary cracking and hydrocarbon rearrangement reactions, resulting in liquid products with improved fuel properties. Previous studies on catalytic pyrolysis have also reported that zeolite catalysts enhance the formation of condensable hydrocarbons, leading to higher product density than that obtained from non-catalytic pyrolysis processes.

Nevertheless, at a catalyst loading of 86 g, the density decreased to 802.3 kg/m³. This reduction indicates a shift in the hydrocarbon composition toward lighter fractions. Excessive catalyst loading may intensify cracking reactions, producing hydrocarbons with lower molecular weights and

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consequently lower density values. Similar observations have been reported in previous studies, demonstrating that catalyst dosage strongly influences both the composition and physicochemical properties of pyrolysis-derived fuels.

C. Effect of Catalyst Addition on Viscosity

The effect of catalyst loading on the viscosity of the liquid fuel product is illustrated in Figure 3.

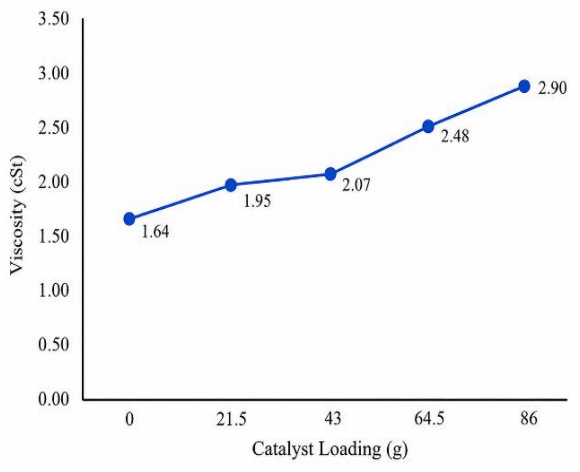

Fig. 3. Effect of Catalyst Addition on Product Viscosity

The results indicate that viscosity increased as the catalyst loading increased. The lowest viscosity value of 1.64 cSt was obtained without catalyst, while the highest value of 2.90 cSt was achieved at a catalyst loading of 86 g. In general, viscosity is directly proportional to density. Fuels with higher density tend to exhibit higher viscosity because they contain larger and more complex hydrocarbon molecules [13].

This relationship can be observed up to the catalyst loading of 64.5 g, where increases in density were accompanied by increases in viscosity. Interestingly, at a catalyst loading of 86 g, the density decreased whereas the viscosity continued to increase. This phenomenon may be attributed to changes in the molecular composition of the liquid product. Although the catalyst promotes cracking reactions, excessive catalyst loading may produce a wider distribution of hydrocarbon fractions, including compounds with relatively high molecular weights that contribute significantly to viscosity, the presence of heavier hydrocarbon fractions can increase viscosity even when the overall density decreases. Similar findings have been reported in catalytic pyrolysis studies, where excessive catalyst loading altered the hydrocarbon distribution and resulted in a non-linear relationship between density and viscosity.

D. Effect of Effect of Catalyst Addition on API Gravity

Figure 4 illustrates the effect of HCl-activated natural zeolite catalyst loading on the API gravity (°API) of the liquid fuel produced from waste engine oil pyrolysis. API gravity is an important parameter used to characterize the lightness of petroleum-derived fuels, where higher °API values indicate lower density and a greater proportion of lighter hydrocarbon fractions. The variation in API gravity with different catalyst loadings provides insight into the effectiveness of the catalyst in promoting the cracking reactions during the pyrolysis process.

The effect of catalyst loading on API gravity (°API) is presented in Figure 4.

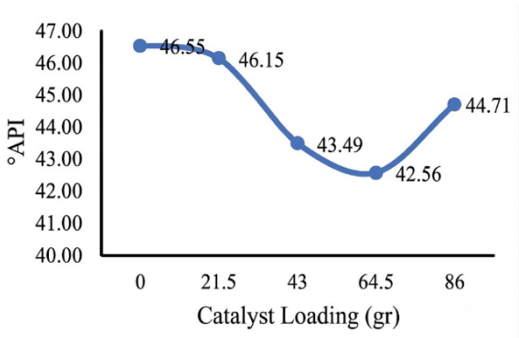

Fig. 4. Effect of Catalyst Addition on API Gravity

API gravity was calculated based on the density of the liquid fuel products. The results indicate that increasing catalyst loading generally decreased API gravity up to a catalyst loading of 64.5 g, after which the API gravity increased at a catalyst loading of 86 g. As illustrated in Fig. 4, API gravity exhibits an inverse relationship with density. Higher density values correspond to lower API gravity values, whereas lower density values result in higher API gravity values. This relationship is consistent with the standard API gravity calculation widely used in the petroleum industry . The decrease in API gravity from 46.55 to 42.56 as catalyst loading increased from 0 to 64.5 g indicates the formation of fuel fractions with properties closer to kerosene and middle-distillate fuels. Subsequently, the increase in API gravity to 44.71 at a catalyst loading of 86 g corresponds to the reduction in density observed under the same condition, suggesting the formation of lighter hydrocarbon fractions [14]. According to the classification provided in the Handbook of Petroleum Product Analysis, all API gravity values obtained in this study fall within the range typically associated with kerosene-type fuels. These findings demonstrate that catalytic pyrolysis of waste engine oil using zeolite catalyst has considerable potential for producing liquid fuels with characteristics comparable to commercial kerosene[15]. Furthermore, the API gravity values obtained in this study are comparable to those reported in previous investigations on waste engine oil pyrolysis. This agreement confirms the effectiveness of zeolite catalysts in improving the quality of pyrolysis-derived hydrocarbons and upgrading waste engine oil into higher-value liquid fuel products.

IV. CONCLUSION

This study evaluated the effect of HCl-activated natural zeolite catalyst loading on liquid fuel production from waste engine oil pyrolysis under identical operating conditions. The optimum catalyst loading was 64.5 g, at a pyrolysis temperature of 350°C for 120 min, producing the highest liquid fuel yield of 88.2%, with a density of 812.2 kg/m³, a viscosity of 2.48 cSt, and an API gravity of 42.56°API, indicating fuel characteristics within the kerosene range. The results demonstrate that catalyst loading is a key factor affecting both liquid fuel yield and physicochemical properties, as the HCl-activated natural zeolite effectively promoted the catalytic cracking of heavy hydrocarbons into condensable liquid fractions, thereby enhancing pyrolysis

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performance compared with the non-catalytic process. However, catalyst loading beyond the optimum level reduced liquid fuel yield, indicating a decline in catalytic effectiveness. Overall, these findings identify the optimum loading of HCl-activated natural zeolite and demonstrate its potential as an effective, low-cost catalyst for upgrading waste engine oil into valuable liquid fuel through catalytic pyrolysis.

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