Study of Optimization of Plastic Waste Pyrolysis into Gasoline Fuel

Arief Yulistianto[1*], **Ade Ruhama**[1], **Iqbal Romadona**[1], **M. Ibrahim Ichsan**[1], **M. Robiansyah**[1], **Prawoto**[1], **Eka Maulana**[1]
[1]Mechanical Engineering Department, Universitas Pancasila, Jakarta, 10320, Indonesia
*Email Corresponding Author: arief.yulis@gmail.com

ABSTRACT

Pyrolysis, which converts plastic waste into energy through a heating process without oxygen, has been proven to reduce waste volume by up to 90% while becoming an alternative fuel with high economic value. The optimal pyrolysis temperature of 380°C produces the most significant amount of pyrolysis oil, with a potential thermal efficiency of up to 80%. The main challenges in optimizing pyrolysis include energy efficiency, operational costs, and production scale. This study aims to improve the efficiency of the pyrolysis process by enhancing the reactor, condenser tube, and control system. With this approach, it is hoped that a more cost-effective, environmentally friendly plastic waste management solution can be created that supports the concept of a circular economy in Cirebon City. The result is that with a plastic waste composition of 30% PP and 70% LDPE and the addition of a kaolin catalyst to the pyrolysis reactor, it can produce oil equivalent to gasoline with an octane rating of 88. This optimization can reduce the use of fossil fuels, create new jobs, and significantly contribute to environmental sustainability.

Keywords: Alternative Fuel; Pyrolysis; Plastic Waste.

INTRODUCTION

Plastic waste is still one of the leading environmental problems in Cirebon City. Data shows that the city produces a significant volume of plastic waste, reaching 203.36 tons per day, with around 18.99% of it being plastic [1]. This large amount creates serious challenges in waste management, considering that plastic waste takes a very long time to decompose naturally. Therefore, a more effective waste management solution is needed, one of which is through pyrolysis.

Based on the composition of waste in Cirebon, plastic contributes around 18.99% of the total waste. This includes various types of plastic, such as PET, HDPE, PVC, LDPE, and PP. The most plastic waste produced in Cirebon City is food waste at 49.28%, plastic waste at 18.99%, and garden waste at 11.77%. LDPE plastic (plastic bags) and PP (transparent plastic sachets and food and beverages) are the most produced plastic types. The daily waste generation rate in Cirebon City is 0.61 kg/person, according to the latest research conducted by the Cirebon City Department of Environment (DLH) in 2020 [1]. By utilizing pyrolysis technology, these types of plastic can be processed into valuable fuels, such as gasoline, diesel, or other crude oil [2].

The National Waste Management Policy and Strategy (JAKSTRANAS) in Presidential Regulation No. 97 of 2017, which the government stipulated, aims to reduce the volume of waste by thirty per cent and handle seventy per cent by 2025 [3]. One strategic step in line with this policy is optimizing the pyrolysis process of plastic waste to produce fuel. Pyrolysis technology can convert plastic waste to make alternative energy sources.

Pyrolysis is a technology that converts plastic to produce fuel in liquid, gas, or solid form by heating without oxygen. This process can reduce the volume of waste by up to 90% and produce diesel fuel or gasoline [4] Which is an innovative solution to the problem of plastic waste. In their research on the pyrolysis process, Putra et al. produced 9000 millilitres of oil, consisting of three types of oil: the first pyrolysis oil 2000 millilitres, the second pyrolysis oil 1500 millilitres, and the third pyrolysis oil 5500 millilitres.

The optimum temperature to produce the most pyrolysis oil is 350°C. In the energy calculation, the results of ΔQin are 19,862.44 kJ/kg, ΔQout are 1,972.35 kJ/kg, and ΔQgenerated are 17,891.094 kJ/kg. The net energy produced in this study also found that RDF combined with LPG was 0.859 kW, which is smaller than LPG alone, making a net energy of 2.239 kW. Pyrolysis using a combination of RDF and LPG at an optimum temperature of 350°C for 180 minutes produced 9000 ml of pyrolysis oil. The economic results show that the cost of using a combination of RDF and LPG is higher than using LPG alone. Still, this method can be called feasible from an environmental management perspective. Laboratory test results show that pyrolysis oil is thinner than previous studies using High-Density Polyethylene (HDPE) plastic, with a cetane number 33.6 and a thickness of 0.7727. This pyrolysis process has successfully reduced plastic waste, one of the leading environmental problems [5].

Research conducted by Maulana et al., focusing on the design of preheaters in the pyrolysis process, shows that the designed preheater can heat LDPE plastic waste to reach tar form with a thermal requirement of 6560 kJ for 1 hour. The thermal efficiency of the preheater using counter flow reaches 76.17%. The time required to convert LDPE plastic into tar is 42 minutes and 14 seconds [6].

Although pyrolysis technology has great potential, some constraints are energy efficiency, operational costs, and production scale. However, with policy support, ongoing research, and active participation from various parties, pyrolysis optimization in Cirebon City can be a successful and sustainable plastic waste management model in Indonesia. Pyrolysis optimization in Cirebon not only answers the waste problem but also supports the idea of a circular economy, where waste is recycled to produce economically valuable fuel. This process can reduce the use of conventional fuels and generate new jobs in waste management and energy production. By improving the Reactor, Condenser Tube, and Control System, this research is hoped to increase process efficiency, cost savings, and more environmentally friendly technology.

RESEARCH METHODS

This research was conducted by conducting an analysis to optimize the pyrolysis tool in the Mechanical Engineering Lab of Pancasila University. The pyrolysis tool consists of a burner, pyrolysis reactor, condenser, water pump, as shown in **Figure** 1. The plastic pyrolysis tool works by heating plastic waste at high temperatures without oxygen, so that the plastic decomposes into diesel, gasoline, and kerosene.

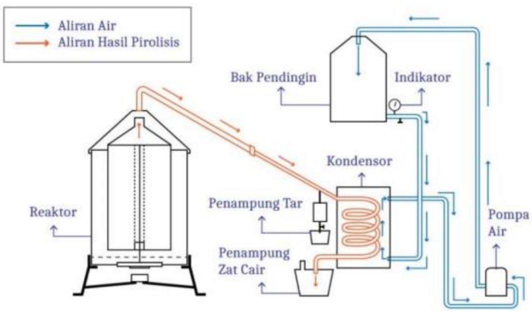


Figure 1 Pyrolysis scheme [7]

Plastic material

Table 1 shows that the raw materials for pyrolysis come from plastic waste purchased by the people of Cirebon City. Natural gas and petroleum are sources of plastic. Heat up to several hundred degrees Celsius will cause plastic to decompose. Most plastics contain carbon, polymers, oxygen, nitrogen, chlorine, or sulfur.

Table 1 Waste profile in Cirebon City [1]

Detail	Kota Bukittinggi	Kota Jambi	Kabupaten Bogor	Kota Cirebon	Kota Malang	Kota Denpasar
Timbulan Sampah						
kg/orang/hari	0,95	0,72	0,49	0,61	0,86	1,18
ton/hari	116,01	446,33	2682,8	203,36	764,34	854,75
Sumber Sampah						
Rumah Tangga	52,38%	57,7%	69,9%	45,69%	47,72%	81,78%
Non-Rumah Tangga	47,62%	42,3%	30,1%	54,31%	52,28%	18,22%
Komposisi Sampah						
1.Sampah makanan	49,71%	48,34%	55,30%	49,28%	54,39%	31,30%
2.Sampah taman	6,27%	13,16%	2,26%	11,77%	13,60%	41,79%
3.Plastik	21,97%	15,60%	16,58%	18,99%	13,66%	9,74%
a. Plastik PET – Kode 1	2,71%	2,76%	1,87%	2,79%	1,52%	1,36%
b. Plastik HDPE – Kode 2	1,93%	0,62%	0,39%	1,10%	0,53%	0,75%
c. Plastik PVC – Kode 3	0,00%	0,12%	0,37%	0,7%	1,17%	0,59%
d. Plastik LDPE – Kode 4	11,43%	5,83%	8,83%	8,57%	6,60%	4,96%
e. Plastik PP – Kode 5	4,11%	2,55%	3,18%	4,20%	1,32%	1,05%
f. Plastik PS – Kode 6	0,84%	0,90%	0,52%	1,08%	0,63%	0,45%
g. Plastik Lainnya – Kode 7	0,95%	2,82%	1,42%	0,55%	1,89%	0,58%
4.Kertas, Kardus, UBC	5,51%	6,66%	7,60%	5,53%	4,47%	4,67%
5.Logam	1,75%	2,08%	1,13%	0,70%	0,98%	1,04%
6.Tekstil	2,30%	1,49%	2,70%	1,76%	0,52%	1,35%
7.Karet	0,34%	0,21%	0,12%	0,58%	0,21%	0,33%
8.Kaca	1,35%	0,94%	1,20%	1,42%	1,78%	1,62%
9.Lainnya	10,80%	11,52%	13,11%	9,97%	10,39%	8,16%

Refuse Derived fuel (RDF)

RDF is an alternative fuel obtained from various types of solid waste, such as household, industrial, and commercial waste. RDF comprises combustible waste components such as plastic, paper, cardboard, textiles, and other organic materials. Waste-based Fuel (RDF) is produced from municipal waste processing. It has high heat energy, low water content, and high volatile matter and carbon content, making it suitable for thermochemical processing. Pyrolysis and gasification are potential methods for processing RDF, providing better energy recovery efficiency and less pollutant exhaust gas than conventional methods [8]. Waste materials such as cloth, wood, rubber, leather, and paper can be converted into waste-derived fuel (RDF). RDF can be used as fuel for pyrolysis equipment [9].

Population and economic activities influence the level of waste production in Cirebon. The city produces significant household waste, with organic waste as the main component. From the data obtained from Table 1, the potential waste generated from the Cirebon TPA and four types of waste compositions were selected with the potential to have optimal calorific value: garden waste, paper/cardboard, rubber, textiles/t-shirts. The calorific value of waste is influenced by the level of humidity, volatile matter content, fixed carbon, and ash content. Novita's research [10] provides data on the calorific value of various waste components as presented in Table 2. The potential RDF value produced with the optimal calorific value of the four types of waste composition selected at the Cirebon TPA is 573.104 kcal/kg or 2397.867 kJ/kg.

Table 2 Comparison of calorific value of waste components [10].

No	Sampel	Nilai Kalor (kcal/kg)					
		Bom Kalorimeter	LHV	Proximate Analysis		Dulong	
				1	2	3*	3**
	Kertas						
1	HVS	3024,24	2884,84	4234,29	1143,01		3591,18
2	Karton	3602,18	3359,17	4118,58	1154,28	6648,26	
3	Koran	3845,53	3618,95	4238,47	1306,64	4205,97	
4	Majalah	2598,95	2476,51	3646,23	992,02	2712,36	
5	Kertas Nasi	4246,92	3920,67	4167,29	1288,89		3591,18
6	Kardus	4487,07	4093,09	4257,12	1284,39	3571,67	
	Plastik						
7	PET Bottle (no.1)	5450,85	5252,42	4445,83	1382,24	11680,56	
8	HDPE Lembaran (no.2)	11207,00	11169,58	4444,73	1386,33		6307,50
9	PVC lembaran (no.3)	5187,91	5138,23	4332,82	1360,11	5448,78	
10	LDPE (no.4)	12318,40	12195,08	4505,66	1356,34		6307,50
11	PP Cup (no.5)	11912,80	11903,06	4426,95	1380,54		6307,50
12	PS (no.6)	11285,50	11269,80	4273,86	1379,38	9645,22	
	Sampah Makanan&Pasar						
13	Makanan tercampur	5162,21	1437,86	3727,54	737,10	4466,11	
14	Daun Pembungkus	4638,37	975,59	4069,59	573,85		4154,72
15	Batok&gambut kelapa	4684,11	3407,90	4446,86	1291,42		3915,63
16	Sayur	4568,29	689,85	4205,94	248,60		4466,11
17	Ikan	5837,12	1567,48	3497,23	581,39		4466,11
18	Lemak	9891,62	5065,61	4442,10	1213,95	9155,28	
19	Daging	7154,78	2597,33	4359,15	1034,45		
20	Tulang	4464,42	1570,90	3169,97	638,29		6951,46
21	Buah	5064,86	392,54	4337,90	-828,00	4347,01	
	Sampah Kebun						
22	Daun	3998,02	1632,60	3644,07	958,76		4154,72
23	Rumput	4153,51	906,08	7365,52	567,68		4154,72
24	Cabang pohon/ranting	4715,66	1997,45	4211,09	1096,14		3915,63
	Tekstil & Karet						
25	Handuk	4435,10	4239,45	4301,44	1348,27		4357,78
26	Jeans	4271,05	4010,65	4393,74	1372,21		4357,78
27	Kaos	4836,68	4664,32	4413,66	1365,93		4357,78
28	Karet	5202,15	5106,45	4218,60	939,96	8598,61	
	Kompos						
29	Mentah	2125,75	675,26	2402,29	420,93		4137,50
30	1/2 Matang	2091,90	979,05	2291,37	484,83		4137,50
31	Matang	1669,73	936,04	1854,94	415,31		4137,50
32	Residu	2211,65	980,02	3007,37	680,21		4137,50

Batch type reactor

Figure 2 shows a batch reactor as a closed system with no flow in or out of the reactor during the reaction. One of the disadvantages of this type of reactor is the variable product that varies from process to process, high employee cost per batch, and the inability to produce large quantities of product. Because of the charging and discharging process, batch reactors have a discontinuous process and extended downtime. All raw materials are fed into the reactor at the beginning of the process, and the reaction continues until completion. After the reaction, the product is removed, and the reactor is recharged for the next batch.

This reactor does not use a catalyst, causing the pyrolysis oil results to be less than optimal catalysts in pyrolysis function to accelerate the reaction by reducing activation energy. Catalysts can also increase the efficiency of plastic degradation and reduce pyrolysis temperatures. Catalysts vary according to the products to be produced. From the research results, Kaolin catalysts are excellent to use if they are going to make gasoline.

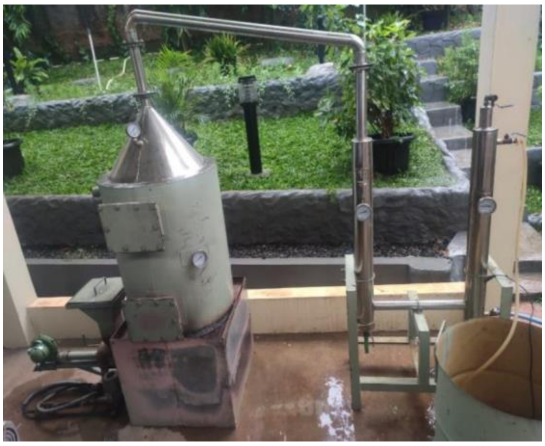


Figure 2 Batch type reactor

Condenser

The condenser is a component that functions to convert steam into water. This component has two primary forms: shell and tube and air-cooled condensers. The condensation process in the condenser tube is the process of changing the vapour phase into a liquid. The hot product vapour from the pyrolysis reactor passes through the condenser tube, which is cooled by a cooling fluid, usually water. The temperature difference between the steam and the cooling fluid causes the steam to lose heat energy and become liquid. The more efficient the condensation process, the more products can be collected, thereby increasing the overall efficiency of the pyrolysis system. Basics of material selection for condenser tubes, including:

1. Thermal properties of the material are a key factor in selecting materials for pyrolysis condenser tubes, including thermal conductivity and high-temperature resistance. The main criteria are thermal conductivity > 50 W/m K, Withstanding operating temperatures of 400-600°C and a low thermal expansion coefficient [11]. The thermal conductivity of several materials can be shown in **Table** 3.

Tabel 3 Thermal Conductivity of materials

Material	Conductivity (% IACS)	Resistivity (μΩ/cm)
Aluminum bronze	14.00	12.32
Aluminum 7075-T6	32.00	5.39
Aluminum 2024-T4	30.00	5.20
Aluminum 6061	42.00	4.10
Brass	28.00	6.20
Copper nickel 70–30	4.60	37.48
Copper	100.00	1.72
Gold	70.00	2.46
Monel	3.60	47.89
Copper nickel 90–10	9.10	18.95
Cast Steel	10.70	16.02
Hastelloy-X	1.50	115.00
Inconel 600	1.72	100.00
Lead	8.35	20.65
Magnesium	38.60	4.45
Phosphor bronze	11.00	16.00
Silver	105.00	1.64
Stainless Steel 316	2.33	74.00
Stainless Steel 304	2.39	72.00
Sodium	41.50	4.20
Ti-6AI-4V	1.00	172.00
Titanium-2	3.55	48.56
Tungsten	30.51	5.65
Zirconium	4.30	40.00
Zircalloy-2	2.40	72.00

2. Corrosion resistance. The material must resist corrosion caused by acidic and corrosive

pyrolysis products and the cooling media used. Factors to Consider: pH of pyrolysis products (2-5), operating temperature, sulfur content, and contact time [12].
3. Mechanical strength. The material must have sufficient mechanical strength to withstand operating stresses and thermal cycles. Parameters: Tensile strength: >250 MPa, Yield strength: >200 MPa, Fatigue strength: >150 MPa, Hardness: >120 HB [11].
4. High-temperature resistance. The material must withstand high temperatures without deformation or degradation of properties. Criteria: Maximum operating temperature: 500-600°C, Dimensional stability, No phase change, and Low coefficient of thermal expansion [13].
5. Fabricability. Ease of manufacture and assembly is an important consideration. Factors to consider in this aspect include ease of forming, weldability, ease of machining, and level of precision.
6. Lifetime and maintainability. Materials must have a long service life and be easy to maintain. Criteria: minimum lifetime: 5 years, ease of inspection, ease of cleaning, ease of repair.

For the selection of laboratory-scale condenser materials, the main priority factors must be thermal conductivity and ease of fabrication. Suitable materials for these points are: copper, aluminium alloy.

Control System

To ensure the effectiveness and efficiency of the pyrolysis process, a reliable control and monitoring system is needed. The monitoring control system can monitor and regulate process parameters in real-time, so that it can maintain the stability and quality of pyrolysis products. In addition, this system can also detect anomalies or problems that occur during the process and provide appropriate corrective actions.

In a pyrolysis system with high combustion temperatures, a sensor is required that can withstand working temperatures, namely in the range of up to 380 ° C. The temperature sensor that is suitable for this purpose is a type K thermocouple. This thermocouple is an analog sensor that produces voltage to be converted into a temperature value [14]. The design of the temperature sensor can be seen in **Figure** 3.

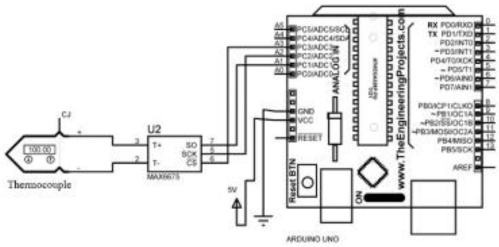


Figure 3 Temperature Circuits and Signal Conditioning [14]

Table 4 K-Type Thermocouple Sensor Specifications.

Specification	Information
Type	Tipe-K
Material	Crhomel (Nickel-Kromium) dan Alumel (Nickel-Aluminium)
Temperature range	-200°C - 1250°C
Accuracy	±2.2°C / ±0.75%

The K-type thermocouple sensor is composed of chromium and nickel on the positive side, which functions as the thermocouple level, and aluminum and nickel on the negative side, which functions as the expansion level. They have a measurement error limit of less than 10 degrees Celsius. This sensor is installed on the Reactor at 3 points, namely the top, middle and bottom. The use of RTD PT100 sensors on the condenser and storage tank in the pyrolysis system is very important to track and control the process optimally. The RTD PT100 sensor can provide accurate and stable temperature readings on the condenser to ensure ideal cooling rates and temperatures [15]. In addition, it is important to monitor the temperature of the holding tank so that the product does not get too cold (increasing viscosity) or too hot (causing decomposition) [16].

To maintain the stability and efficiency of the pyrolysis process in the raw material flow system, the use of hoppers and load cell sensors is a good solution, this is a key element to monitor the flow of plastic raw materials entering the reactor. A load cell sensor is a transducer that converts the weight of an object into electrical energy because there is resistance in the strain gauge. There are four strain arrangements on one load cell sensor. The conductance value of this sensor is proportional to the force/load it receives and is resistive in nature. The resistance value will be the same on each side if the load cell does not have a large load, but when the load cell is under pressure, the resistance value will be unbalanced. This is a procedure for measuring the load of an object [17]. The working principle of this sensor is as follows: when the strain gauge is subjected to a load, the other side changes its strain. This happens because the changing force is converted into a voltage generated by the existing measuring circuit. Table 3 shows the sensor specifications after being installed on the reactor input.

Table 5 Loadcell Sensor Specifications

Parameter	Specification
Nominal Load Capacity	100 kg
Accuracy	± 0.05% of Full Capacity
Hysterasis	± 0,05% of Full Capacity
Linearity	± 0,05% of Full Capacity
Temperature Stability	± 0,02% / °C of Full Capacity

This sensor is capable of measuring the mass of plastic being fed in real-time, providing accurate feedback to the control system to ensure the feed rate remains consistent and uniform. This allows operators to maintain optimal operating conditions throughout the process, minimizing fluctuations that can compromise conversion efficiency and end product quality. The integration of this weight sensor at the inlet hopper is a critical step in optimizing the overall performance of the plastic waste pyrolysis system [18]. A simple load cell circuit can be seen in **Figure** 4.

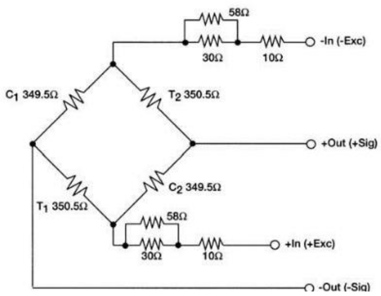


Figure 4 Simple Loadcell Circuit [17].

RESULTS AND DISCUSSION

1. Analysis of the most optimal plastic for producing gasoline

Research by Suhendi et al, 2023, obtained results that the composition of 30% PP and 70% LDPE will produce a pyrolysis product that has an octane number of 81.4, close to the octane number of gasoline at 88. So this composition is the most effective for producing gasoline.

Table 6 Results of testing different raw materials [19].

Parameters	Standard test	Gasoline product				SNI for gasoline
		100 PP	**70: kg pp:30 kg LDPE**	**50: kg pp:50 kg LDPE**	**30: kg pp:70 kg LDPE**	
Density (kg/m^3)	ASTM D 1298	772	760	780	779	715-770
Octane number	ASTM D 163	76.7	78.9	79.7	81.4	88
Heating value	Bomb Calorimeter 6400	10,926.30	10,836.30	10,780.30	10,660.30	10,160-11,000

The results of the research showed that pyrolysis of LDPE and PP plastics can provide results comparable to fuel due to the presence of alkane and alkene groups in both types of plastics. Based on the FTIR analysis that is most similar to gasoline fuel, the pyrolysis product of PP plastic shows the results most similar to gasoline fuel.

2. Modify the preheater burner by utilizing hot air from the gas output (Flue Gas)

The preheater heats plastic waste into tar using residual gas from the pyrolysis process. This tool requires 6560 kJ to convert plastic waste into tar at a temperature of 300°C and has a thermal efficiency of 76.17% through different flows [6]. Abdullah Research [20] investigated a modified pyrolysis system, where solar energy is used for preheating. This system has been proven to reduce fuel costs, energy use becomes more efficient, and prevent global warming. The solar-assisted system managed to save almost 38% of conventional energy and significantly reduce CO2 emissions, demonstrating its effectiveness in reducing pollution and heating costs. In this research optimization, a preheater will be used that utilizes exhaust gas from the remaining combustion in the combustion chamber into the preheater as shown in **Figure** 5.

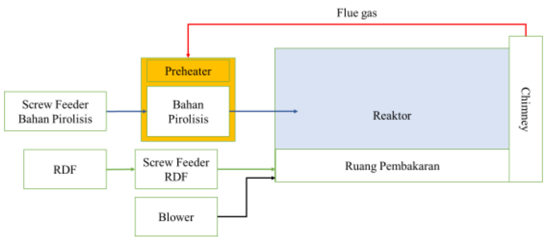


Figure 5 Schematic of the pyrolysis process using a preheater.

The exhaust gas coming out of the combustion chamber is channeled using a pipe to a preheater made of stainless steel to heat the pyrolysis plastic material contained in the preheater before being fed into the reactor.

3. Modification of electric screw hopper in burner and addition of blower using Solar PV

Feeding biomass or RDF into a thermochemical reactor encounters various obstacles such as bridging, ratholes, and blockages. These obstacles prevent continuous operation. Various feeder systems are applied in biomass gasification and combustion processes, such as screw feeders, rotary valves, hoppers, and pneumatic systems. Each system has its own specific uses and limitations. An effective feeder system requires proper speed control, resistance to back pressure, and adaptability to various fuel properties [21]. The advantages of using an electric screw feeder with a flexible hopper are that the accurate flow control of the screw feeder allows for very accurate capacity or flow rate control. By using an electric screw feeder, the fuel flow can be precisely controlled. The flexible hopper gently conditions the fuel into a uniform bulk density. This is essential to ensure consistent and accurate material flow. Helps prevent material segregation, as segregation occurs when heavy particles are more likely to settle at the bottom of the hopper, disrupting the “first-in, first-out” flow pattern.

The addition of a blower allows for optimal airflow rates, which increases combustion efficiency by ensuring that the fuel is completely burned. Blowers that use electricity from Solar PV and batteries can operate at night and during cloudy/rainy weather, ensuring that the process continues without interruption. In this research optimization, solar PV will be used as an energy source to drive the screw feeder hopper and blower as shown in **Figure** 6.

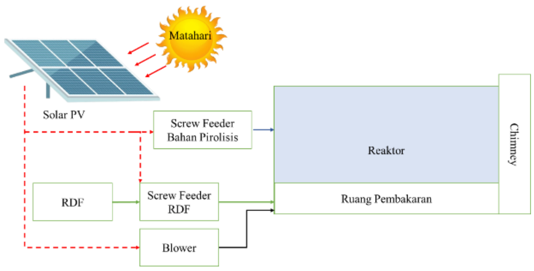


Figure 6 Schematic optimization of solar PV utilization as a power source to drive the screw feeder hopper and blower.

4. Analysis of plastic pyrolysis reactor design

Catalyst Addition

Catalysts in pyrolysis function to accelerate the reaction by reducing activation energy. Catalysts can also increase the efficiency of plastic degradation and reduce pyrolysis temperatures. Catalysts vary according to the products to be produced. From the research results, Kaolin catalysts are very good to use if they will produce gasoline as shown in **Figure** 7.

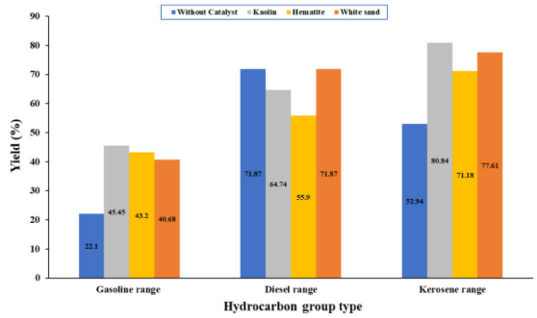


Figure 7 Catalyst used in pyrolysis

The reactor modeling is shown in **Figure** 8.

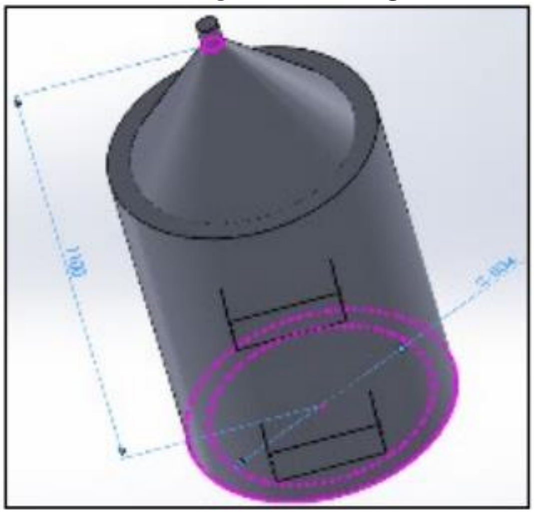


Figure 8 Reactor modeling [22]

- The RDF value produced with the optimal calorific value at the Cirebon TPA is: 964,28 kcal/kg = 4034,54 kJ/kg
- $\rho_{\text{plastic PP \& LDPE}} = 855\ kg/m^3$
- Plastic mass = 50 kg
- Reactor Mass = 10 kg
- Reactor diameter = 50 cm = 0,5 m

- $V = \frac{1}{4} \cdot d^2 \cdot t = \frac{1}{4} \cdot 0{,}5^2 \cdot 1$
  $= 0{,}0625\ m^3 = 62{,}5$ liter

- Volume (V) $= \frac{m}{\rho} = \frac{20\ kg}{855\ kg/m3}$
  $0{,}0625 = \frac{m}{855\ kg/m3}$
  $m = 855\ \frac{kg}{m3} \cdot 0{,}0625\ m^3 = 53{,}43\ kg$

- The mass of plastic that can be put into the reactor is 50 kg.

Table 7 Optimal pyrolysis temperature of plastic pyrolysis results [23]

Plastic Type	Temp (°C)	Char (%wt)	Liquid (% wt)	Gas (% wt)
PET	500	8.98	52.13	39.89
HDPE	300–400	33.05–0.54	80.88	–
HDPE	600	34.7	18.1	28.9
PP	300–700	78.8	21.8	7.2
PVC	500–700	–	29.65–0.38	–
LDPE	350–600	12.7	74.4	36.8
PP	380	13.3	80.1	6.6
PP	740	1.6	48.8	49.6
PP	400	16	76	8

The reactor is made of mild steel with cp = 490 J/kg°C, the energy required to heat the reactor up to 500 °C:

Q $= m \bullet c_p \bullet \Delta T$
= 10 kg • 490 J/kg°C • (500-30) °C
= 2,303,000 J = 2,3 x 10^6 J

The energy required to heat PP plastic to 380 °C:

Q $= m \bullet c_{p\ plastic\ pp\ \text{LDPE}} \bullet \Delta T$
= 25 x 1,030 x (380-300)
= 2,060,000 J
= 2,06 x 10^6 J

5. RDF energy analysis

The potential RDF value produced with the optimal calorific value of the four types of waste composition selected at the Cirebon TPA (in Table 2) is 573.104 kcal/kg or 2397.867 kJ/kg (2.4 x 106 J/kg). These results indicate that RDF fuel is capable of producing the energy required by the reactor. The mass of RDF gas used and the calorific value of RDF can be used to calculate the amount of energy required by the burner to distill plastic at the desired temperature.

It is known that LHV RDF = 2.4 x 103 J/kg
Mass used (m) = 0.284 kg = 284 g
Heating time = 60 minutes

I = $\frac{284 \text{ x } 2400}{60}$ = 11,36 kJ/ minutes

6. Condenser design analysis

Increasing the Surface Area of the Condenser Tube

Increasing the surface area of the condenser tube will increase the heat transfer rate and condensation efficiency. Lower coolant temperature will increase the temperature difference between the vapor and the fluid, which will increase the condensation rate. Higher coolant flow rate will increase the fluid's ability to absorb heat from the vapor. The type of condenser tube material that has high thermal conductivity will increase the heat transfer rate. The surface area of the condenser tube is the total contact area between the heat transfer surface and the fluid (pyrolysis vapor and cooling medium) which affects the heat transfer efficiency and condensation rate. The parameters that need to be considered include: Heat transfer area: 0.5-2 m²/kg input/hour, Surface area/volume ratio: 150-300 m²/m³, and Heat transfer efficiency: 85-95% [24].

Increasing the Cooling Fluid Temperature in the Condenser Tube

Increasing the temperature of the coolant in the condenser tube is a thermal process in which the temperature of the coolant flowing in the condenser system increases as a result of heat transfer from the hot fluid (usually steam) being condensed [25]. As for the Important Aspects:

1) Heat Transfer Methods [26]:
   - Convection heat transfer between hot fluid and tube wall
   - Conduction through tube wall
   - Convection from tube wall to cooling fluid
2) Factors Affecting Operational Parameters [27]:
   - Cooling fluid mass flow rate
   - Operating pressure
   - Cooling fluid inlet temperature
   - Fluid heat capacity

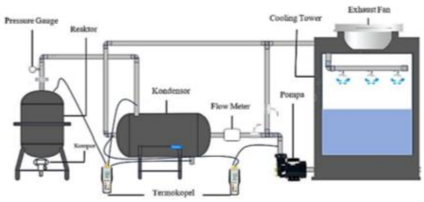
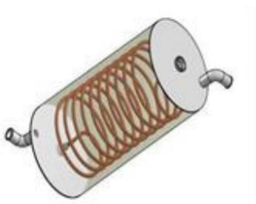


Figure 8 Condenser cooling system optimization scheme

The copper pipe used for the condenser has k=360.5 W/m°C, an outer diameter of 0.013 m, an inner diameter of 0.0115 m, and an inlet water temperature of 25 °C. The gas temperature through the condenser is 65 °C, and the surface temperature of the pipe is 35 °C.



Gambar 9 Condenser [28]

The condensation event occurs inside the condenser. The film temperature Tf:

$Tf = \frac{100}{50}$

= 2 °C

Inside the condenser the heat transfer is by conduction:

$$q = \frac{\text{In}\frac{(5{,}715 \cdot 10^{-3})}{(5{,}715 \cdot 10^{-3})}}{2 \cdot \pi \cdot 360{,}5}$$

= 6.670 x 10^5 W/m°C

The outer condenser tube undergoes convection. The film temperature Tf is:

$$Tf = \frac{50+20}{2}$$

= 35 °C

Forced convection occurs on the outside of the condenser, so:

$$Re = \frac{\mu \text{ x } D}{v}$$

$$= \frac{0{,}0022 \text{ x } 0{,}013}{0{,}00000089}$$

= 32,134

In the condenser, the crossflow in the cylinder is turbulent flow, so the Nucyl value is:

Nucyl = C. Red^m . Pr^n

= C. Red^m . $Pr^{1/3}$

= 0.683 x $32{,}134^{0.466}$ x $6{,}3^{1/3}$

= 5,971

So the value of:

$$ho = 0.591 \frac{5{,}971}{0{,}013}$$

= 277.3 W/m°C

Overall Heat Transfer Coefficient is calculated using the following equation:

$$Uo = \frac{1}{\frac{0{,}013}{0{,}0115} \cdot \frac{1}{66{,}65} \cdot \frac{0{,}013 \cdot \text{In}(\frac{0{,}013}{0{,}0115})}{2 \cdot \pi \cdot 360{,}5} \cdot \frac{1}{277{,}3}}$$

= 277.29 W/m.°C

Determining the length of the condenser pipe required to produce the specified plastic pyrolysis parameters from the overall heat transfer coefficient value.

$$\Delta T \text{ LMTD} = \frac{(260-35)-(65-25)}{\text{In}\frac{(260-35)}{(65-25)}}$$

$$= \frac{185}{1{,}727}$$

= 107,12 °C

$$A = \frac{59.81}{277.29 \text{ x } 107{,}12}$$

= 0.00122 m^2

If the outer diameter of the condenser pipe is 0.013 m, then the length of the condenser pipe is:

$$L = \frac{0.00122}{0.013}$$

= 1.8 m

Pump and Motor Power

Cooling water is flowed into the condenser tube using a pump during the distillation equipment testing process with the following specifications:

Pump Input = 220 v, 2 A

Pump power:

P = V x I
= 220 V x 2 A
= 440 watt x 60 minute
= 440 watt x (1 hours)
= 440 watt
= 440 watt x (60x60)
= 1.584.000 Joule

Distillate Efficiency

Method for comparing the amount (quantity) of oil produced from the distillation process:

Distillate efficiency (%):

ηdestilat

$$= \frac{(\text{Berat basah (kg)}) - \text{Berat kering (kg)})}{\text{Berat basah (kg)}} \text{x } 100 \%$$

$$= \frac{25000 \text{ gr} - 5000 \text{ gr}}{25000 \text{ gr}} \text{x } 100 \%$$

= 80 %

7. Control system optimization

Given the many interrelated variables that contribute to this process, including pressure, temperature, heating rate, and feedstock flow rate. A responsive and reliable control system is required to ensure stable and consistent operation and the production of high-quality products. In this regard, the Proportional-Integral-Derivative (PID) controller has proven to be an effective method for using pyrolysis machines. [29].

There are many methods used to obtain Kd, Ki, Kp, but in this design, the Ziegler-Nichols method 1also known as the response curve method is used. [30].

The PID controller will combine these three components to produce a control signal that is sent to the actuator. This control signal will adjust the process parameters, such as temperature, pressure, or raw material flow rate so that the actual value is close to the desired set point.

The integrated PID control system with K-type thermocouple temperature sensors on the reactor, RTD PT100 temperature sensors on the condenser and storage tank, and loadcell sensors on the hopper provide an intelligent and responsive solution to maintain process stability. The combination of these sensors not only provides accuracy temperature and load measurements at every stage, but also ensuring that each component works optimally in perfect synchronization. As a result, the process runs more efficiently, safely, and is able to maintain consistent quality results..

Techno Economic Analysis

Tabel 8 Perhitungan tekno ekonomi

No	Rincian Biaya	Total
1	Biaya modifikasi	69.000.000,00
2	Pinjaman pokok per bulan selama 5 tahun	1.150.000,00
3	Bunga per tahun	9,25%
4	Bunga per bulan	531.875,00
5	Cicilan per bulan (+ bunga)	1.681.875
6	Biaya Cicilan dibagi per hari (22 hari)	76.449
7	Kapasitas produksi per jam (kg)	20
8	Kapasitas produksi per hari 24 jam (kg)	480
9	Harga Limbah Plastik PP & LDPE pr kg	4.000
10	Biaya pembelian limbah plastik per hari	1.920.000
11	Laju pembakaran per jam (kg)	6
12	Konsumsi RDF per hari (kg)	144
13	Harga RDF per kg (rupiah)	350
14	Biaya pembelian RDF per hari	50.400
15	Octane Booster untuk 480 liter	446.400
16	Total biaya produksi per hari (Kapasitas 480 kg)	2.493.249
17	Produk yang dihasilkan per hari (liter)	480
18	Biaya untuk menghasilkan produk pirolisis bensin per liter	5.194
19	Harga Jual produk pirolisis per liter	10.000
20	**Omset per bulan (22 hari)**	**4.800.000,00**
21	**Keuntungan bersih per bulan (22 hari)**	**2.306.751**

From the research conducted, it is known that:

- 1 kg of pyrolysis raw materials (LDPE & PP) can produce 1 liter of pyrolysis oil with the same quality as gasoline.
- The octane number of the pyrolysis results is 81.4 (SNI Standard 88) So additives or octane boosters must be added to achieve the quality.
- The results of techno-economic calculations show that the pyrolysis tool has economic value. With a net profit of 2.3 million per month.
- So that the product can be used for fuel for garbage transport motorbikes.

CONCLUSION

Pyrolysis can be optimized using the following methods:

1. Selection of the most optimal plastic material, namely 30% PP and 70% LDPE
2. Using RDF for burner fuel with optimal calorific value at the Cirebon TPA, namely: 964.28 kcal / kg = 4034.54 kJ / kg
3. Kaolin catalyst is very good to use if it will produce gasoline with a yield of 45%
4. Increasing the Surface Area of the Condenser Tube
5. Maintaining the Temperature of 25oC Cooling Fluid in the Condenser Tube
6. Modifying the burner preheater by utilizing hot air from the gas output (Flue Gas)
7. Modifying the electric screw hopper in the burner and adding a blower using Solar PV

REFERENCES

[1] K. Ppn et al., "Laporan kajian data timbulan dan komposisi sampah di 6 kota/kabupaten di Indonesia," 2023.

[2] B. Wajdi, B. Aryani Novianti, and L. Zahara, "Pengolahan sampah plastik menjadi bahan bakar minyak (BBM) dengan metode pirolisis sebagai energi alternatif," 2020. [Online]. Available: http://e-journal.hamzanwadi.ac.id/index.php/kpj/index

[3] Kementrian Sekretariat Negara RI, "Perpres No. 97 Tahun 2017," 2017.

[4] H. Prasetiawan, T. Danik Nafasyeila, and D. Selvia Fardhayanti, "Pengolahan sampah plastik menggunakan metode pirolisis sebagai upaya pengurangan limbah plastik pada lingkungan: Review," 2022.

[5] H. N. Putra, A. N. Lasman, and E. Maulana, "Analisis termoekonomi pada pemanfaatan alat pirolisis dengan menggunakan kombinasi RDF dan LPG," 2022.

[6] E. Maulana and K. G. Sitinjak, "Perancangan Preheater pada Sistem Pirolisis Kapasitas 20 Kg/Jam," 2022.

[7] G. R. Suyanto and S. Harahap, "Analisis penggunaan campuran minyak hasil pirolisis dan pertalite sebagai bahan bakar genset EP1000," 2019.

[8] M. Alfè et al., "Pyrolysis and gasification of a real refuse-derived fuel (RDF): The potential use of the products under a circular economy vision," Molecules, vol. 27, no. 23, Dec. 2022, doi: 10.3390/molecules27238114.

[9] E. Maulana et al., "Analisis kinerja refuse derived fuel (RDF) dari sampah organik dan non organik dengan pendekatan simulasi software," vol. 13, no. 1, 2021, doi: 10.24853/jurtek.13.1.109-114.

[10] D. M. Novita and D. E. Damanhuri, “Perhitungan nilai kalor berdasarkan komposisi dan karakteristik sampah perkotaan di Indonesia dalam konsep waste to energy,” 2010.

[11] A. Abdulwahab and S. Mysen, “Experimental study of condenser material in the air conditioning system,” Mater Today Proc, vol. 61, pp. 860–864, Jan. 2022, doi: 10.1016/j.matpr.2021.09.303.

[12] V. A. Owoeye et al., “Effect of precursor concentration on corrosion resistance and microstructure of ZnO thin films using spray pyrolysis method,” Sci Afr, vol. 15, Mar. 2022, doi: 10.1016/j.sciaf.2021.e01073.

[13] H. Saputro et al., “Modeling and experimental study condenser performance of fixed bed pyrolysis reactor: A case study of solid waste palm starch processing,” Clean Eng Technol, vol. 16, Oct. 2023, doi: 10.1016/j.clet.2023.100677.

[14] B. Rachmanto, M. Fauziyah, and Sungkono, “Sistem kontrol suhu dan laju pemanasan proses pirolisis pengolahan limbah plastik menjadi BBM dengan metode PID,” 2020.

[15] P. Dasar, A. Rekayasa, R. Zainul, S. Pd, and M. Si, “Teknologi material maju,” 2018.

[16] A. Mohanty, S. Ajmera, S. Chinnam, V. Kumar, R. K. Mishra, and B. Archarya, “Pyrolysis ofwaste oils for biofuel production: An economic and life cycle assessment,” 2024.

[17] A. Wibowo and L. A. Supriyono, “Analisis pemakaian sensor loadcell dalam perhitungan berat benda padat dan cair berbasis microcontroller,” 2019.

[18] M. V. Driantama, “Rancang bangun sistem otomasi berat bahan baku mesin crusher pada mini plant produksi bahan bakar minyak (BBM) dari limbah plastik berbasis mikrokontroller,” Institut Teknologi Sepuluh Nopember, 2018.

[19] E. Suhendi, H. Heriyanto, M. Ammar, A. Tsania, and M. K. Anam, “The Effect of Polypropylene and Low-Density Polyethylene Mixtures in the Pyrolysis Process on the Quantity and Quality of the Oil Products ARTICLE HISTORY ABSTRACT,” 2023. [Online]. Available: http://jurnal.untirta.ac.id/index.php/WCEJ

[20] M. A. Abdullah, “Improvement of the Pyrolysis System by Integrating Solar Energy Based Preheating System,” IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE, vol. 18, pp. 25–30, 2021, doi: 10.9790/1684-1803042530.

[21] J. Dai, H. Cui, and J. R. Grace, “Biomass feeding for thermochemical reactors,” Oct. 2012. doi: 10.1016/j.pecs.2012.04.002.

[22] R. Sirait, E. Maulana, and D. Mahardika, “Analisis Keseimbangan Energi pada Reaktor Pirolisis Kapasitas 75 Kg/Jam,” 2023. [Online]. Available: http://jurnal.umj.ac.id/index.php/semnaslit

[23] A. Al-Rumaihi, M. Shahbaz, G. Mckay, H. Mackey, and T. Al-Ansari, “A review of pyrolysis technologies and feedstock: A blending approach for plastic and biomass towards optimum biochar yield,” Oct. 01, 2022, Elsevier Ltd. doi: 10.1016/j.rser.2022.112715.

[24] B. Rubianto, R. Winarso, and R. Wibowo, “Rancang bangun kondensor pada destilator bioetanol kapasitas 5 liter/jam dengan skala UMKM,” Jurnal CRANKSHAFT, vol. 1, 2018.

[25] H. Poernomo, J. Teknik Permesinan Kapal, and P. Perkapalan Negeri Surabaya, “Analisis karakteristik unjuk kerja sistem pendingian (air conditioning) yang menggunakan freon R-22 berdasarkan pada variasi putaran kipas pendingin kondensor,” 2015.

[26] M. M. Sari et al., “Transforming disposable masks to sustainable gasoline-like fuel via pyrolysis,” Environmental Advances, vol. 15, Apr. 2024, doi: 10.1016/j.envadv.2023.100466.

[27] K. Ridhuan, I. J. Gede Angga, J. Teknik Mesin Fakultas Teknik Universitas Muhammadiyah Metro, J. Ki Hjar Dewantara No, and K. Metro, “Pengaruh media pendingin air pada kondensor terhadap kemampuan kerja mesin pendingin”.

[28] L. Ode, M. Firman, E. Maulana, and G. Panjaitan, “Yield bahan bakar alternatif dari optimasi pirolisis sampah plastik polypropylene,” 2023.

[29] P. Parthasarathy and K. S. Narayan, “Hydrogen production from steam of biomass,” 2013.

[30] M. Andrian, A. Kurniawan, I. Saukani, and P. N. Malang, “Sistem kendali suhu menggunakan metode PID dalam proses deasetilasi kitin,” Jurnal Ilmu Teknik, vol. 1, no. 2, pp. 131–137, 2024.