Condenser Design on Plastic Oil Distillation Equipment

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Abstract

The pyrolysis method is a technology in energy conversion that can be applied in processing plastic waste into alternative fuels in liquid form. The pyrolysis method begins with heating the plastic waste in the reactor at a temperature of more than 400°C so that the thermal degradation process of the material occurs without oxygen content, causing a phase change to the vapor phase. The vapor phase is cooled into the condenser to convert it into a liquid phase to obtain liquid fuel from plastic waste. In this study, the pyrolysis condenser design in changing the vapor phase from the reactor to the liquid phase was designed using water as a coolant on the annular side with a coolant inlet temperature of 25 ° C and a coolant outlet temperature of 35°C. The results showed that an annular side dimension with a diameter of 250 mm and a height of 250 mm was needed to reduce the temperature of the inlet condenser fuel vapor from 60°C to 30°C. Furthermore, the inner pipe of the condenser is made of copper material, which is formed by a spiral with a spiral diameter of 250 mm, an inner diameter of 25 mm, and a tubing length of 4,870 mm.

Keywords: Pyrolysis, Condensor, Plastic Waste

Introduction Section

Plastic waste is the biggest obstacle in the world currently, and in Indonesia in particular. This is due to the consumptive Indonesian society culture, but efforts to deal with plastic waste are minimal (Mafruddin et al., 2017) (Bow et al., 2019a)(Hissa et al., 2019a). The various types of plastic waste are High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), Poly Propylene (PP), Poly Styrene (PS), Poly Vinyl Chloride (PVC), and Polyethylene Terephthalate (PET). Scavengers do not take five of these plastic types except the LDPE type because they have no selling value, and no plastic collecting agent wants to buy this type of plastic waste (Novarini et al, 2018) (Pratama et al, 2014) (Karthikeyan et al., 2016) . So far, this type of plastic bag / LDPE type of waste has been destroyed by burning.

Destruction of plastic waste by burning (incineration) is risky to the environment because, by combustion, there will be pollutants from the emission of CO2, CO, NOx, and SOx exhaust gases as well as some other pollutant particulars so that other processing methods are needed to process plastic waste (Bow et al., 2019) (Okunola A et al., 2019)(Verma et al., 2016)(Meidinariasty et al., 2019). For now, several technologies can be applied to convert plastic waste into alternative fuels, one of which is converted into liquid fuel using the pyrolysis method. According to (Mafruddin et al., 2017) (Tahdid et al., 2020) (Bow et al., 2019), pyrolysis is a process of thermal degradation of the material in the absence of oxygen or a little oxygen where plastic waste is heated in the reactor at a high temperature above 400 ° C so that the phase will turn into steam and then cool back in the condenser to get liquid fuel from plastic waste (Hissa et al., 2019b)(Saxena et al., 2017).

In the pyrolysis process, things that need to be considered are the temperature in the reactor and the design of the condenser. Several studies on the design of pyrolysis equipment were carried out, one of which was research on the design and testing of oil distillation equipment from plastic waste with a capacity of 3 kg (Fauzie & Kohar, 2017). The results of this study obtained 74 grams of condensate with an operation time of 2 hours 30 minutes. According to the author, these condensate results can be maximized if the surface area of the condenser tube is enlarged. This study's novelty is that the condenser capacity reaches 2.5 kg, and the use of pipes in using copper pipe material with a size of 1 inch.

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Experimental Method

The experimental setup of the pyrolysis tool can be seen in Figure 1.

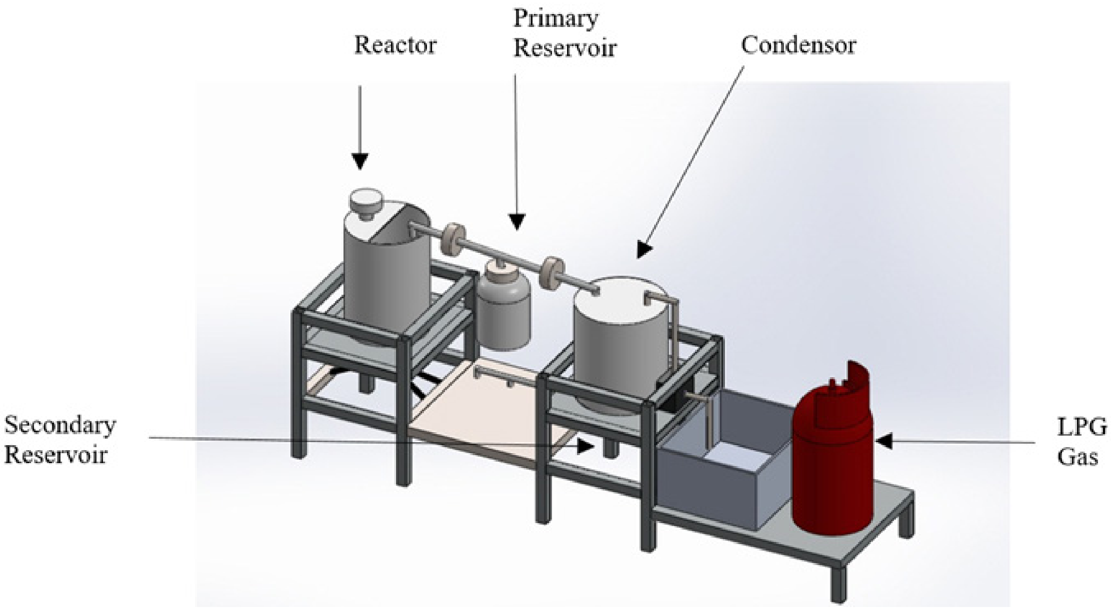


Figure 1. *Experimental Setup*

Figure 1. shows 1 unit of LPG-fueled pyrolysis equipment consisting of a reactor, tar storage or resevoir, and condenser. The reactor is equipped with temperature control made of stainless steel with a thickness of 3 mm with a capacity of 2.5 kg and a height of 450 mm, and a diameter of 320 mm and coated with glass wool to withstand heat transfer to the environment. The primary steel tar reservoirs were 200 mm high and 80 mm in diameter. The shell side of the condenser is made of steel with 600 mm height and 350 mm diameter. The tube is made of copper pipe with a diameter of 0.5 in and 4,870 mm length formed in a spiral wound. The product exits the condenser as a secondary tar.

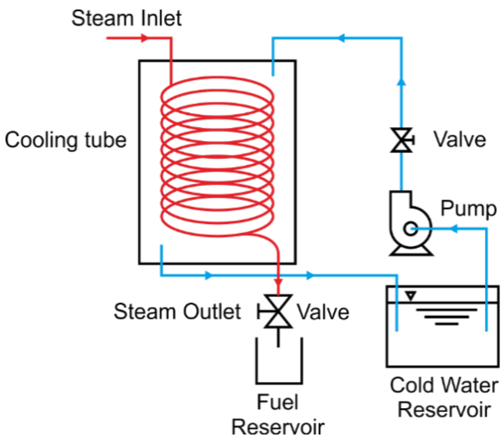
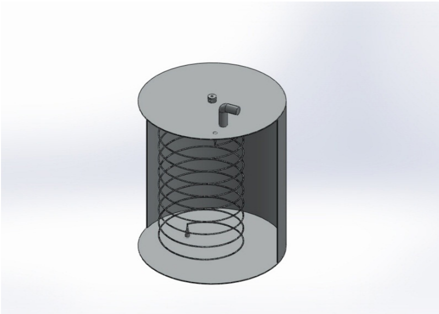


Figure 2. Condenser Schematic Diagram

Figure 2. shows a schematic diagram of the condenser in a plastic oil distillation unit. The condenser system consists of a cooling fluid flow, a hot steam stream. The flow control system used is the parallel flow regime where hot steam flows in the inner pipe while the cooling fluid flows on the annular side (Rubianto et al., 2018). Annulus side dimensions are a diameter of 250 mm and a height of 250 mm. Furthermore, the inner pipe of the condenser is made of copper material, which is formed by a spiral with a spiral diameter of 250 mm, an inner

diameter of 1 mm tubing, and a tubing length of 4,870 mm. Plastic materials are heated using an LPG stove and kept constant at a temperature of 250°C. The temperature setting is carried out using a thermocontrol device and by using a type K thermocouple. Furthermore, the cooling fluid is flowed using a centrifugal pump with a constant flow rate of 25 liters/minute. The inlet and outlet temperatures on the annulus and inner tube surfaces were measured using a thermogun with a measuring accuracy of 0.01°C. The inlet temperature of the condenser is 60°C, while the temperature of the cooling fluid is kept constant in the temperature range of 25°C - 30°C. The 3D condenser design made using CAD 2020 can be seen in Figure 3.



Gambar 3. Condenser Design

Data Reduction

In this experimental study, the investigation of the coefficient of heat transfer can be calculated using the equation (Hammer, 1950):

Overall energy equilibrium for heat fluid and coolant fluid can be stated by:

$$Q_h = \dot{m}_h C_{p,h} (T_{h,in} - T_{h,out}) \quad (1)$$

The heat transfer rate on the annular side is:

$$Q_c = \dot{m}_c C_{p,c} (T_{c,in} - T_{c,out}) \quad (2)$$

So that the outlet temperature of the cooling fluid can be calculated with the equation:

$$T_{c,out} = \frac{Q_c}{\dot{m}_c C_{p,c}} T_{c,in} \quad (3)$$

Q is the heat transfer rate, m mass flow rate, Cp is the specific heat of the working fluid, and ΔT is the difference in inlet and outlet temperatures. Subscript h and c are hot and cold fluids.

The overall heat transfer coefficient on the pipe side in U_i can be determined from:

$$U = \frac{Q}{A \Delta T_{LMTD}} \quad (4)$$

where $A = \pi D_i L$ and ΔT_{LMTD} are the logarithmic temperature difference.

$$\Delta T_{LMTD} = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln(T_{h,in} - T_{c,out}) / (T_{h,out} - T_{c,in})} \quad (5)$$

Heat transfer of inner pipe is:

$$h_o = \frac{1}{\left(\frac{1}{U}\right) + \left(\frac{1}{h_i}\right)} \quad (6)$$

where h_o is the outer pipe heat transfer coefficient, U is the overall heat transfer coefficient, and h_i is the inner pipe heat transfer coefficient.

The flow calculation on the inner pipe section and the annulus side and Prandtl number can be expressed as:

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$$Re = \frac{4\dot{m}_h}{\pi D_i \mu} \quad (7)$$

$$Pr = \frac{\mu Cp}{k} \quad (8)$$

So that the flow in the pipe is turbulent, then the convection heat transfer coefficient can be calculated by the equation:

then

$$h_i = Nu\frac{k}{D_i} \quad (9)$$

Nu is the Nusselt Number, k is the thermal conductivity, Di is the inner pipe diameter, h is the heat transfer coefficient.

The cooling fluid flow on the annular side, the hydraulic dimension is Dh = Do - Di, the Reynolds number is:

$$Re = \frac{4\dot{m}_c}{\pi(D_o + D_i)\mu} \quad (10)$$

the length of the inner pipe can follow the following equation:

$$L = \frac{Q}{U\pi D_i \Delta T_{LMTD}} \quad (11)$$

where L is the length of the pipe, Q is the heat transfer rate, U is the overall heat transfer coefficient, Di is the inner diameter of the pipe, and ΔT is the temperature difference.

Results and Discussion

Work Fluid Properties

The properties of the working fluid required in calculating the heat transfer rate include inlet temperature, outlet temperature, and mass flow rate (Stephenraj & Sathishkumar, 2018)(Wei et al., 2012). Table 1 shows the properties of the working fluid in the inner pipe and the annulus.

Tabel 1. Working fluid properties

Working fluid properties	Inner pipe	Annulus
Inlet Temperature (T_{in})	60 ^{0}C	30 ^{0}C
Outlet Temperature (T_{out})	35 ^{0}C	-
Mass Flowrate ($\dot{m}$)	0.1 kg/s	0.38 kg/s

Thermophysical Properties of Working Fluid

The thermophysical properties of the working fluid are fundamental in heat transfer applications. This is because the value of thermophysical properties, especially thermal conductivity, has a major role in increasing the heat transfer coefficient. The thermophysical properties of the working fluid are obtained based on the empirical correlation in Table 2.(Kristiawan et al., 2020)(Silaipillayarputhur & Khurshid, 2019)(Mohammadaliha et al., 2020)(Hammer, 1950).

Tabel 2. H_2O Thermophysical Properties

Thermophysical properties	**Correlation**
Density (ρ)	$1001.1-0.0867T-0.0035T^2$
Heat Capacity (Cp)	$4.214-2.286\times10^{(-3)}T+4.992\times10^{(-5)}T^2-4.519\times10^{(-7)}T^3+1.857\times10^{(-9)}T^4$
Thermal Conductivity (K)	$0.5636+1.946\times10^{(-3)}T-8.151\times10^{(-6)}T^2$
Viscosity (μ)	$0.0015-1.684\times10^{(-3)}-4.264\times10^{(-5)}T-5.062\times10^{(-7)}T^2-2.244\times10^{(-9)}T^3$

Heat Transfer Rate Calculation

The heat transfer rate is an indicator of a conductor's capabilities. The increase in the heat transfer value is influenced by the mass flow rate and the difference in inlet and outlet temperatures on the inner pipe side and the annular side. The mass flow rate on the inner side of the pipe is $(\dot{m} = 0.1 \text{ kg / s})$. So that the heat transfer rate can be determined from:

$$Q_c = 0.38 \text{ kg.s} \times 4178 \text{ J/kg.}^\circ\text{C} \times (25\text{-}35)^\circ\text{C}$$
$$= 15.876 \text{ W}$$

The heat transfer that occurs in the condenser of the pyrolysis apparatus is a hot fluid that has a high temperature, which moves through convection heat transfer in the inner pipe material and conduction transfer in the working fluid. Therefore, the outlet temperature of the plastic oil is:

$$T_{hot,out} = \frac{15.876 \text{ W}}{0.38 \text{ kg/s} \times 4178 \text{ J/kg.}^\circ\text{C}} + 60^\circ\text{C}$$
$$= 38^\circ\text{C}$$

While the heat transfer rate on the annular side is:

$$\Delta T_{LMTD} = \frac{(60^\circ C - 35^\circ C) - (38^\circ C - 25^\circ C)}{\ln(60^\circ C - 35^\circ C) / (38^\circ C - 25^\circ C)}$$
$$= 18.4^\circ C$$

Heat Transfer Coefficient

$$\text{Re} = \frac{4 \times 0.1 \ kg / s}{\pi \times 0.025 \ m \times 725 \times 10^{-3} \ N.s / m^2}$$
$$= 7.025$$

In determining the principle of the fluid flow regime in a pipe, it can be obtained by the term Reynolds number. Fluid flow is divided into three flow regimes, namely laminar, transitional, and turbulent. The calculation of the Reynolds number in the inner pipe flow is turbulent because it has a value of more than 4000. Therefore, the Nusselt number (Nu) for the cooling process can be determined based on the following Dittus-Boelter [10] correlation:

$$Nu = 0.023 \text{Re}^{0.8} \text{Pr}^{0.3}$$

Thus,

$$Nu = 0.023 \times 7025^{0.8} \times 4.85^{0.3}$$

Inner pipe heat transfer coefficient is:

$$h_i = 44.13 \frac{360.5 \ W / m.^\circ C}{0.025 \ m}$$
$$= 1103 \ W / m^2.^\circ C$$

The greater the heat transfer coefficient value achieved, the better the ability to conduct heat. Furthermore, the hot steam condensation process becomes faster in producing plastic oil in the pyrolysis process.

Convection of the outside of the pipe in the condenser

$$\begin{aligned} Re &= \frac{4 \times 0.38 \ kg/s}{\pi \times (0.026 \ m + 0.045 \ m) \times 725 \times 10^{-3} N.s/m^2} \\ &= 9.399 \end{aligned}$$

The flow on the annular side is laminar regime flow. Assuming that the temperature along the inner surface of the annulus side and heat loss to the environment is negligible, the convection heat transfer coefficient can be determined by:

$$Nu = \frac{h_o D_h}{k} = 5.63$$

$$\begin{aligned} h_o &= 5.63 \frac{0.625 \ W/m.^oC}{0.071 \ m} \\ &= 49.56 \ W/m^2.^oC \end{aligned}$$

So that the overall heat transfer coefficient is;

$$\begin{aligned} U &= \frac{1}{(1/1103 \ W/m^2.K) + (1/49.56 \ W/m^2.K)} \\ &= 47.43 \ W/m^2.K \end{aligned}$$

If the outer diameter of the inner pipe is 0.026 m, the length of the condenser pipe can be obtained:

$$\begin{aligned} A &= \frac{Q_{ave}}{U. \rightleftarrows \Delta T_{LMTD}} \\ &= \frac{12.534 \ W}{47.43 \ W/m^2.^oC \times 18.4^oC} \\ &= 14.4 \ m^2 \end{aligned}$$

Conclusion

The condenser design in the plastic oil distillation device has been carried out, so it can be concluded that:

1. The condenser design can reduce the hot steam inlet temperature from 60°C to 30°C by using water as the cooling fluid.
2. The inner pipe uses copper material with spiral coils with a spiral diameter of 250 mm, an inner diameter of 25 mm, and a tubing length of 4,870 mm.

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