The Optimization of Flue Gas Utilization from Furnace-02 as a Heat Source in a Pyrolysis Reactor Design for Energy Converting of Polypropylene into Fuel Oil at PPSDM Migas, Cepu

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***Abstract*— Furnace-02 at PPSDM Migas is utilised in the petroleum processing of residual fuel. The efficiency value of furnace-02 is 62.71%, with 119,1763 Btu/h of heat being wasted through flue gas and a flow velocity of 164 m3/min. The heat value in the flue gas is utilised for the purpose of pyrolysis of the plastic, with a view to optimising energy use in the furnace. The process of plastic pyrolysis has been demonstrated to yield pyrolysis oil, which possesses a calorific value comparable to that of gasoline (10,520 kcal/kg). This pyrolysis oil has the potential to serve as a substitute fuel source for fossil fuels. The design of the pyrolysis system burner modification is such that its capacity is 75 kg/hour. The energy utilisation in the design amounted to 28,645.02 kJ/h, representing 2.3% of the total flue gas heat.**

Keywords*—Pyrolysis, Flue Gas, Furnace, Polypropylene*

I. Introduction

Petroleum is one of the natural resources that humankind has successfully exploited and utilised in its daily lives. As stated in [1], non-renewable energy sources are defined as energy sources that are produced from energy resources which will be depleted if exploited continuously. Such energy sources include petroleum, natural gas, coal, peat, and bituminous shale.

The utilisation of furnace fuel for oil processing at PPSDM Migas employs diesel and gas as its primary energy sources. The research results indicate that the efficiency levels of furnaces 03, 02 and 01 are 68.45%, 86.16% and 71.809%, respectively (see [2], [3]). It is evident that further potential energy exists that can be harnessed [4]. This efficiency assessment, in conjunction with several studies pertaining to the pyrolysis of plastic, which results in the production of oil as an alternative energy source, has given rise to the concept of designing and modifying the burner in a pyrolysis reactor. This reactor operates under conditions analogous to those employed in waste treatment tests utilising the pyrolysis process, as outlined in [5]. The focus of this process is the conversion of polypropylene (PP) plastic into fuel oil. The utilisation of the flue gas is intended to ascertain its calorific value and heat potential, and to determine a method for its utilisation. The pyrolysis system is capable of producing pyrolysis oil, which can then be utilised as an alternative energy source. The calorific value of pyrolysis oil has been determined to be 10,520 kcal/g [6], whereas the calorific value of conventional fuels is typically found to range from 10,160 kcal/g to 11,000 kcal/g.

The objective of this study is to ascertain the viability of utilising flue gas for pyrolysis. Furthermore, the objective of this study is to ascertain the minimum amount of energy required for pyrolysis in the designed pyrolysis reactor. The objectives of the study are to propose a pyrolysis reactor design suitable for separating flue gas from polypropylene fuel. The focal point of this study is the energy efficiency of furnace-02 at PPSDM Migas Cepu, with the analysis encompassing recorded furnace operating data comprising temperature, pressure, flow rate, and fuel oil mass. These data are then used as input for data processing. The subsequent results of the energy usage calculations will reveal the amount of unused energy, which will be used as material for the design and visualisation of the flow in the pyrolysis reactor design in accordance with the specifications of the related research on the Conversion of Polypropylene Plastic into Fuel Oil [5].

II. Methods

Exergy is defined as the maximum amount of work that can be obtained from a reversible process change in equilibrium with the environment [7]. In essence, exergy can be defined as the quantity of energy that can be converted into work. The potential for energy savings, even if modest, in the distillation process is significant, resulting in substantial economic benefits [8].

A furnace is a device employed in petroleum operations for the purpose of heating crude oil to a specific temperature, in accordance with the stipulated process plan. The furnace's efficiency is measured as a performance indicator during the process. The calculation of efficiency in this article employs an indirect calculation scheme. This is achieved by means of a comparison of the heat entering and exiting the system, as illustrated in Figure 1. In order to calculate the efficiency value of the system, a number of calculations must be performed in order to determine furnace efficiency indirectly. These calculations include the specific gravity (SG) value, the °API value of crude oil and fuel oil, and the KUOP value. The specific gravity value is shown in equation 1.

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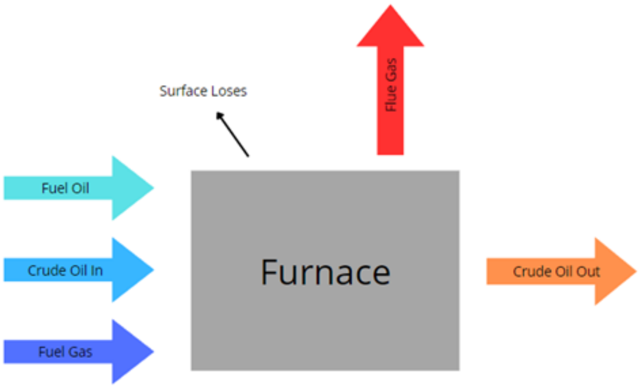

Figure 1. Furnace Efficiency Scheme

$$Specific\ Gravity\left(\frac{60}{60}°F\right) = \frac{density\ of\ liquid\ at\ 60°f\ in\ g/cm^3}{0{,}999g/cm^3} \quad (1)$$

The calculation of API gravity in crude oil and fuel oil can be achieved through the utilisation of the following equation 2.

$$°API = \frac{141{,}5}{SG(\frac{60}{60}°F)} - 131{,}5 \quad (2)$$

The KUOP value can be calculated using equation 4 below.

$$K = \frac{\sqrt[3]{Tb}}{SG(\frac{60}{60}°F)} \quad (3)$$

Referring to Figure 5.1[9], the boiling point is indicated by Tb. The calculation of the heat of combustion is performed using equation 5.

$$Q_o = m_o \cdot GHV \quad (4)$$

The quantity of oil is denoted by m_o. The calculation of the sensible heat of fuel oil is to be undertaken using equation 5.

$$Q_{so} = m_o \cdot Cp \cdot (T_2 - T_1) \quad (5)$$

The calculation of the heat of combustion in fuel oil is achieved through the utilisation of equation 6.

$$Q_{Fg} = m_g \cdot LHV \quad (6)$$

The amount of fuel gas can be calculated using equation 7.

$$Q_g = 443{,}45\ \frac{Ts}{Ps}\ x\ D^{2{,}667}\ x\ \frac{\sqrt{P1^2+P2^2}}{L\ x\ SG\ x\ T} \quad (7)$$

The calculation of the sensible heat of fuel gas can be performed using equation 8.

$$Q_{sg} = m_o \cdot Cp \cdot (T_2 - T_1) \quad (8)$$

The calculation of the heat of combustion and excess air can be facilitated by equation 9.

$$Excess\ Air = \frac{O^2 berlebih - \sum O^2\ pembakaran}{\sum O^2\ pembakaran} \quad (9)$$

The heat contained in flue gas can be determined using equation 10.

$$Q7 = \sum n_{gas}\ x\ Cp\ udara\ keluar\ Stack \quad (10)$$

The C_P emanating from the stack can be observed in Figure 14.1 [9]. It is estimated that the heat lost through the walls is approximately 2-3% of the total radiant heat input [9].

$$Q_D = 2\%\ x\ Q_{in} \quad (11)$$

The calculation of furnace efficiency can be achieved by utilising equation 12.

$$Efisiensi = \frac{Panas\ Masuk - Panas\ Keluar}{Panas\ Masuk}\ x\ 100\% \quad (12)$$

Pyrolysis is defined as the process of reducing the thermal properties of polymer or plastic materials by heating in the absence of chemical reactions with oxygen. The raw material undergoes chemical structural breakdown until it changes phase [10]. The objective of pyrolysis is to release volatile substances contained within biomass, which are present in significant quantities, and materials that can be converted through pyrolysis are those with a high cellulose content. The utilisation of pyrolysis as a method for the decomposition of plastic is due to the fact that the decomposition of plastic at high temperatures is the simplest process for recycling plastic [11]. The process of pyrolysis involves the combustion of organic materials in the absence of or at a low concentration of oxygen. Pyrolysis is a process that yields a range of by-products, including exhaust gases such as carbon monoxide, hydrogen, and methane, as well as charcoal, ash, and non-combustible materials [12].

Thermoplastics are defined as a category of plastic that undergoes a phase transition into a liquid state when subjected to heating until the melting point is reached. The process of moulding thermoplastics in liquid form allows for the creation of the desired shape. It is evident that thermoplastics can be recycled based on the type of plastic, which has been coded to facilitate identification and use. The thermoplastic employed in this study is polypropylene, which has a specific heat of 1700 J/kg·°C, a melting point of 110°C, and a vaporization temperature of 300°C. Polypropylene requires latent heat of fusion at 207 kJ/kg and latent heat of vaporization at 4640 kJ/kg.

The heat transfer process in a cylindrical pyrolysis reactor occurs through radial conduction which satisfying the following equation.

$$Q = \frac{2\pi L(T_1 - T_2)}{\frac{\ln(r_2/r_1)}{k_A} + \frac{\ln(r_3/r_2)}{k_B} + \frac{\ln(r_4/r_3)}{k_C}}$$

The convection flow passing through the rough pipe satisfies the following equation.

$$N_{ud} = \frac{(\frac{f}{8})R_{ed}\,P_r}{1{,}07+12{,}7(f/8)^{1/2}(P_r^{2/3}-1)}\left[\frac{\mu}{\mu_w}\right]^n$$

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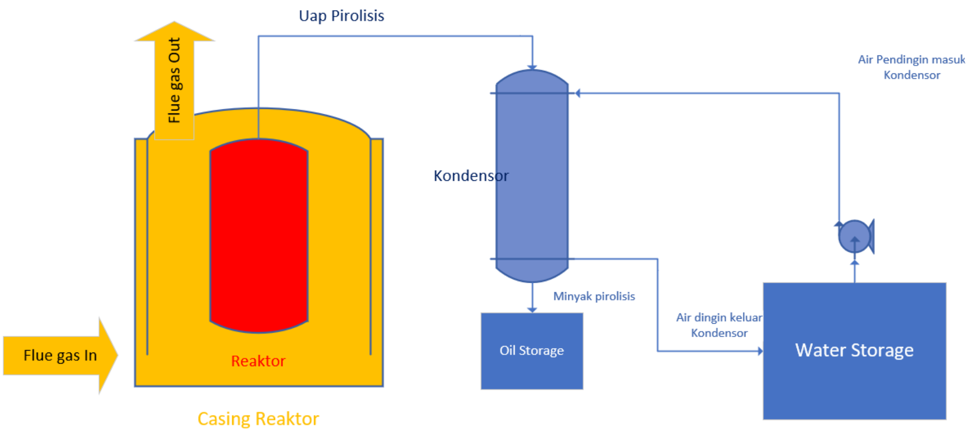

Figure 2. The scheme of a pyrolysis system design

The convection flow passing through the inner pipe of the cylinder can be determined using the following equation.

$$N_u^{1/2} = 0{,}6 + 0{,}387\left(\frac{Gr\ Pr^{1/6}}{\left[1+\left(\frac{0{,}559}{Pr}\right)^{9/16}\right]^{16/9}}\right)$$

The reactor pressure vessel, otherwise referred to as a closed cylindrical tube, fulfils the function of a container for both internal and external pressure [13].

In the following equation, the variables are defined as follows: t is Wall Thickness, P is Pressure, S is Material Tensile Stress, R is Inner Radius, and E is Joint Efficiency. In this formula, t denotes the thickness of the wall, P is the pressure, S is the tensile stress of the material, R is the inner radius, and E is the joint efficiency.

The pyrolysis design employs the heat contained within the flue gas. The flue gas enters the casing of the pyrolysis reactor, where it undergoes a process of heat transfer with the reactor. The heat from the reactor has the capacity to affect a phase change in the plastic, altering its state from a solid to a gas. This gas is then condensed in order to produce pyrolysis oil.

The objective of this study is to analyse the energy efficiency of the furnace at PPSDM Migas Cepu, utilising furnace operating data recorded by operators. This data encompasses parameters such as temperature, pressure, flow rate, and fuel oil mass. The results of this study will be used to support the research process. The calculated energy usage will then reveal the amount of unused energy, which will be used as input for the design and visualisation of the flow in the pyrolysis reactor design, in accordance with the specifications of the research conducted by [5] regarding the conversion of polypropylene plastic into petroleum fuel.

The research project on Pyrolysis Reactor Design necessitates the utilisation of specific instruments and materials, including an operation log sheet, Computer Aided-Design (CAD) software, and Computational Fluid Dynamics (CFD) software. The furnace's operating log sheet is utilised for the calculation of fuel consumption and furnace efficiency during operation, incorporating parameters such as the quantity of fuel oil, crude oil, temperature, pressure, and the flow rate of incoming and outgoing air. Furthermore, both CFD and CAD software are utilised for process simulation, with both CFD and CAD serving as integrated supporting software for the design and visualisation of fluid flow.

Table 1. Thermal balance at Furnace-02

Heat inlet		Heat Outlet	
Heat combustion of fuel oil (Q1)	7052142,69 Btu/h	Heat outlet in liquid phase of crude oil (Q6A)	168244,12 Btu/h
Sensible heat of fuel oil (Q2)	7043,10 Btu/h	Heat of crude oil in gas phase (Q 6B)	1608815,84 Btu/h
Crude oil inlet (Q3)	1123546,93 Btu/h	Heat calculation of flue gas (Q7)	1191763,21 Btu/h
Sensible heat combustion of fuel gas (Q4)	87074,15 Btu/h	Heat losses through the boundary walls (Q8)	168244,12 Btu/h
Heat calculation of air combustion (Q5)	142399,29 Btu/h		
Inlet heat quantity	8412206,184 Btu/h	Outlet heat quantity	3137067,3 14 Btu/h

III. Results and Discussion

The energy balance presented in Table 1 was derived through a series of calculations employing an indirect approach, with particular reference to the values of heat input and output in Furnace-02.

The efficiency of a furnace can be determined by comparing the heat absorbed by the crude oil with the total heat entering the furnace. The calculation has been recalibrated to align with equation 12, thereby yielding an efficiency value of for Furnace-02.

The efficiency value and flue gas resultant from the thermal balance calculation are presented herewith. The usable heat value is 70% at 880,167.19 kJ/h with a

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temperature of 314.98°C. It has been demonstrated that the heat value of the flue gas has the potential to perform 4.4 times more pyrolysis processes than those performed by [5]. In the study under consideration, LPG gas was used as fuel, and there is potential to replace it with flue gas. The pyrolysis process necessitates a specific amount of heat in order to affect a phase change in the plastic. The total heat required for one cycle of the system is 198,975 kJ/h, and Figure 3 shows the amount of heat required for each phase change of PP plastic in the pyrolysis system used.

$$\text{Efisiensi} = \frac{Panas\ Masuk - Panas\ Keluar}{Panas\ Masuk} x\ 100\%$$

$$= \frac{8412206{,}184\ \text{Btu/h} - 3137067{,}314\ \text{Btu/h}}{8412206{,}184\ \text{Btu/h}} x\ 100\%$$

$$= 62{,}71\%$$

The material utilised for the construction of the pyrolysis reactor is stainless steel, with the following specifications: maximum stress allowance of 107.117 MPa and thermal conductivity of 16.2 W/mK. The PP plastic pyrolysis reactor functions at atmospheric pressure [15]. In such instances, the minimum permissible wall thickness of the pyrolysis reactor is determined to be 0.681 mm, a calculation that is derived from the established pressure vessel equation. It is imperative to ascertain the dimensions of the pyrolysis reactor in order to achieve a thermal condition of 300 °C during the process of pyrolysis. The necessary dimensions for this purpose are enumerated in Table 2.

Table 2. Pyrolisis Reactor Dimensions

Reactor Component	Dimension
Inner Diameter	504 mm
Outer Dimension	520 mm
Height	680 mm
Wall Thickness	8 mm

The reactor casing is a replacement part for the burner, as the casing is where the flue gas flows around the reactor as a heater. The outer surface temperature of the casing is designed to be 35°C with a flue gas flow velocity of 3.4 m/s, which is the flue gas flow velocity entering the casing. The reactor casing is made of refractory brick with a thermal conductivity of 2 W/mK [16]. The dimensional requirements for the casing are provided in Table 3.

Table 3. Case Pyrolisis Reactor Dimensions

Casing component	Dimensi
Outer Diameter	1020 mm
Inner Diameter	1012 mm
Thickness	4 mm
Thermal Conductivity	2 W/mK
Height	680 mm

The pyrolysis system produces a vapor flow rate of 0.01191 kg/s, which is considered to have thermal characteristics similar to air [17]. Consequently, the utilisation of a shell and tube condenser for the purpose of pyrolysis vapour cooling is imperative. Within the inner pipe, pyrolysis gas flows and is subsequently condensed into pyrolysis oil, while the shell contains water, which functions as a cooling medium. The technical specifications of the condenser employed are delineated in Table 4.

Table 4. Condenser Dimensions

Condensor Component	Inner Diameter (m)	Outer Diameter (m)	Material
Inner pipe	0,01579	0,0213	Stainless Steel
Shell	0,1541	0,1683	Stainless Steel

The LMTD value of the condenser is divided into three sections, as illustrated in Table 5. The initial phase pertains to the decline in temperature of the pyrolysis vapour until it attains the vapour point of water. The second stage is the phase transition from vapor to liquid. The third part of the process under consideration is the decrease in temperature of the resulting pyrolysis oil liquid.

Table 5. Log Mean Temperature Difference

Indicator	Section 1	Section 2	Section 3
T_{ci}	30 $^{\circ}C$	32,31 $^{\circ}C$	32,33 $^{\circ}C$
T_{hi}	300 $^{\circ}C$	99,97 $^{\circ}C$	99,97 $^{\circ}C$
T_{co}	32,31 $^{\circ}C$	32,33 $^{\circ}C$	33,1 $^{\circ}C$
T_{ho}	99,97 $^{\circ}C$	99,97 $^{\circ}C$	70 $^{\circ}C$
ΔTin	270 $^{\circ}C$	67,66 $^{\circ}C$	67,64 $^{\circ}C$
ΔTout	67,66 $^{\circ}C$	67,64 $^{\circ}C$	36,9 $^{\circ}C$
LMTD	146,31	67,65	50,73

The design of the pyrolysis reactor depicted in Figures 3 and 4a was derived from the calculations performed. The results of the calculations performed are shown in Figures 3 and 4a. The figures encompass the designs of the condenser, reactor, casing, and pump.

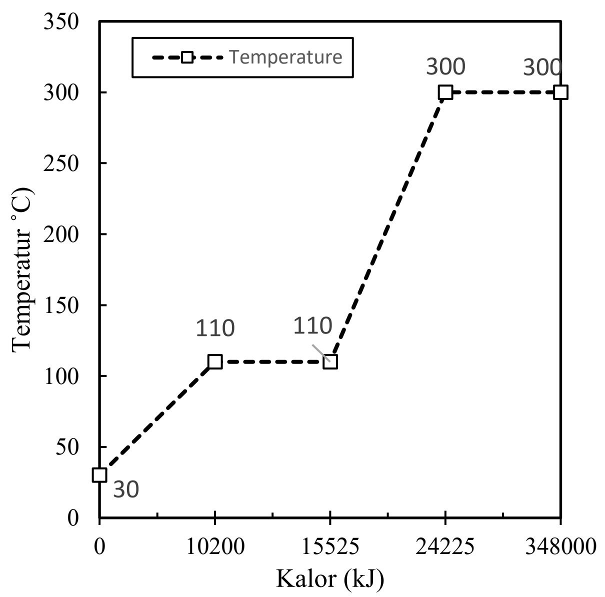

Figure 3. Heat requirement for phase change in polypropylene plastic

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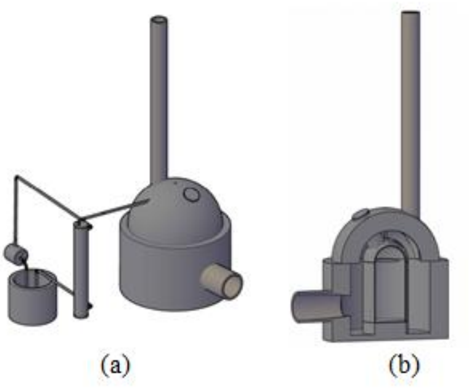

Figure 4. The design of pyrolisis isomestric (a) and reactor pyrolisis (b)

As illustrated in Figure 4b, the heat transfer within the reactor exhibits an uneven temperature distribution across specific regions. The front part of the reactor, located directly in front of the flue gas inlet, has the highest temperature, while the opposite side has the lowest temperature among all parts of the reactor. This phenomenon is demonstrated in Figure 5, where the flow of flue gas entering the reactor directly impacts it, causing the flow to spread and undergo flow separation at the rear of the reactor before exiting through the stack/chimney.

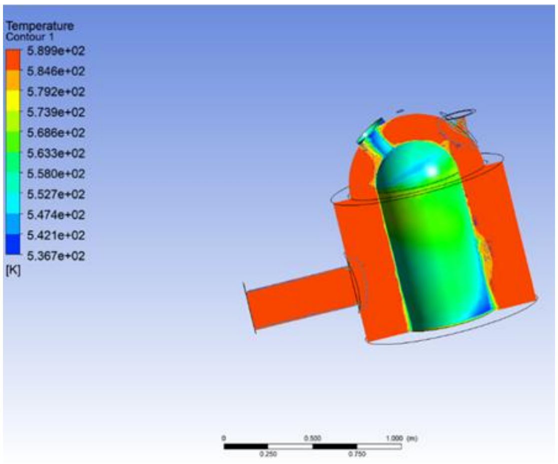

Figure 5. Temperature distribution in the pyrolysis reactor

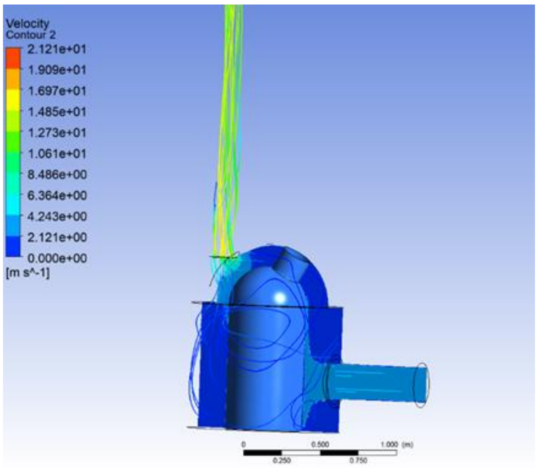

Figure 6. Velocity distribution of flue gas in the pyrolisis reactor

Consequently, the flue gas flow in direct contact with the reactor at the front is greater than the flue gas flow in direct contact with the rear of the reactor. Furthermore, the distribution of exhaust gas velocity in the pyrolysis reactor is illustrated in Figure 6.

IV. Conclusion

The study undertook an analysis of the potential utilisation of flue gas, and calculated the dimensions of the reactor and casing in the pyrolysis system. The pyrolysis reactor is a modification of a gas burner, which functions as a heat source by utilising flue gas. The following conclusions can be deduced from the calculations that have been carried out.

1. The heat demand from flue gas required for the operation of a pyrolysis reactor with a capacity of 75 kg/hour reaches 198,975 kJ/hour.
2. The potential heat that can be utilized is 70% of the total flue gas, which requires 4.4 times the system or 880,167.19 kJ/h.
3. The utilisation of heat within a system that circulates exhaust gas around a pilot reactor, with an outer diameter of 521 mm, a height of 830 mm, and a wall thickness of 8.6 mm made of stainless steel, has been demonstrated to effectively replace alternative burner systems.

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References

[1] “Undang-Undang Republik Indonesia Nomor 30 Tahun 2007 tentang Energi,” 2007.

[2] Y. Hr, “Evaluasi Kinerja Furnace-3 Ppt Migas Cepu,” Yogyakarta, Feb. 2011.

[3] O. A. Shahab and A. Faisal, “Evaluation Of Furnace-02 Efficiency Using The Heat Loss Method in Refinery Units At Pusat Pengembangan Sumber Daya Manusia Minyak Dan Gas Bumi Cepu-Java,” 2023. [Online]. Available: http://bajangjournal.com/index.php/JCI

[4] C. F. Prihantono, “Evaluasi Efisiensi Furnace-01 Pada Kilang Di Pusat Pengembangan Sumber Daya Manusia Minyak Dan Gas Bumi,” 2019.

[5] R. Sirait *et al.*, “Analisis KeseimbanganEnergi pada Reaktor Pirolisis Kapasitas 75 Kg/Jam,” 2021. [Online]. Available: http://jurnal.umj.ac.id/index.php/semnaslit

[6] I. D. K. Anom and J. Z. Lombok, “Karakterisasi Asap Cair Hasil Pirolisis Sampah Kantong Plastik sebagai Bahan Bakar Bensin,” *Fullerene Journal of Chemistry*, vol. 5, no. 2, p. 96, Oct. 2020, doi: 10.37033/fjc.v5i2.206.

[7] T.J. Kotas, *The Exergy Method of Thermal Plant Analysis*. Florida: Kreiger Publishing Company, 1995.

[8] R. Smith, M. Jobson, L. Chen, and S. Farrokhpanah, “Heat Integrated Distillation System Design,” Centre for Process Integration, School of Chemical Engineering

ISSN 0216-8685 (print); 2528-6889 (online)

and Analytical Science, The University of Manchester, 2010.

[9] W.L.Nelson, "Petroleum Refinery Engineering," 2006.

[10] E. Maulana, B. N. Fajri, and D. Mahardika, "Perancangan Proses Pembuatan Reaktor Pirolisis Model Horizontal Kapasitas 75 Kg/Jam," Jagakarsa Jakarta Selatan. [Online]. Available: http://jurnal.umj.ac.id/index.php/semnaslit

[11] Nuryati dkk, "Optimasi Proses Pirolisis Asap Cair Dari Tempurung Kelapa dan Aplikasinya Sebagai Koagulan Lateks," 2015.

[12] A. Hadi, "Desain Instalasi Pirolisis Limbah Pertanian Dalam Rangka Minimalisasi Emisi Gas Rumah Kaca Dari Lahan Basah," *Prosiding SNST. Fakultas Teknik. Universitas Wahid Hasyim. Semarang*, 2014.

[13] Eugene F. Megyesy, "Pressure Vessel Handbook 12th ed (2001)," 2001.

[14] D. I. Permana and M. A. Mahardika, "Pemanfaatan Panas Buang Flue Gas Pltu Dengan Aplikasi Siklus Rankine Organik," *Barometer*, vol. 4, no. 2, Aug. 2019, doi: 10.35261/barometer.v4i2.1851.

[15] M. A. Martín-Lara, A. Piñar, A. Ligero, G. Blázquez, and M. Calero, "Characterization and use of char produced from pyrolysis of post-consumer mixed plastic waste," *Water (Switzerland)*, vol. 13, no. 9, May 2021, doi: 10.3390/w13091188.

[16] F. Astuti, "Pengukuran Konduktivitas Panas Material Bata Api Menggunakan Sistem Hote Plate Berbasis Arduino Measurement Of Thermal Conductivity Of Fire Brick Using Hot Plate System Base On Arduino," 2020.

[17] C. Zhuo, "Synthesis of carbon nanotubes from waste polyethylene plastics Mechanical and Industrial Engineering," Massachusetts(US), 2009.

[18] Novrianto F., "Perancangan Mesin Pengolah Sampah Plastik Menjadi Bahan Bakar Minyak dengan Metode Pirolisis," 2023

https://jurnal.polines.ac.id/index.php/eksergi

ISSN 0216-8685 (print); 2528-6889 (online)