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Development of a rotary kiln reactor for pyrolytic oil production from waste tire in Indonesia

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Abstract. Development of a rotary kiln reactor for pyrolytic oil production from waste tire has been successfully fabricated and tested. The reactor has been designed with the diameter and length of 260 mm and 400 mm respectively. The reactor was equipped with the lifter which has a segment length of 28 mm. The pyrolysis experiments were conducted using a semi-batch rotary kiln reactor and carried out at the temperature of 300°C. The materials used in this experiment is waste tire collected from the local recycling company. This study aims to investigate the effect of rotational speed and lifter presence on the product distribution and oil characteristics including viscosity, density, and heating value. From the preliminary result of the experiment, it can be seen that the rotational speed and lifter affect the product distribution and oil characteristics. The experiment without lifter shows that at the rotational speed of 15 rpm produced highest liquid product. However, the liquid product produced in this experiment is still low in all condition. The use of lifter reduced the liquid and solid products while the gaseous product increases. The viscosity, density, and heating value of the oil still acceptable for using it in the engine.

1. Introduction

Indonesia's economic growth in recent years has increased the mobility of people and goods. Consequently, more transportation modes, especially land (rail and road) transportation, are needed such as passenger cars, trucks, buses and motorcycles. This is evident from the growth in the number of motor vehicles in Indonesia as shown in Table 1. Based on the data from BPS [1], the average growth of motor vehicles during the time period of 2012-2016 reached more than 9% with the largest growth in passenger vehicles reaching almost 10%.

As a result, more waste tires will be generated from such transportation modes. With an average tire lifetime of 5 years for cars and 2 years for motorcycles, it can be estimated that millions of waste tires are thrown away and potentially harmful to the environment. These waste tires will pollute the surrounding environment because they may not be decomposed easily without any treatment. It will take decades or even hundreds of year to decompose waste tire. Therefore, some efforts are needed to recycle and convert waste tire into more useful products. A rubber-based tire is one type of polystyrene synthetic polymers which can not be easily recycled so that the treatment must be properly conducted in order to prevent the environment.

On the other hand, the depletion of fossil fuel reserves is another issue related to the supply of energy needs for industry and daily life. Therefore, the development and implementation of alternative fuels that are environmentally friendly need pay more attention by the government. The use of energy which is still dominated by the fossil fuels should gradually be reduced and replaced by the new and renewable energy sources. The solution to solve both waste and energy problems is to develop new environmentally friendly renewable energy converting waste tires into fuel oil by using pyrolysis concept. Waste to energy technology or waste biorefinery provides cost-effective and promising solutions for both the increasing energy demands and the sustainable waste management in the developing countries like Indonesia [2].

Pyrolysis is a process used to recover the energy contained in the waste tire by involving the decomposition process at high temperatures (300-900ºC) under oxygen-free conditions [3]. Three products obtained from this pyrolysis process are liquid, solid charcoal, and gas. Waste tire pyrolysis has received serious attention because it can produce liquid fuels that can be stored easily and efficiently. The research on the pyrolysis of waste polymeric materials into liquid oil has been investigated by many researchers such as waste plastics [4,5] and waste tires [6-8] to obtain the optimum oil yield. Various types of reactors have been used including fixed bed, moving bed, rotary kiln, conical spouted bed [9] and fluidized bed. Waste tire pyrolysis oil has also been tested on diesel engines and provide good results [10-12].

In this study, the type of reactor used is rotary kiln, a tubular horizontal tube with a material inside the tube, which is driven at a certain rotational speed. The particle motion of the material inside the rotary kiln is concentrated on the kiln wall in the passive layer. This layer will reach the surface area where the layer is shifted down in the active layer. This repetitive process causes the particles to move in the axial direction each time they move to the active layer. This process forms the basis for particle motion modeling in the rotary kiln in the axial direction.

The use of rotary kiln technology is expected to produce oil with the desired characteristics. This paper aims to design and fabricate the rotary kiln reactor and to study the influence of lifter and rotational speed on the product distribution, viscosity, and density of pyrolysis oil. The main goal of this research is to produce oil that can be used as an alternative fuel in order to supply the needs of small and medium industries in Yogyakarta province and surrounding areas. Furthermore, an effort to improve public understanding and awareness on the benefit of this technology should be initiated to ensure the successfull application of this technology in the community [13].

Table 1. Number of motor vehicles by types in Indonesia [1].

Vehicle type	**Year**				
	2012	**2013**	**2014**	**2015**	**2016**
Passenger vehicles	10,432,259	11,484,514	12,599,038	13,480,973	14,580,666
Buses	2,273,821	2,286,309	2,398,846	2,420,917	2,486,898
Trucks	5,286,061	5,615,494	6,235,136	6,611,028	7,063,433
Motorcycles	76,381,183	84,732,652	92,976,240	98,881,267	105,150,082
Total	**94,373,324**	**104,118,969**	**114,209,260**	**121,394,185**	**129,281,079**

2. Design and Fabrication of Rotary Kiln Reactor

The rotary kiln reactor has been designed to provide uniform heating and enhance the heat transfer during the pyrolysis process. Therefore, the reactor can be rotated at a constant speed and has been installed the lifter for better mixing of the materials. The reactor must also be able to drain the pyrolysis gas to a non-rotating cooling device. The reactor should be able to work above 300°C in order to ensure the pyrolysis process takes place.

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2.1. Rotary kiln reactor
The reactor has been successfully designed and fabricated by a local workshop. The reactor has been designed with the diameter and length of 260 mm and 400 mm respectively. The reactor was equipped with the lifter which has a segment length of 28 mm. The fabrication process was done at PT. Sarana Andalan Enggal including rolling, drilling, welding and reactor assembly.

The reactor design should be fabricated in a local workshop with a limited equipment. Therefore, the simpler design has been chosen to ensure the local workshop in rural areas can also fabricate this reactor. The reactor was equipped with a shaft supported by 2 sets of bearings as shown in figure 1(a). The shaft is installed to support of the reactor and also equipped with holes for pyrolysis gas output. The use of such a shaft can minimize the vibration that arises because the output hole is not affected by the run-out of the heated reactor. Another reason for using shaft is also to anticipate an asymmetric cylindrical shape of the reactor due to machining processes during fabrication and also due to the heat expansion that can change the shape of the reactor.

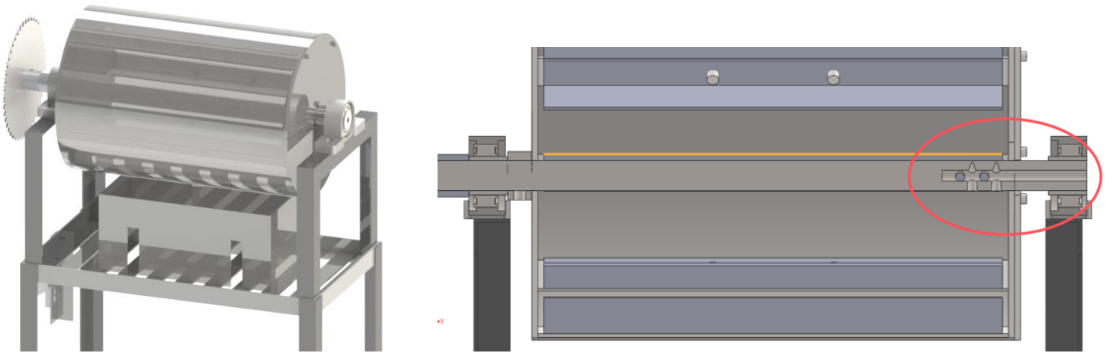

Figure 1. (a) Design of rotary kiln pyrolysis reactor for waste tire, (b) Output hole for pyrolysis gas.

The outlet pyrolysis gas channel was designed on the reactor shaft. The shaft is perforated horizontally as deep as 120 mm with a diameter of 12 mm. The shaft is then perforated vertically with a diameter of 8 mm as many as 4 holes crossed with the distance between the axis hole of 20 mm as shown in figure 1(b).

2.2. Motor and power transmission design
The reactor requires a motor that has a low speed of 5-15 rpm but has a large torque to rotate 24 kg load. To meet this requirement, a 12V DC motor was used which has a rotational speed of 80 rpm (no load) and torque of 30 kg.cm.

To reduce the motor speed, the system equipped with the power transmission system by using chain and sprocket. The upper sprocket has 48 teeth while the lower sprocket has 10 teeth. Thus, the gear ratio is 4.8. In order to vary the rotational speed i.e. 5, 10 and 15 rpm, it is necessary to have a system which can adjust the speed. A microcontroller has been chosen to control the speed which is programmed using a pulse width modulation (PWM). The PWM value for 5, 10 and 15 rpm are 125, 175 and 225 respectively.

2.3. Burner
The pyrolysis process requires heating from the outside and no direct contact with the raw material. In this study, we used a small burner that can provide a heat up to 500˚C. The burner is usually used in liquefied petroleum gas (LPG) cooking stove since the LPG has also been used as a fuel in this experimental work.

2.4. Condensor
Condensor was used to condense the pyrolysis gas into liquid (oil) product. The condenser has 3 stage condensing system which has an oil outlet to collect the condensed liquid oil as shown in figure 2. The first stage used ambient air as a cooling media which can collect heavy oil fraction. The second and third stage used water to condense a lighter fraction of oil which can not condense in the first stage. An uncondensable gas which can not be converted into liquid product come out through the exhaust hole on the condenser tube number 3. The snapshot of the complete system of waste tire pyrolysis apparatus can be seen in figure 2.

Figure 2. The snapshot of waste tire pyrolysis apparatus.

3. Methodology
The materials used in this experiment is waste tire collected from the recycling company in Cilacap city, Indonesia. The pyrolysis experiments were conducted using a semi-batch rotary kiln reactor. The pyrolysis was carried out at the temperature of 300°C. The sample used for each experiment is 500 grams. First, put 500 grams of the waste tire into the reactor. After that, start the gas cooking stove as a source of heating until it reaches the specified temperature.

Once the temperature has been reached, the waste tire begins to be pyrolyzed and partially converted to gas. The pyrolysis gas then exits the reactor toward the condenser. In this step, the gas will be cooled and partly condensed into liquid. Some gasess that does not convert into liquid goes out and burned. The liquid product is then weighed for mass balance calculations. The remaining solids in the reactor are residue and are weighed after the experiment is completed. The mass difference of the waste tire with the mass of the liquid and the residue is considered as the gaseous product. Analysis of the physical characteristics of waste tire pyrolysis oil includes viscosity, density, and calorific value. Viscosity was measured using Ostwald viscometer, while density was measured using Piknometer. The heating value of liquid oil was tested using bomb calorimeter.

4. Result and Discussion
The pyrolysis experiments were carried out at the temperature of 300°C. We studied the effect of rotational speed and lifter presence on the product distribution and oil characteristics including viscosity, density, and heating value.

4.1. Effect of rotational speed on product distribution
The experiment has been conducted to study the effect of rotational speed on product distribution of waste tire pyrolysis. Figure 3(a) shows the mass yield obtained from the pyrolysis of the waste tire as the effect of rotational speed. The result shows that at the rotational speed of 15 rpm produced highest liquid product. At higher rotational speed, the material will be mixed better in the reactor which means that the heat transfer from the outer surface of the reactor to the materials will be high. However, the

liquid product produced in this experiment is still low in all condition. This is maybe due to the low temperature that is not high enough to decompose waste tire into pyrolysis gas. It can be seen from the solid product which is still high more than 50%.

4.2. Effect of lifter on product distribution
Lifter installed in the rotary kiln reactor has a function to make a better mixing of the waste tire and to increase heat transfer due to a wider surface contact between the waste tire and reactor surface. Figure 3(b) shows the mass yield of waste tire pyrolysis with lifter installation in the reactor. From the figure, we can see that the use of lifter reduced the liquid and solid products while the gaseous product increases. The increase of heat transfer as the effect of lifter resulted in more decomposition of the waste tire which can be indicated by reducing the solid product. The higher gaseous product in this condition due to a more cracking reaction which converts the liquid product into the gaseous product.

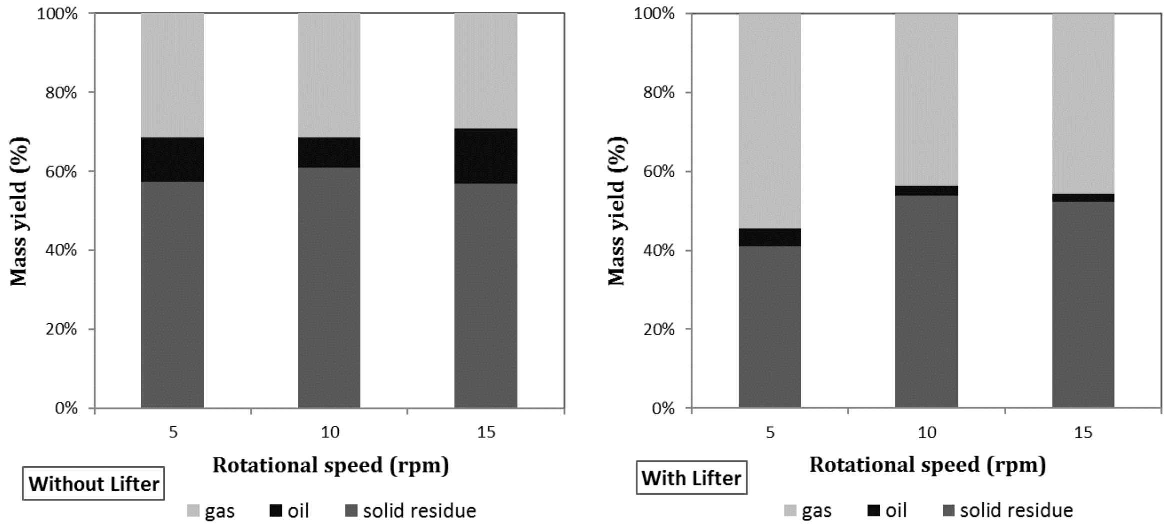

Figure 3. (a) Effect of rotational speed (without lifter) and (b) the lifter presence on product distribution at the temperature of 300°C.

4.3. Oil characteristics
The oil characteristics study performed in this work includes viscosity, density, and heating value. The viscosity and density of waste tire pyrolysis oil (WTPO) can be seen in table 2. It can be seen that the viscosity of WTPO is in the range of 0.79 – 6.50 cSt. Based on the standards of diesel fuel in Indonesia, the viscosity values are in the range of 2.0 – 5.0 cSt for diesel [4]. Viscosity plays an important role in the operation of a diesel engine. Viscosity is required for the lubrication process inside the machine, so that if the viscosity is too low then the lubrication function becomes not optimal which impact on engine damage. However, very high viscosity will have an impact on the larger fuel pump power that will shorten the life time of the pump. So the viscosity value should be within the range required on the diesel engine.

Table 2. Viscosity and density of liquid oil produced from pyrolysis of waste tire

Properties		**Rotational speed (RPM)**		
		5	**10**	**15**
Viscosity (cSt)	Without Lifter	1.39	2.63	1.55
	With Lifter	2.94	6.50	0.79
Density (g/cm^3)	Without Lifter	0.94	0.86	0.85
	With Lifter	0.83	0.86	0.79

The oil density resulting from the pyrolysis of the waste tire is in the range 0.79-0.94 g/cm^3 as shown in table 2. Density determines the amount of energy content in the fuel per unit of the same volume. According to Indonesian standards for diesel fuel, the density values are 0.815-0.870 g/cm^3 for diesel fuel. In general, most of the pyrolysis oil of waste tire are in that range. The most important parameter in pyrolysis of waste tire into alternative fuels is the heating value. This parameter describes the energy content present in the fuel. The amount of calorific value of WTPO can be seen in table 3 compared with other fuels. It can be seen that the heating value of WTPO was still lower than diesel fuel and plastic pyrolysis oil. However, the value was higher than bio-oil from bagasse

Table 3. The heating value of WTPO and other fuels.

Fuel	Heating value (MJ/kg)	References
WTPO	32.43	Experiment
Plastic pyrolysis oil	41.45-46.67	[4]
Diesel fuel	44.00-46.00	[14]
Bio-oil from bagasse	23.50	[14]
Microalgae biodiesel	40.40	[15]

5. Conclusion

Development of a rotary kiln reactor for pyrolytic oil production from waste tire has been successfully fabricated and tested. Fabrication of the reactor was conducted by a local workshop to ensure the equipment can be produced locally. From the preliminary result of the experiment, we can see that the rotational speed and lifter affect the product distribution and oil characteristics. The experiment without lifter shows that at the rotational speed of 15 rpm produced highest liquid product. However, the liquid product produced in this experiment is still low in all condition. The use of lifter reduced the liquid and solid products while the gaseous product increases. The viscosity, density, and heating value of the oil still acceptable for using it in the engine.

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