

Energy balance analysis of thermal and catalytic degradation processes of polyethylene plastic waste to liquid fuel

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ABSTRACT

A simple thermal and catalytic degradation of polyethylene plastic waste has been carried out to produce alternative liquid fuel. Plastic of 1500 grams was pyrolyzed at a specific temperature of 450 °C. The gases were condensed in a water-cooled condenser and collected in a liquid container. Energy balance calculation was done where catalytic cracking with Y zeolite as catalyst seemed to be the best because the generated thermal energy from waste plastic oil was already higher than the required electric energy supplied for the cracking. However, several improvements must always be made in order to save more energy and create the best result for commercialization.

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1. Introduction

Fuel oil has been a crucial problem in Indonesia and the world as well. It is an impact of population growth and the rapid growth of the people's economy, leading to an increase in fuel consumption. This is inversely proportional to the production of fuel in the country which is unable to fulfil consumer demands and in the meantime, the oil reserve from production well is declining. Another problem that is no less crucial is the problem of waste management, especially plastic waste. The classic problem that occurs is mostly due to limited land for landfills, while waste quantity is increasing along with the increase in human population and lifestyle changes. Plastics are macromolecules that are formed by a polymerization process, namely the joining of several simple molecules through a chemical process into large molecules called polymers [1]. Plastics as a product from petroleum have the same high energy content as fuels made from petroleum [2]. Table 1 shows the calorific values of various plastic materials and fuels. Several types of plastic have a calorific value that is almost similar to fuel oils. Therefore, converting plastic waste into fuel by thermal and catalytic degradation methods is a promising option for processing plastic waste. Besides we can reduce plastic waste, recycling, and preserving the environment, we can also produce fuel with quality that resembles conventional fuel oil.

A catalyst is a chemical substance that increases the reaction rate and is involved in a chemical reaction even though the substance itself does not permanently react [3]. The catalyst can be reused in the next process by first cleaning and calcining it to remove impurities and open the pores of the catalyst. With the presence of a catalyst, the activation energy for the cracking reaction to occur is smaller so that the temperature required for the reactor is lower. This is very different from the thermal

cracking method (without a catalyst) which requires a much higher reactor temperature because it requires a large enough heat energy to cut the chain bonds in the polymer.

Table 1. Calorific value of plastics and oils

Material Type	Calorific Value (MJ/kg)
Polyethylene	43.3 – 46.5
Polypropylene	46.50
Polystyrene	41.90
Kerosene	46.50
Solar	45.20
Heavy oil	42.50
Crude oil	42.30

Zeolite is a group of minerals produced from hydrothermal processes in alkaline igneous rocks [3]. Several types of zeolites are white, bluish, reddish, brown, and others. This is due to the presence of iron oxide or other metals. The density of zeolite ranges from 2.0 - 2.3 grams/cm³. Zeolite is classified into two, namely natural zeolite and synthetic zeolite. Zeolites have adsorbing properties, as cation exchangers and catalysts or supports. Y synthetic zeolite is widely used as a catalyst in the cracking process. In some studies, there have been suggestions that natural zeolite catalysts that have been activated can be used as catalysts in the cracking process because they have a large surface area and an acidity level that can help crack hydrocarbons [4]. This reactor is widely used because of its simple construction and easy maintenance, but this does not reduce the ability of the reactor to convert plastic waste into fuel oil. Feedstock recycling is a better technology where plastic waste is converted into smaller molecules in the form of liquids or gases to produce fuel and chemicals [2].

2. Method

The research was conducted using test equipment as shown in Figure 1. About 1500 grams of polyethylene plastic waste as a raw material was put into the reactor which was made of stainless steel and then tightly closed to prevent leakage. After that, the reactor was heated at a temperature of 450 °C for approximately 4 hours. This temperature could be achieved by using an electric heater which was controlled with the help of a thermocouple. The pyrolysis gas was flowed through a pipe and channelled to a circulating water-cooled condenser with the help of a water pump. Condensed oil was stored in containers to inspect the quality and quantity. The uncondensable gas was then flowed to the output pipe which was then ignited to avoid excess air pollution. Similar test equipment has also been made by planning a reactor with a capacity of 4 kg and a heating temperature of $\pm 300^{\circ}\text{C}$ using a heater from an LPG furnace [5]. This pyrolysis was carried out until no more oil flowed out of the container. The products of this process are char, oil and gas. This present study focused on liquid products in the form of oil due to its considerable potential as a fuel. The oil was then sent to the laboratory to be analyzed both physically and chemically to determine its physical characteristics and calorific value.

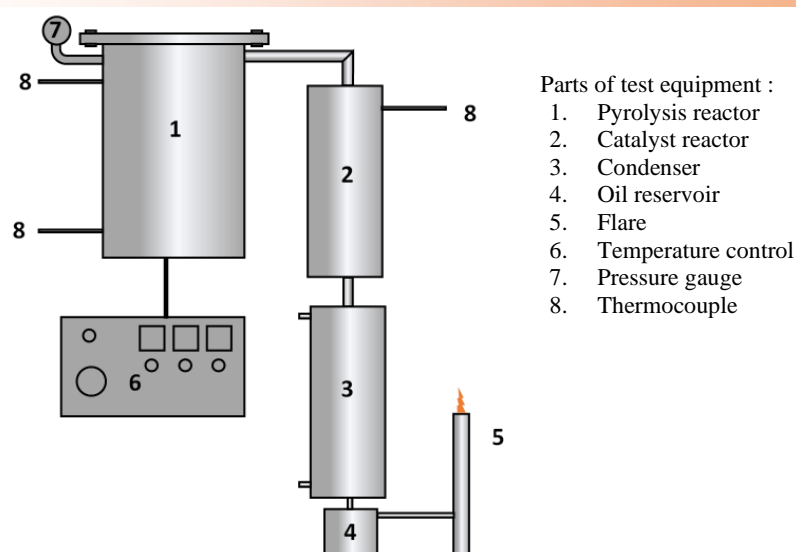


Fig. 1. Schematic of test equipment

3. Results and Discussion

3.1. Pyrolysis product composition

The distribution of products resulting from plastic pyrolysis with catalyst has been studied by several researchers and the results can be seen in Table 2. In general, the use of a catalyst will reduce the oil and residue fractions but will increase the gas fraction when compared to thermal degradation. The phenomenon was caused by the oil fraction from thermal degradation having been cracked using a catalyst so that long hydrocarbon chains were broken into shorter chain bonds. This resulted in an increase in the gas fraction from the conversion of the oil fraction [2]. Another research also examined the effect of catalyst mass on the distribution of products, where at the same process temperature, the greater the mass of the catalyst, the lower the oil fraction and the greater the gas fraction [6]. This was because the addition of catalyst mass affected the cracking of long hydrocarbon chain bonds into shorter bonds. Previous researchers have conducted similar research using almost similar equipment schemes but using a slightly different type of feedstock, namely using a mixture of various types of plastic [7]–[10]. The research shows that most plastic waste oils were produced from a mixture of 50 % polyethylene and 50 % polystyrene with an amount of 52.36 % of the total mass of raw materials.

Table 2. Product distribution of HDPE pyrolysis at a temperature of 450 °C with catalysts

Product Results	Oil (wt%)	Gas (wt%)	Residue (wt%)
Thermal	84.00	13.00	3.00
ZSM-5 (powder)	35.00	63.50	1.50
Zeolit Y (powder)	71.50	27.00	1.50
Zeolit Y (pellets)	81.00	17.50	1.50
Mordenite (pellets)	78.50	18.50	3.00
Silika-alumina (powder)	78.00	21.00	1.00
Alumina (powder)	82.00	15.90	2.10

Several works have also researched plastic waste pyrolysis using this method with a similar catalyst. The resulting liquid or oil fraction consists of gasoline, diesel and heavy oil components [11]. The gas fraction components produced mostly consisted of propane and propene which shows that the product gas was almost equivalent to LPG gas, where the main component was propane gas. The use of natural zeolite catalysts for catalytic degradation is a promising option due to the high price of commercial catalysts which can result in high operational costs for fuel production from plastic waste [12]–[14].

The distribution of liquid products from the thermal and catalytic degradation processes is shown in Fig. 2 below. More than 60 % of the total mass of processed plastic waste is liquid or oil products [15]. This proves that this degradation process is capable of turning plastic waste into a liquid product in the form of oil. For the thermal degradation process, it produces 0.975 kg of oil or about 65%, while for the natural zeolite catalytic degradation process, it produces 0.885 kg of oil or about 59%, and for the Y zeolite catalytic degradation process it produces 0.915 kg of oil or about 61%. The data shows that the thermal degradation process produces oil with the largest proportion among the other degradation processes. The data also states that the use of a catalyst reduces oil production but increases gas production, this is because the catalyst plays an active role in breaking long-chain hydrocarbon chains into shorter hydrocarbons. This result was also confirmed by other researchers who did the same thing where the use of a zeolite catalyst would reduce the quantity of oil but would increase the quantity of gas [16]. Thus, this data gives us information about how we determine the proportion of the product we prefer. If we prefer more oil production, it is better to use a thermal degradation process, so if we prefer more gas products, we use a catalytic degradation process.

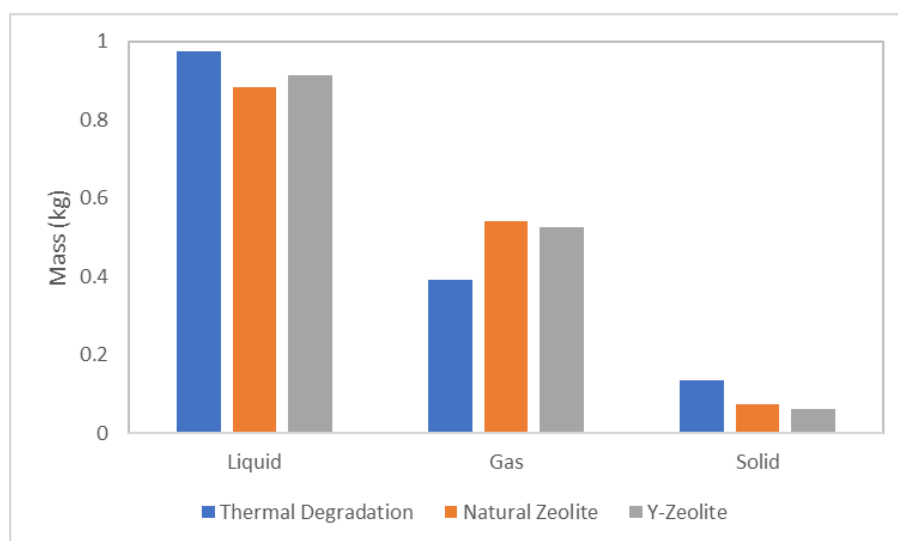


Fig. 2. Composition of plastic waste pyrolysis products

3.2. Physical Characteristics

In addition to several chemical properties, the physical properties of oil from plastic waste must also be studied to determine its characteristics if it is to be applied in internal combustion engines such as gasoline or diesel engines. In general, plastic waste oil can be used to substitute diesel fuel in diesel engines either as a single fuel or as a mixture with diesel fuel with a certain percentage. This is evidenced by the calorific value which is not much different when compared to diesel fuel. However,

several characteristics must be improved to improve performance. A lower viscosity value than diesel fuel will greatly affect the performance of fuel atomization and vaporization which will result in fuel consumption, emissions and deposits on the engine. The viscosity that is too low will allegedly cause problems with the injectors, such as leaks and greater energy for pumping fuel.

The analysis states that plastic waste oil has a specific gravity (SG) value similar to the specific gravity of diesel engine fuel. This is also in accordance with what was done by previous researchers who stated that the physical properties of plastic waste oil show a lower density compared to diesel fuel [17]. The specific gravity value for thermal degradation is 0.8052; for natural zeolite catalytic degradation of 0.8137; for catalytic degradation of Y zeolite of 0.8050; and biodiesel of 0.8445. The value of specific gravity is closely related to density. Specific gravity is the ratio of the density of a fluid to the density of water at a certain temperature [18].

Density is the ratio between the mass and volume of a fluid. That is, a fluid can have a large mass for a small volume size. This can be advantageous because, in a small volume, the fluid has a large mass content so the energy contained in the fluid is also large for a limited volume. Plastic waste oil also has a higher pour point than diesel. This will have an effect if using this fuel in areas with relatively low air temperatures because it will result in fuel freezing. The flash point of plastic waste oil is also far below that of diesel. This is certainly very dangerous because the lower the flash point, the more flammable the fuel will be. It will affect fuel storage, where a storage area is needed with a temperature setting below the flash point of the fuel to ensure safety in storage.

3.3. Calorific Value and Energy Equilibrium

Fig. 3 shows the testing results of the calorific value of each oil sample resulting from thermal and catalytic degradation from plastic waste. The test results showed that catalytic pyrolysis oil with zeolite Y contained the highest calorific value of 47,980 kJ/kg, followed by catalytic pyrolysis oil with natural zeolite with a heating value of 44,900 kJ/kg and thermal pyrolysis oil with a heating value of 43,800 kJ/kg. Meanwhile, the heating value for biodiesel is 45,000 kJ/kg. These data show that the use of a catalyst increases the calorific value of the liquid product or oil resulting from the pyrolysis of plastic waste.

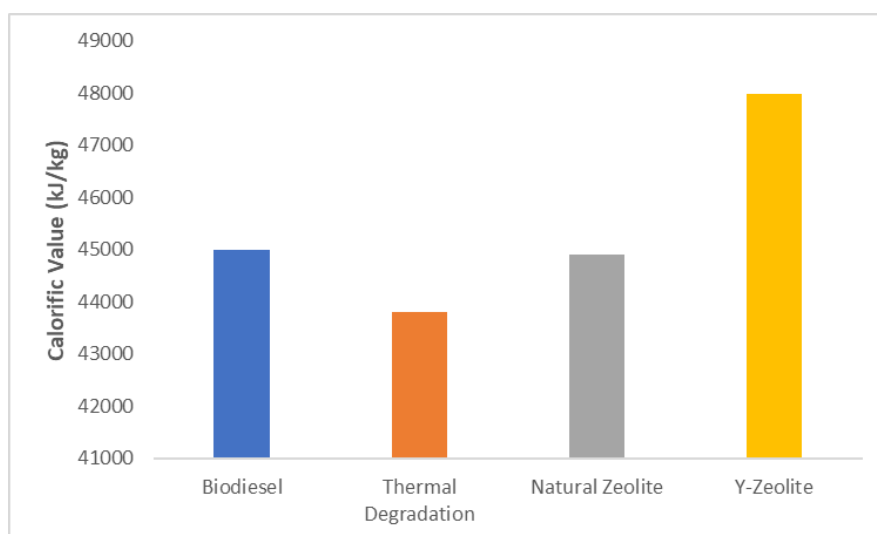


Fig. 3. Calorific value of oil from the degradation of plastic waste

Both thermal and catalytic degradation have been shown to be capable of converting polyethylene plastic waste into useful liquid fuels. Although there is still gas that cannot be condensed which is then ignited to reduce air pollution, this clearly shows that flammable hydrocarbons can be produced from the degradation process of plastic waste. The resulting liquid product contains energy which can later be released during the combustion process as seen in the calorific value. Solid products in the form of char and gas also contain energy, but this is not included in the discussion of this study. To produce heat in the decomposition process, the researchers used an electric heater with a power of 4000 watts located on the reactor wall. This heater uses a thermostatic control where the heater will automatically turn off when the desired temperature is reached and will turn on again if the temperature is lower than a predetermined one. Electrical energy is not supplied continuously but is distributed intermittently. Pyrolysis at a temperature of 450 °C for example, is not supplied by electrical energy for 240 minutes continuously, but less than that. The calculation results are shown in Table 3 and Table 4 below.

Table 3. Electrical energy consumption

Sample	Reactor Power (kW)	Pyrolysis duration (Hour)	Electricity Consumption (kWh)	Electricity Consumption (kJ)
Thermal Degradation	4	4	16	57600
Catalytic Degradation NZ	4	4	16	57600
Catalytic Degradation YZ	4	4	16	57600

Table 4. Comparison of electrical energy consumption with calorific value

Sample	Mass WPO (kg)	Calorific Value (kJ/kg)	Thermal Energy (kJ)	Electricity Consumption (kJ)
Thermal Degradation	1.5	43800	65700	57600
Catalytic Degradation NZ	1.5	44900	67350	57600
Catalytic Degradation YZ	1.5	47980	71970	57600

From the data in Tables 3 and 4, an initial analysis can be drawn that the use of a catalyst is capable of producing higher thermal energy than thermal degradation. When viewed from an energy and environmental perspective, the results of this study indicate that this thermal and catalytic degradation method is very suitable for application to plastic waste. The energy performance of this method is considered appropriate based on the calculation of the cumulative energy requirement and the energy comparison value. As we all know thermal energy cannot be directly compared to electrical energy even though in quantity they have the same value [19].

Thermal energy is energy that has a relatively low quality, while electrical energy is energy with a higher quality. This is because electrical energy can be applied to a wider field than thermal energy. Roughly speaking, thermal energy generally must be multiplied by 0.4 before it is balanced with electrical energy, bearing in mind that efficiency in steam power plants generally ranges from 34-44% [20] so that the average value is taken to simplify the analysis by 40% [19]. In this research, both thermal and catalytic degradation have been able to meet the requirements because the thermal energy

content is greater than the electrical energy required for the degradation process. The comparison between the thermal energy content and the electricity consumption used is shown in Figure 4 below.

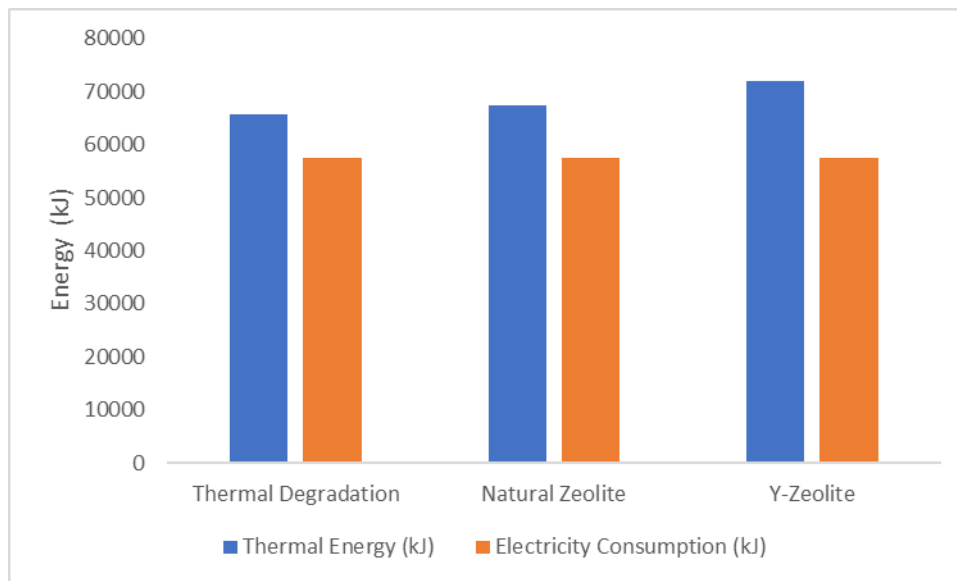


Fig. 4. Comparison of pyrolysis oil energy content with reactor power consumption

4. Conclusion

Fuel oil from plastic waste has good prospects to replace gasoline and diesel fuel. From the results of this study, it can be concluded that the use of thermal and catalytic degradation methods can be used to produce fuel oil from polyethylene plastic waste. The use of catalysts for the catalytic degradation process of plastic waste runs quite effectively to improve the characteristics of plastic oil. This is indicated by the increasing calorific value and energy content of plastic waste oil. The presence of a catalyst can change the distribution of oil, gas and residue products and reduce the production of char/wax or solid products which are usually produced in the thermal degradation process. The cracking ability of the catalyst causes the oil product to decrease while the gas product increases because some of the oil product is converted into a gas product. The energy balance can be made more accurate by considering neglected factors, such as the energy content of the char and gas. The use of other heating energy sources at lower prices such as LPG, kerosene, wood charcoal or biomass waste can be used for commercialization of this system.

References

- [1] R. P. Liestiono, M. S. Cahyono, W. Widyawidura, A. Prasetya, and M. Syamsiro, "Karakteristik Minyak dan Gas Hasil Proses Dekomposisi Termal Plastik Jenis Low Density Polyethylene (LDPE)," *J. Offshore*, vol. 1, pp. 1–9, 2017.
- [2] M. Syamsiro, "Kajian Pengaruh Penggunaan Katalis terhadap Kualitas Produk Minyak Hasil Pirolisis Sampah Plastik," *J. Tek. Univ. Janabadra Yogyakarta*, pp. 47–56, 2015.
- [3] Istadi, *Teknologi Katalis untuk Konversi Energi: Fundamental dan Aplikasi*. Yogyakarta: Graha Ilmu, 2011.

- [4] Sania and L. Rubianto, "Studi Literatur Pengaruh Suhu Pemanasan dan Jenis Katalis Terhadap Produksi Minyak Pirolisis Sampah Plastik," *Distilat - J. Teknol. Separasi*, vol. 6, pp. 171–175, 2020.
- [5] P. B. W. Wardhana, A. Finali, and A. F. Hanafi, "Pengembangan Reaktor Pirolisis Termal Limbah Plastik Skala Laboratorium," *J. Tek. Mesin - Elem.*, pp. 39–44, 2020.
- [6] S. D. Kurniawan and H. Saptoadi, "Pengaruh Massa Katalis Zeolit Alam pada Proses Pirolisis Limbah Plastik Low Density Polyethylene (LDPE)," *J. Teknol. TECHNOSCIENTIA*, pp. 81–85, 2016.
- [7] G. B. Susilo, "Pembuatan Bahan Bakar dari Pirolisis Limbah Plastik Jenis Polietilen, Polistiren dan Other," *J. Teknol. TECHNOSCIENTIA*, pp. 147–154, 2016.
- [8] Subhashini and T. Mondal, "Experimental investigation on slow thermal pyrolysis of real-world plastic wastes in a fixed bed reactor to obtain aromatic rich fuel grade liquid oil," *J. Environ. Manage.*, vol. 344, no. March, p. 118680, 2023, doi: 10.1016/j.jenvman.2023.118680.
- [9] S. H. Chang, "Plastic waste as pyrolysis feedstock for plastic oil production: A review," *Sci. Total Environ.*, vol. 877, no. March, p. 162719, 2023, doi: 10.1016/j.scitotenv.2023.162719.
- [10] K. Moorthy Rajendran, D. Kumar, B. Yadav Lamba, and P. Kumar Ghodke, "Production and characterization of plastic oil from mixed plastic waste through the pyrolysis process," *Mater. Today Proc.*, no. xxxx, 2023, doi: 10.1016/j.matpr.2023.02.277.
- [11] M. Syamsiro *et al.*, "Co-Production of Liquid and Gaseous Fuels from Polyethylene and Polystyrene in a Continuous Sequential Pyrolysis and Catalytic Reforming System," *Energy Environ. Res.*, pp. 90–106, 2013.
- [12] M. Syamsiro *et al.*, "Liquid and Gaseous Fuels from Waste Plastics by Sequential Pyrolysis and Catalytic Reforming Processes over Indonesian Natural Zeolite Catalysts," *An Int. J. Waste Technol.*, pp. 44–51, 2014.
- [13] Hendrawati, A. R. Liandi, M. Solehah, M. H. Setyono, I. Aziz, and Y. D. I. Siregar, "Pyrolysis of PP and HDPE from plastic packaging waste into liquid hydrocarbons using natural zeolite Lampung as a catalyst," *Case Stud. Chem. Environ. Eng.*, vol. 7, no. October 2022, p. 100290, 2023, doi: 10.1016/j.cscee.2022.100290.
- [14] R. Miandad, M. A. Barakat, M. Rehan, A. S. Aburiazzaiza, I. M. I. Ismail, and A. S. Nizami, "Plastic waste to liquid oil through catalytic pyrolysis using natural and synthetic zeolite catalysts," *Waste Manag.*, vol. 69, pp. 66–78, 2017, doi: 10.1016/j.wasman.2017.08.032.
- [15] P. B. W. Wardhana and H. Saptoadi, "KONVERSI LIMBAH PLASTIK POLIETILEN MENJADI BAHAN BAKAR DENGAN METODE PIROLISIS," *DISPROTEK*, pp. 1–4, 2016.
- [16] M. Syamsiro, Z. Mufrodi, R. Raffly, and S. Machmud, "Universal Journal of Mechanical Engineering," *Univers. J. Mech. Eng.*, pp. 51–58, 2020.
- [17] R. K. Singh, B. Ruj, A. K. Sadhukhan, P. Gupta, and V. Tigga, "Waste plastic to pyrolytic oil and its utilization in CI engine: Performance analysis and combustion characteristics," *FUEL*, pp. 1–10, 2019.
- [18] B. R. Munson, D. F. Young, and T. H. Okiishi, *Mekanika Fluida*. Jakarta: Erlangga, 2003.
- [19] H. Saptoadi, A. K. Putra, W. Trisunaryanti, Z. Alimuddin, M. Syamsiro, and K. Yoshikawa, "Energy Balance of non-catalytic Pyrolysis of Plastic Wastes to produce LiquidFuel," *12th Annu. Natl. Semin. Mech. Eng. (SNTTM XII)*, pp. 1571–1577, 2013.
- [20] P. Nag, *Power Plant Engineering 3rd Edition*. New Delhi: Tata McGraw-Hill, 2008.