

The application of pyrolysis for the thermal decomposition of tire waste can be taken as the ideal concept to reduce and recycle tire waste. The product of the process can produce condensate oil, a typical oil that is close to crude oil properties. The critical aspect of the pyrolysis process is the design of the reactor, particularly for the condenser where the rate of heat transfer contributes to the overall quality and quantity of the produced condensate oil. This study focused on the effect of water flow direction on the condensation process of pyrolysis gas. The quantity and quality of the produced oil are examined to observe the effect of the condensation process. Two different water flow directions are tested in the process, namely, counter flow and parallel flow direction. The effect of water flow direction in the condenser clearly affects the pyrolysis process to produce the condensate oil. Based on the production quantity, the counter flow condenser is able to produce 355 ml of condensate oil while the parallel flow one merely 290 ml. Based on the quality of the produced condensate oil, the counter flow condenser is generally better than the parallel flow one where the density, flash point and viscosity are close to crude oil properties. The rate of heat transfer from the condenser to the pyrolysis gas is the main factor that contributes to the quality and quantity of the condensate oil. The average heat transfer for the counter and parallel flow is 2,728 W and 1,865 W, respectively. It can be said that using the counter flow condenser for the pyrolysis reactor can improve the quality and quantity of the condensate oil

Keywords: counter flow, parallel flow, pyrolysis, condenser, heat transfer

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AN EFFECT ANALYSIS OF COOLING WATER DIRECTION TOWARDS CONDENSATE OIL FROM SCRAP TIRES

Budhi M Suyitno

Doctor of Mechanical Engineering, Associate Professor*
E-mail: suyitnbudhi2020@gmail.com

Erlanda Augupta Pane

Master of Mechanical Engineering, Assistant Professor*
E-mail: erlanda.pane@univpancasila.ac.id

Wina Libyawati

Master of Mechanical Engineering, Assistant Professor*
E-mail: wlibyawati@gmail.com

Chatrine Jelita

Bachelor Student*
E-mail: chatrin.jelita@yahoo.com

Hendri Sukma

Master of Mechanical Engineering, Associate Professor*
E-mail: hendrisukma@gmail.com

Ismail

Doctoral of Mechanical Engineering, Associate Professor*
E-mail: ismail@univpancasila.ac.id

*Department of Mechanical Engineering
Universitas Pancasila

Jl. Srengseng Sawah, Jagakarsa, South Jakarta,
DKI Jakarta, Indonesia, 12640

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1. Introduction

Table 1

The increment of vehicle production influences tire production, which is its primary component. In 2010, tire production reached 12 million, while in 2011, it reached 14.5 million, i.e., the average increase in tire production reached 1.5 million per year [1–3]. Tire composition (as seen in Table 1), which is complex and susceptible to the environment, is a consideration in controlling tire production, especially its waste treatment [3, 4], where only 15–20 % of the composition of tires degraded (microbiological processes) [5], while the rest is neglected without special handling. Tires with the highest polymer rubber composition are difficult to decompose through biological processes, therefore, the treatment is performed only through the vulcanization process. The vulcanization process is an alternative treatment to recycle polymer rubber, therefore, it can be reused. The results of vulcanization can only be used in a short time so that the tire is discharged into an open environment and burned as a scrap tire.

Tire composition [6]

No.	Composition	Percentage (%)
1	Polymer rubber	40–60
2	Reinforcing agents (Black carbon)	20–35
3	Aromatic extender oils	15–20
4	Vulcanization additives (zinc oxide, benzothiazole and derivatives)	~4
5	Antioxidants	~1
6	Processing aids (plasticizers and softeners)	<1

The scrap tire piles in an open environment can be a source of diseases and reduce the quality of soil and water in the surrounding environment (Fig. 1). Besides that, its combustion process can cause air pollution, which contains toxic gas emissions [3, 7, 8] and which has a negative impact on human health. Based on those impacts, it can be concluded that the vulcanization process is not economical and harmful to the environment [9].



Fig. 1. Scrap tires: *a* – bulk tube-type tire; *b* – pieces of scrap tire

Some technologies to reduce the scrap tire negative impact have been developed previously, among others are incineration [10], gasification [11], and pyrolysis [12]. Pyrolysis is a more promising process for scrap tire treatment because the thermochemical decomposition process with high-temperature control [13] is capable of producing three pyrolysis products, including pyrolysis gas, pyrolysis oil, and charcoal [14]. Pyrolysis products are used as fuel and raw materials for processed chemical products [15].

2. Literature review and problem statement

Several studies on the pyrolysis process for waste tires have been done before, in which several studies use temperature control methods for pyrolysis of several types of waste tires to improve the quality and quantity of the produced pyrolysis oil and combustible gas products [16]. Besides the temperature control method, another study has used the catalyst one [17] in order to decrease the reaction temperature and improve the quantity of the produced pyrolysis oil [18]. The catalyst method leaves by-products during the process, i.e., scale deposits, which are acid and unsaturated hydrocarbon that could decrease the quality of the pyrolysis oil [19]. Combustible gas can be taken as an alternative option to maximize the pyrolysis product besides the oil. Combustible gas can be maximized as long as the pyrolysis process is handled carefully because combustible gas can easily react with air and lead to incomplete combustion [20]. The common method for handling combustible gas is through the condensation process where combustible gas is condensed into condensate oil. The condensation method is able to improve the escalation value of the condensate oil from combustible gas up to 80 % of the molecular weight of the gas [21]. Compared to combustible gas, condensate oil is considered more feasible since it can be easily stored for a longer period.

The process of condensing a combustible gas can be done through two methods, namely by decreasing the temperature and or pressure of the process [22]. The temperature can be easily decreased by setting the temperature of pyrolysis between 300 °C to 600 °C to obtain reliable condensate oil [23]. One good example of this method is done by Catherine [24] with the following results (Table 2).

Compared to the input of waste tires, the quantity of condensate oil is extremely low. The flowrate of cooling water is the main reason why the production is extremely low. The flowrate of cooling water should be addressed carefully by adjusting the flow direction inside the condenser, where the flow direction can affect directly the heat transfer between the cooling water and the combustible gas [25]. Therefore, modifying the flow direction of cooling water will affect the results of the produced combustible gas, both in quantity

and quality. The main challenge is obtaining the ideal flow direction of cooling water and heat transfer rate to improve the quality and quantity of the produced combustible gas.

Table 2

Results of pyrolysis process from Catherine [24]

No.	Parameter	Value
1	Tire mass (kg)	3
2	Condensate oil volume (lt)	1.3
3	Process duration (hour)	4
4	Temperature of combustible gas (°C)	300
5	Total volume of cooling water (lt)	82
6	Cooling water flowrate (lt/hour)	2.8
7	Temperature of cooling water at the inlet (°C)	25
8	Temperature of cooling water at the outlet (°C)	32

3. The aim and objectives of the study

The aim of the study is to determine the characteristics of condensate oil that are close to the characteristics of conventional fuels.

To achieve the aim, the following objectives are accomplished:

- water flow direction (parallel and counter);
- measurement of volume and heat transfer activity;
- density analysis of condensate oil;
- viscosity analysis of condensate oil;
- flaming point analysis of condensate oil.

4. Materials and Methods

4.1. Experimental Procedure

The study focused on the experimental method to extract the condensate oil from scrap tube tires. The scrap tires are collected from the disposal and charged into the shredder machine in order to decrease the size where the average output of the shredder machine is ± 4 cm. The pieces of scrap tires proceed to the pyrolysis reactor as shown in Fig. 2. The selection of pyrolysis reactor type also determines the rate of heat transfer from the heat source to the reactor during the decomposition of scrap tires [26]. The temperature of the pyrolysis process is controlled between 300–350 °C under atmospheric pressure using the fixed bed reactor by considering the ease of the process and results of the condensate oil [23]. The vapor from the combustion process of scrap tires is condensed through the condenser. The temperature of the process is monitored through the thermocouple type K while the pressure is maintained using the safety valve in order to ensure a stable pyrolysis process.

The condensation process uses three condensers arranged in a series [27] with each condenser having a length of 300 mm and a diameter of 250 mm. Series arrangement of condensers has a relationship with pyrolysis gas residence time in the condenser, where residence time influences the distribution and composition of condensate oil [28]. The condensate oil volume is measured by the amount of oil stored in a beaker glass. Condensate water as a condensation cooling medium is analyzed for its flow type and mass flow rate. The water mass flow rate results using values of $3.34 \times 10^{-5} \text{ m}^3/\text{sec}$, $4.16 \times 10^{-5} \text{ m}^3/\text{sec}$, $5.00 \times 10^{-5} \text{ m}^3/\text{sec}$, $5.83 \times 10^{-5} \text{ m}^3/\text{sec}$, and $6.67 \times 10^{-5} \text{ m}^3/\text{sec}$.

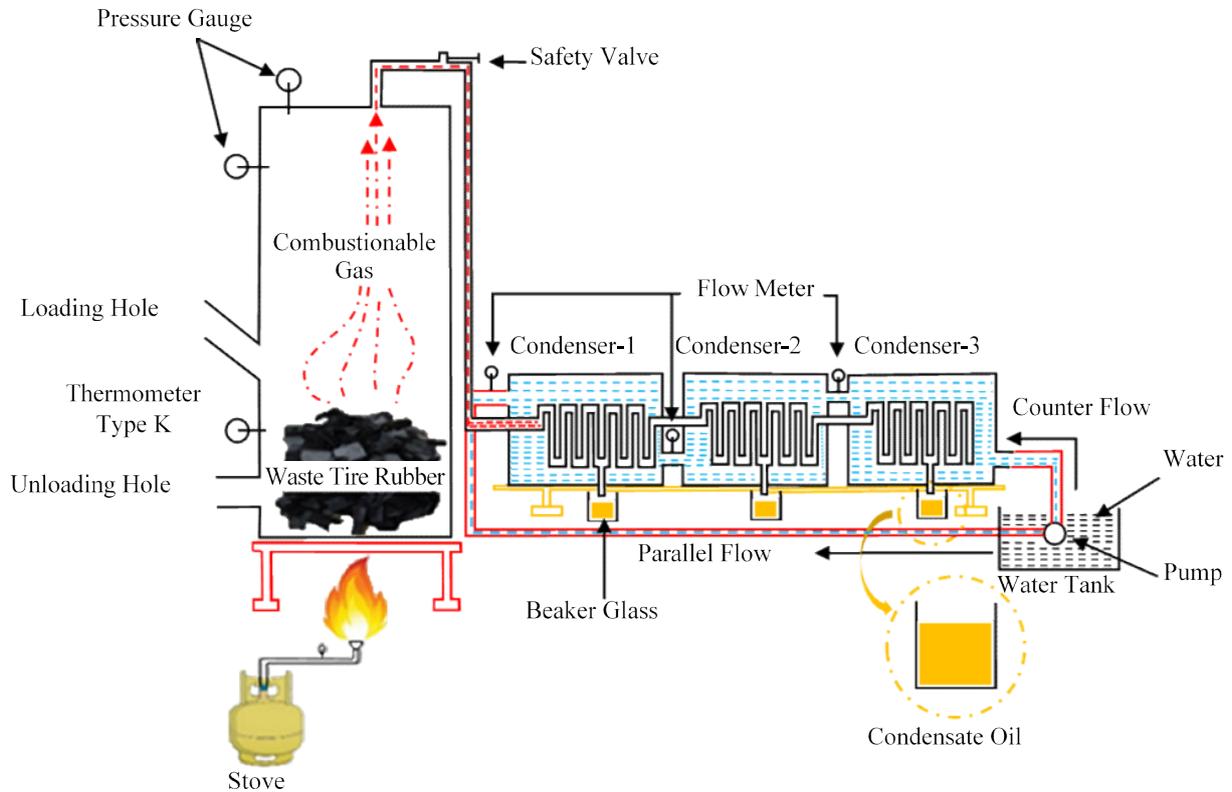


Fig. 2. Scheme of experimental test

The heat transfer activity between condensate water and pyrolysis gas has different conditions. Fig. 3 shows the direction of heat transfer activity where Fig. 3, *a* is the parallel direction and Fig. 3, *b* counter flow direction. According to Fig. 3, *a*, different flow directions between condensate water and pyrolysis gas can increase the condensate water exit temperature after the heat transfer process in the condenser. The heat transfer rate analysis that occurs inside the condenser is known through the temperature difference of condensate water and pyrolysis gas at different distances in the condenser. For the parallel flow direction (Fig. 3, *b*), the condensate water inlet has the same direction as pyrolysis gas, nevertheless, the condensate water inlet temperature is lower than the pyrolysis gas inlet temperature.

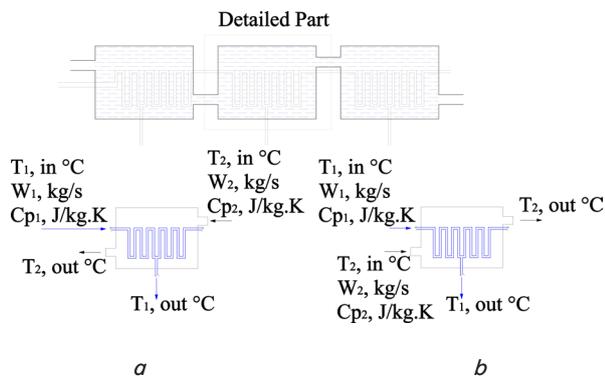


Fig. 3. Condensate water and pyrolysis gas flow:
a – counter flow direction;
b – parallel flow direction

4. 2. Condensate Oil Analysis

Chemical analysis test measures the condensate oil characteristics with a test of density, viscosity, and flaming point, the results of which are compared with conventional fuel characteristics. Condensate oil density test uses the ASTM D-4052 method that analyzes the density [29]. Condensate oil density test results were compared to conventional fuel density shown in Tables 3, 4.

Table 3

Fuel density				
No.	Fuel Type	Method	Density (gr/ml)	Density (kg/m ³)
1	Kerosene [30]	ASTM D-2500	0.830	830.00
2	Mahua methyl ester [30]	ASTM D-2500	0.860	860.00
3	Palm oil [31]	ASTM D-1298	0.864	864.42
4	Bio-rapeseed cake oil [32]	ASTM D-1298	0.993	993.00
5	Vegetable oil [33] a) linseed oil; b) canola oil; c) sunflower oil; d) rapeseed oil	ASTM D-5002	0.925 0.912 0.914 0.908	925.00 912.00 914.00 908.00
6	Gasoline [34]	ASTM D-4502	0.753	753.40
7	Ethanol [35]	ASTM D-4052	0.785	785.00
8	Diesel fuel [36]	ASTM D-4052-96	0.860– 0.900	860.00 – 890.00
9	Beeswax oil [37]	ASTM D-1298	0.880	880.00
10	Plastic pyrolysis oil [38]	ASTM D-2500	0.830	830.00
11	Algal Biodiesel[39]	ASTM D-445	0.886	886.00
12	Butanol [39]	ASTM D-445	0.810	810.00

Table 4

Specific gravity and API of crude oil [37, 40]

Crude oil levels	Specific gravity (ASTM D-1298)	API
Light	<0.830	39°
Light medium	0.830–0.850	39–35°
Heavy medium	0.850–0.865	35–32.1°
Heavy	0.865–0.905	32.1–24°
Very Heavy	>0.905	24.8°

Viscosity tests are used to analyze the condensate oil resistance in different media and kinematic viscosity coefficient. Viscosity test uses the ASTM D-445 method for analyzing the time requirements of condensate oil flow in the viscometer tube, which utilizes gravity (stoke) at temperatures of 35 °C to 40 °C [39]. The results of the condensate oil viscosity will be compared to the results of conventional fuel viscosity shown in Table 5.

Table 5

Fuel viscosity

No.	Fuel Type	Method	Viscosity (cSt)
1	Kerosene @ (40 °C) [30]	ASTM D-97	1.50
2	Mahua methyl ester @ (40 °C) [34]	ASTM D-97	5.00
3	Palm oil @ (40 °C) [31]	ASTM D-445	4.71
4	Bio-rapeseed cake oil [32] a) @ (37.8 °C); b) @ (50 °C)	ASTM D-88 ASTM D-88	62.00 38.00
5	Vegetable oil @ (40 °C) [33] a) Linseed oil; b) Canola oil; c) Sunflower oil; d) Rapeseed oil	ASTM D-445	2.24 3.34 2.89 4.51
6	Gasoline @ (40 °C) [30]	ASTM D-97	2.67
7	Ethanol @ (40 °C) [35]	ASTM D-88	1.10
8	Diesel fuel @ (40 °C) [36]	ASTM D-6751	1.90– 6.00
9	Beeswax oil @ (40 °C) [37]	ASTM D-445	3.50
10	Plastic pyrolysis oil @ (40 °C) [38]	ASTM D-97	2.54
11	Algal Biodiesel @ (40 °C) [39]	ASTM D-445	4.47
12	Butanol @ (40 °C) [39]	ASTM D-445	0.4–0.8

The condensate oil flame point describes the lowest temperature point of condensate oil to start the combustion process when the oil is close to the flame. The condensate oil flame point test uses the ASTM D-93 (Standard Test Methods for Flash Point by Pensky-Martens Closed Cup Tester) test, which will be compared to the conventional fuel flame point conditions. Based on the data of the flame point of conventional fuels, it can be seen that the flash points of kerosene, diesel oil and light fuel oil requires a minimum temperature of 23 °C, 55 °C, and 79 °C, respectively [40].

5. Results of different water flow directions in the condenser

5.1. Quantity of the condensate oil under different water flow directions in the condenser

The condensate water flow direction, which has two types, i.e. parallel and counter flow directions, has a significant impact on the characteristics of condensate oil in terms of quality and quantity. The heat transfer rate is the main

quantity parameter of the condensate water temperature difference under diffusivity conditions to increase the condensate oil volume as a result of the condensation process. The determination of condensate oil characteristics as a quality aspect is determined by the test of density, viscosity, and flame point, followed by the comparison of the results of the condensate oil characteristic test towards the conventional fuels characteristics. The condensate oil volume (quantity aspect) as a field experiment result is shown in Table 6.

Table 6

Volume of condensate oil on the variant of flow direction and discharge

Flow direction	Cooling water discharge ($\times 10^{-5}$) (m ³ /s)	Condensate oil volume (ml)			Total
		1 st condenser	2 nd condenser	3 rd condenser	
Counter flow	3.34	128	100	30	258
	4.16	122	115	45	282
	5.00	125	133	52	310
	5.83	126	158	68	352
	6.67	127	138	80	355
Parallel flow	3.34	130	116	–	246
	4.16	125	118	25	268
	5.00	137	111	37	285
	5.83	126	135	40	300
	6.67	116	106	68	290

The heat transfer activity between condensate water and pyrolysis gas is influenced by some factors, including the inlet position of condensate water and pyrolysis gas, heat transfer area, and condensate water mass flow rate. The results of the heat transfer rate in the two condensate water flow conditions can be seen in Table 7.

Table 7

Heat transfer capacity on the variety of flow direction and discharge

Flow direction	Cooling water discharge ($\times 10^{-3}$) (m ³ /s)	Heat transfer capacity (W)		
		T_{in} (°C)	T_{out} (°C)	q (W)
Counter flow	3.34	26	30.5	626
	4.16	26	30.6	799
	5.00	26	31.2	1,086
	5.83	26	32.5	1,584
	6.67	26	35.8	2,728
Parallel flow	3.34	26	29.7	515
	4.16	26	30.2	730
	5.00	26	31.4	1,128
	5.83	26	32.0	1,462
	6.67	26	32.7	1,865

Condensate oil has disadvantages, namely, a large amount of by-products and stinging odor, so the addition of additive substances can be a suggestion for improving the condensate oil quality. The analysis of initial conditions and distribution points of the condensation process by changing the transparent condenser material, analysis of heat transfer in the capillary pipe in the condenser and characteristic analysis of condensate oil after the addition of additive substances become the focus of future research. Condensate oil yield conditions can be seen in Fig. 4.



Fig. 4. Produced condensate oil: *a* – condensate oil based on condenser; *b* – condensate oil based on flow type

Table 6 shows that the first condenser produces a large volume of condensate oil. This condition occurs because of the long residence time of pyrolysis gas for the heat transfer activity towards the condensate water. Meanwhile, the conditions of the other two condensers are only used for optimizing the pyrolysis gas condensation, which is not condensed in the first condenser. However, the visualization condition of condensate oil in the first condenser still leaves a by-product that can be seen in Fig. 6. The first condenser visualization condition is different from the visualization conditions of the other two condensers. The pyrolysis gas condensation process also affects the viscosity of condensate oil, where pyrolysis gas, which has a long residence time in the condenser, can reduce its viscosity. The water flow direction influences the condensate oil volume, where the counter flow direction produces a small volume of condensate oil when compared to the parallel flow direction. This condition occurs due to the influence of the condensate water inlet temperature difference.

The graph of condensate oil volume towards the condensate water mass flow rate shown in Fig. 5 can explain that the relationship between the two parameters has a high degree of correlation, where an increase in the condensate water flow rate can increase the volume of condensate oil.

Table 7 shows that the condensate water mass flow rate can increase the surface area for the heat transfer effectiveness process so that it can influence the outlet temperature of water condensate. The difference in the inlet position of condensate water towards the pyrolysis gas flow that is classified into parallel flow and counter flow directions also affects the condensate water outlet temperature.

Based on Fig. 6, the relationship between heat transfer rate and condensate water mass flow rate has a high correlation, so this condition means that increasing the mass flow rate can increase the heat transfer rate that occurs in the heat transfer surface area.

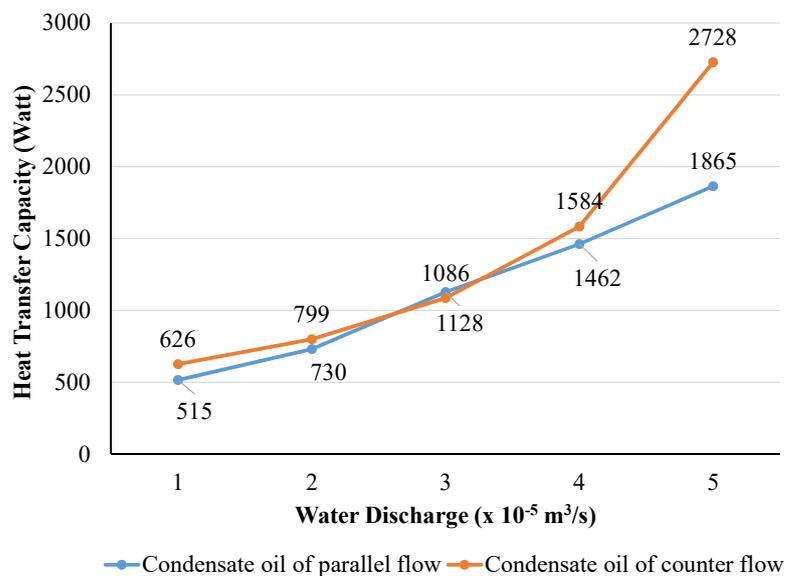


Fig. 5. Condensate oil produced by different condensation methods

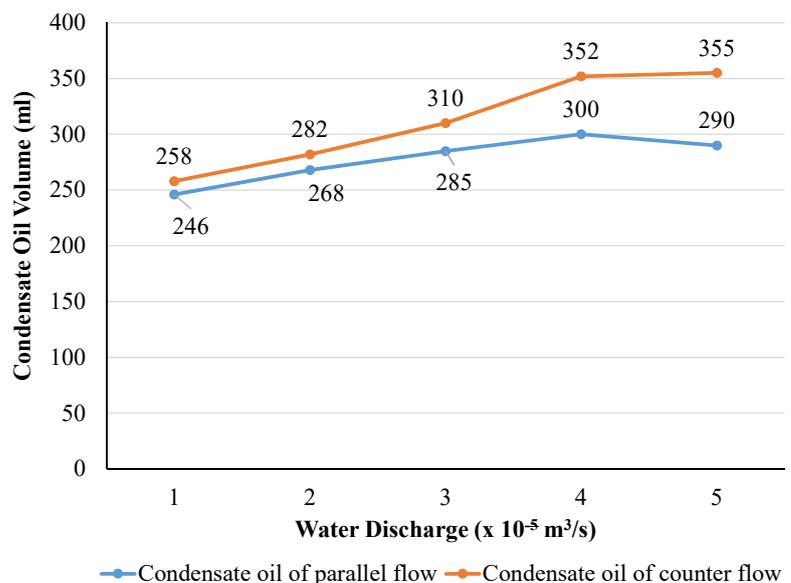


Fig. 6. Heat transfer capacity under different condensation flows

5. 2. Quality of the condensate oil under different water flow directions in the condenser

Chemical test analysis measures the condensate oil characteristics through a test of density, viscosity, and flaming point. The density test occurs at a temperature of 15 °C, where the density and gravity of condensate oil in parallel conditions are 925.9 kg/m³, while the counter flow conditions are 865.8 kg/m³. This statement explains that the mass and number of condensate oil particles are greater in the counter flow direction conditions compared to the parallel flow direction conditions. The greater mass and number of condensate oil particles can support the combustion process inside the engine.

Condensate oil density test results continued with a comparison of conventional fuel density in Table 3, 4 so it was concluded that condensate oil density approached the density of diesel oil with medium particle size. Viscosity test of condensate oil, which was carried out at 40 °C, got a value of 1.263439 cSt in the counter-flow condition, while in parallel conditions got a viscosity value of 1.22825 cSt. This statement explains that the condensate oil condition under the counter flow direction has a high viscosity when compared to parallel conditions. The high viscosity value of condensate oil can save fuel for the combustion process in the reactor. The high viscosity value of condensate oil can save fuel utilization for the combustion process in the reactor. The viscosity results of condensate oil compared to conventional fuel viscosity suggest that the viscosity of condensate oil is close to the viscosity of diesel oil.

Condensate oil flame point test gets a minimum temperature of 21 °C in the counter flow direction conditions, while in parallel conditions gets a minimum temperature of 23.5 °C. This explains that condensate oil in counter-flow conditions is flammable and explosive when condensate oil is brought close to the flame light. The whole chemical analysis test reveals that condensate oil in counter flow conditions has good quantity and quality when compared to condensate oil in the parallel flow direction and has characteristics close to the characteristics of crude oil. The study is limited at given temperatures (ranging from 300–350 °C) by varying the water flow direction in the condenser. The finding in our study can be further developed as a basis idea to optimize the pyrolysis process of scrap tires using computational fluid dynamics to increase the overall quality both for the process and produced condensate oil.

6. Discussion of the effect of water flow direction for the condensate oil

The condensation process from gas to liquid is highly influenced by the heat transfer rate between the cold fluid and pyrolysis gas. The higher rate of heat transfer in the counter flow causes the heat absorption process to increase from the pyrolysis gas to the cooling water through the condenser. It contributes directly to the condensation process of pyrolysis gas because the higher heat absorption affects rapid temperature drop in pyrolysis gas. The quicker temperature drop from the gas is due to the high rate of heat transfer, which has a direct impact on the increased capacity of the produced condensate oil.

The lower heat transfer rate in the parallel flow is due to the small rate of the heat exchanging process between the fluid and the gas as a consequence of the parallel flow direction from the cooling water and the direction of the gas flow. The heat exchange between the gas and the pipe wall on the

outside of the condenser and the heat exchange between the fluid at the inside wall of the condenser pipe are not effective as the fluid goes in the same direction. It makes the rate of convection heat transfer rate between both the fluid and the pipe wall being insufficient. The end result has an impact on the decrease in heat transfer rate capacity. This can also be proven based on Fig. 6 where changes in flow rate in the parallel flow do not have a significant effect on the average heat transfer, while changes in flow rate cause a significant increase in the average heat transfer for the counter flow direction.

The difference in heat transfer rate is the most important key of the pyrolysis reactor because it does not only affect the production capacity, but also the properties of the produced condensate oil. The density of condensate oil produced by the counter flow is higher than the condensate oil produced from the parallel flow, which is good evidence that the rate of heat transfer in the condenser influences the properties of condensate oil. The higher density in the counter flow is mainly affected by the change in the gas phase to liquid oil where molecular gas becomes denser in the liquid form. The heat releasing from gas to liquid is related to standard entropy gases, which in this case is an exothermic reaction, so that the better heat absorption causes the reaction rate to be quicker, thus the molecular liquid bonds of the produced condensate oil are stronger. The increase in the strength of molecular liquid causes an increase in fluid density.

The viscosity index of the condensate oil produced from the parallel flow is relatively smaller than that of the condensate oil produced from the counter flow. The lower density is directly related to the lower viscosity index of the produced condensate oil from the parallel flow. It is caused by the slower heat release from gas to liquid where the exothermic process goes sluggish. It makes the molecular interaction between oil molecules weaker, which decreases the density of the condensate oil. The weak molecular interaction also affects the viscosity index where the surface tension of fluid decreases significantly. The density and viscosity index for the oil are highly associated with the flash point. The flash point of the condensate oil as the product of the pyrolysis process is a critical indicator. This association is linked where based on the test, the flash point from condensate oil produced from the counter flow is 21 °C, which is lower than the one from the parallel flow 23.5 °C. The tight molecular bonding of the condensate oil from the counter flow facilitates the combustion or flashing at lower temperatures. It is also supported by the rapid condensation for the liquid, where it decreases the activation energy to release the stored chemical energy through combustion with oxygen.

7. Conclusions

1. Counter flow direction can produce more condensate oil with 355 ml for the counter flow and 290 ml for the parallel flow.
2. The heat transfer rate for the counter flow is 2,728 W where the parallel flow has a lower rate with 1,865 W.
3. The density of condensate oil at 15 °C from the counter flow is 925.9 kg/m³ with a specific gravity of 0.8623; the condensate oil from the parallel flow is smaller with a density of 865.8 kg/m³ and specific gravity of 0.9226.
4. The viscosity of condensate oil at 40 °C for the counter flow is 1.22825 and 1.263439 where a higher

viscosity can be used to maximize the burning process in the burner.

5. The condensate oil with the counter flow direction is flammable and explodable when it is close to flame.

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