

DEVELOPMENT OF A SELF SUFFICIENT PYROLYSIS SYSTEM FOR PRODUCTION OF LIQUID FUEL FROM WASTE TIRE

M. A. Kader^{1,*}, M. R. Islam² and H. Haniu³

^{1,2}Department of Mechanical Engineering, Rajshahi University of Engineering & Technology, Rajshahi-6204, Bangladesh

³Department of mechanical Engineering, Kitami Institute of Technology, Kitami City, Hokkaido 090-8507, Japan

^{1,*}kader_042017@yahoo.com, ²mrislam1985@yahoo.com, ³harry@mail.kitami-it.ac.jp

Abstract- In this study a fixed bed fire tube heating reactor for pilot scale pyrolysis unit has been designed and fabricated for obtaining liquid fuel from organic solid waste tire. The main components of the complete pyrolysis unit are fire tube heating reactor, oil/gas/char fired furnace, fractionating column, condensers and liquid collector. The major components of the reactor were made of stainless steel sheet and pipes. A number of trial runs have been carried out with waste tires as feedstock. At an optimum pyrolysis condition of fixed bed reactor temperature of 430°C with 200 × 110 × 25 mm feed size, the maximum liquid product was found to be 49 wt %, of tire feed. Other two by-products were solid char and gases with their yields of 38 and 13 wt %, respectively. The oil obtained at this optimum condition was analyzed for their fuel properties compared with other petroleum products. The density and viscosity of the liquid was 950 kg/m³ and 4.0 cSt at 30°C, respectively. The higher calorific value of the liquid was about 42 MJ/kg while that of char was 28 MJ/kg. The energy content of by-product gases was sufficient to provide part of heat (23%) required by the pyrolysis reactor. The properties of pyrolytic liquid were much closer to that of conventional diesel fuels. From the study, it was found that pyrolysis of solid waste tires may be a potential source of liquid hydrocarbon fuels.

Keywords: Pyrolysis Pilot Plant, Waste Tire, Liquid Fuel

1. INTRODUCTION

Different organic waste materials available in the modern society that are important sources of energy all over the world. Among the common organic wastes the scrap tires are most important and their number is increasing every year at an alarming rate. In Bangladesh, total scrap tires generation each year is about 90,000 tones [1].

One common way of disposal for these waste tires is land filling. Tires are bulky, and 75% of the space a tire occupies is void, so that the land filling of waste tires has several difficulties [2]. It needs a considerable amount of space because of the volume of tires can not be compacted. Tires tend to float or rise in a landfill and come to the surface. Under the ground, the void space of waste tires captures various gases such as methane which has a tendency to burn suddenly with a vast explosion. If the waste tire is scattered on land in vain then it comes with rain water and may be a good place for breeding mosquitoes or others bacteria. This causes various harmful diseases to human beings. If the scrap tires burn directly in brick fields or any other incineration plant then various harmful gases such as CO₂, CO, SO_x, NO_x, etc will produce which cause environmental pollution.

Thus an environmental friendly and economic technology should be developed to recovery the energy from tire wastes. It will also help to reduce disposal problem for the waste tires effectively. There are different alternative techniques have been using for recycling the waste tires such as retreating, reclaiming, incineration, grinding, etc. However, all of them have significant drawbacks and limitations [3].

Pyrolysis is a thermal degradation process in which the material is heated indirectly in an oxygen free atmosphere. The word pyrolysis comes from the Greek word pyro which means "fire" and lysis which means "separating". Pyrolysis is generally described as the thermal decomposition of the organic wastes in the absence of oxygen at temperature about 400°C. Three products are typically obtained from the organic solid wastes: liquids, solid char and gases. The pyrolysis of solid tire wastes has received increasing attention because the process conditions may be optimized to produce high energy density liquids, char and gases. In addition, the liquid products can be stored until required, or readily transported to where they can be most efficiently utilized. Tire pyrolysis liquids (a mixture of paraffins, olefins and aromatic compounds) have been

found to have a high gross calorific value (GCV) of around 41-44 MJ/kg, which would encourage their use as replacements for conventional liquid fuels [4-12]. In addition to their use as fuels, the liquids have been shown to be a potential source of light aromatics such as benzene, toluene and xylene (BTX), which command a higher market value than the raw oils [2-6, 10, 13, 14]. Similarly, the liquids have been shown to contain monoterpenes such as limonene [1-methyl-4-(1-methylethenyl)-cyclohexene], a high value light hydrocarbon. Limonene has rapidly growing and wide industrial applications including the formulation of industrial solvents, resins and adhesives, as a dispersing agent for pigments, as a fragrance in cleaning products, and as an environmentally acceptable solvent [9-11, 15-17]. Pyrolytic char may be used as a solid fuel or as a precursor for the manufacture of activated carbon [4, 10, 12, 18]. Roy et al. [11] found that another potentially important end-use of the pyrolytic carbon black (CBp) may be as an additive for road bitumen. Furthermore, active carbons were prepared from used tires and their characteristics were investigated by Roy et al. [11], Zabaniotou and Stavropoulos [19], and Zabaniotou et al. [20]. They reported that active carbons, produced from tire chars, possess surface areas comparable with those of commercially available active carbons (areas around 1100 m²/g). Some of the previous research groups [4, 6, 10, 13, 21] studied the composition of evolved pyrolysis gas fraction and reported that it contains high concentrations of methane, ethane, butadiene and other hydrocarbon gases with a GCV of approximately 37 MJ/m³, a value sufficient to provide the energy required by the pyrolysis process.

The main purposes of this research work is to design a self sufficient pyrolysis pilot plant for production of liquid fuel from solid tire waste by using pyrolysis technology.

2. MATERIALS AND METHODS

2.1 Collection and Preparation of Feed Material

The collected scrap tires were of Birla and Apollo brand produced in India. The tire was used in truck or bus and net weight was about 50 kg each. The waste tires were collected locally from a dump site in Rajshahi city of Bangladesh. The tire was steel cord free that chopped into the sizes of 16 × 11 × 3 cm, 20 × 12 × 3cm, 20 × 11 × 2.5 cm etc.

2.2 Proximate and Elemental Analysis of Solid Tire Waste

The proximate and elemental analysis of solid waste tires is very important to find out various properties of solid tires. The heating value and volatile components are the main factors for tire pyrolysis. Higher volatile components indicate higher liquid product in tire pyrolysis process. The proximate and elemental analysis of solid waste tires with higher calorific value is shown in Table 1.

2.3 Thermogravimetric and Differential Thermogravimetric Analyses

The TG and DTG plots obtained at heating rates of 10

and 60°C/min for the sample of truck tire waste are presented in Fig. 1. It display the variations of fractional mass-loss (TG curves) and derivative of mass-loss (DTG curves) with respect to pyrolysis reaction temperature T for two different heating rates for truck tire wastes.

Table 1: Proximate and elemental analysis of solid waste tires

Proximate analysis (wt %)		Elemental analysis (wt %)	
Moisture	0.82	Carbon (C)	80.30
Volatile	62.70	Hydrogen (H)	7.18
Fixed carbon	32.31	Nitrogen (N)	0.50
Ash	4.17	Oxygen (O)	8.33
H.C.V (MJ/kg)	33.30	Others	3.69

The comparisons of the TG and DTG curves for the two heating rates of the sample shows that they vary with respective to one another. It shows that the DTG curves for the two different heating rates of a single sample are similar in appearance, but that both the TG and DTG curves shift to higher temperature regions when the heating rate is increased. This means that the reaction zones shift to the higher temperature regions and the peak heights increase with the increase of heating rate. The most common rubbers used for tires are NR, SBR, and BR. The rubbers mostly consist of blends of two or three rubbers together with tire additives. Several authors [22-24] reported that the thermal degradation behavior of a solid tire waste gives information about the type of rubber contents itself. Williams and Besler [22] reported after exhaustive investigations that during thermal decomposition, NR gives a peak at 375°C, SBR gives a peak at around 450°C whereas BR gives two peaks at 400 and 475°C for a heating rate of 5°C/min. Seidelt et al. [23] proved that at heating rate of 10 °C /min tire rubber DTG curves are characterized by their peak temperature: 378°C for NR, 430–458°C for SBR and 468°C for BR. Similar results were also found by Liu et al. [24]. They investigated the pyrolysis of NR, BR, and SBR, and reported that the maximum weight loss rate of NR occurs at a temperature of 373°C, BR at 372°C and 460°C, SBR at 372°C and 429–460°C.

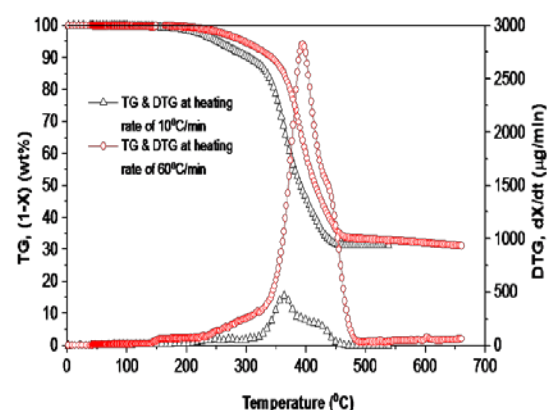


Fig. 1: TG and DTG of bus and truck tire at heating rate of 10 and 60 °C/min

Little variation in peak temperatures for respective rubber component among different studies is due to the variation in test apparatus and environment used. Thus, it can be concluded that when a rubber composition contains NR, SBR, and BR components, peaks at around 370°C, between 400 and 460°C and at around 460°C must be found in their DTG curve, respectively.

3. EXPERIMENTAL SECTION

3.1 Reactor

Vapor residence time is an important factor for optimum liquid production. Its value should be less than 5 seconds otherwise secondary cracking of vapor product would occur resulting higher amount of gases and lower amount of liquid production [25]. When the solid tire waste thermally decomposes inside the reactor chamber at an elevated temperature around 430°C then product volatile expands at this temperature and consequently its pressure is increased. Due to the difference in pressure between reactor and atmosphere, the volatile comes out fast from the reactor through condenser. The pressure of volatile and gases is slightly higher than atmospheric pressure, but the simplicity of design calculation gas pressure has assumed equal to atmospheric pressure 101325 N/m². Mass of the volatiles and gases measured on the basis of weight percentage of liquid and gases. Assuming 35 kg feed material, total amount of liquid and gases was about of 62 wt %. Hence, the mass of the volatiles and gases was about 21kg. The universal gas constant for hydrocarbon gases like methane is about 518.3 J/kg.K [26]. The maximum operating temperature of the reactor was about 450°C and gas production started at 200°C. Hence, the average operating temperature was taken at 300°C or 573 K. If the total running time is 180 minute and gases production start after 60 minute from beginning, then total volatile and gases production time is 120 minute.

The Vapor Residence Time (VRT) may be calculated by the following way:

Total volume of the reactor,

$$V_{fsp} = \left[\frac{\pi d^2 l}{4} + \frac{\pi d_1^2 l_1}{4} + \frac{\pi d_2^2 l_2}{4} \right] \times \left(1 - \frac{V_m}{100} \right) + \frac{\pi d_3^2 l_3}{4} = 0.1266 \text{ m}^3$$

Volume occupied by waste tire is 70 % of total volume of reactor. So the free space in the reactor, $V_r = (100 - 70) = 30$ % of total reactor volume (0.03705 m³). Now from $PV = mRT$, The volume of the volatile and gas generated, $V = 53.70 \text{ m}^3$. Where, P is the Product volatile and gases pressure in the reactor (101325 N/m²), m is the mass of volatiles and gases (assume 60% of solid tire, $35 \times 0.6 = 21 \text{ kg}$), T is average operating temperature (573 K) and R is universal gas constant (for hydrocarbon vapor, $R = 518.3 \text{ J/kg.K}$).

So, volume flow rate, V_f

$$= \frac{\text{Volume of the volatile and gas generated}}{\text{Total time of reaction}}$$

$$= \frac{53.70}{100 \times 60} \text{ m}^3/\text{sec} = 0.00895 \text{ m}^3/\text{sec}$$

Volatile and gas production rate,

$$V_f = \frac{V}{t} = \frac{61.52}{120 \times 60} = 0.0085 \text{ m}^3/\text{sec}.$$

$$\text{Vapor residence time, } t = \frac{V_r}{V_f} = 4.13 \text{ sec} \sim 4 \text{ sec}$$

3.2 Furnace

Furnace is the most important thing in pyrolysis process. If furnace does not create sufficient heat then the process will take more time to complete a run. And hence the fuel cost will increase. Thus the proper design of furnace can maintain the efficient heating of reactor. At the middle of the slab a hole of 20 cm ensured the easy char removal through the bottom of the reactor. The furnace was made of fire brick so that it ensured minimum heat loss. The height of the fire brick wall was 25 cm. The burner was placed into the furnace and it mixed and burned both compressed air and fuel using nozzle. The side wall was insulated with glass wool having 5 cm thickness. The side wall was divided into four parts. Among them two parts were fixed with exhaust pipe and other two parts were movable. These movable parts were designed for faster cooling after completing a run. These parts were moved manually. Finally, the flue gas was exhausted through the exhaust pipe. Pyrolysis oil, pyro-gas and solid char from previous run were used for burning in the furnace.

3.3 Fractionating Column

Pyro-gas contains light hydrocarbons and tarry substances. It deposits and blocks the connecting pipe and condensing shell and produce low grade oil. So to promote high grade liquid oil a separator (a fractionating column) was used. Heavy compounds whose boiling points were high separated and fall downward from the light fraction due to gravity action. Fractionating column was a hollow cylinder has two flanges at its two ends. Upper flange was used for assemble and cleaning the inside of the fractionating column. The inlet port of the fractionating column was at 304 mm height from the bottom flange for storing the tarry substances during running time and collecting after completing the run.

3.4 Condenser

A condenser is a device or unit used to condense a substance from its gaseous to its liquid state, typically by cooling it. In so doing, the latent heat is given up by the substance, and will transfer to the condenser coolant. After separating the heavy compounds in the fractionating column the pyro-gas was flown into the condensers for condensing to liquid oil. There were two condensers were used in this project work: one was placed in vertical and the other was in horizontal position. Condensers were hollow pipe with another pipe inside. Pyro-gas was passed through the inside pipe while cooling water was passed around it. For proper cooling of the vapor, the assumed parameter were water inlet temperature, $T_{c1} = 27^\circ\text{C}$, Water outlet temperature, $T_{c2} = 30^\circ\text{C}$, Vapor inlet temperature, $T_{h1} = 200^\circ\text{C}$, Vapor outlet temperature, $T_{h2} = 38^\circ\text{C}$.

So the minimum log mean temperature difference,

$$\Delta T_m = \frac{(T_{h2} - T_{c2}) - (T_{h1} - T_{c1})}{\ln \frac{T_{h2} - T_{c2}}{T_{h1} - T_{c1}}} = 53.67^\circ\text{C}$$

Where specific heat of water, $C_w = 4.2 \text{ kJ/kg.K}$

The overall heat transfer between water and vapor was calculated from the equation, $Q = U_o A \Delta T_m$. Again from the rate of heat flow equation, $Q = m_w C_w (t_{w1} - t_{w2})$, we get the required mass flow rate of water for proper cooling, $m_w = 0.64 \text{ kg/sec} = 38 \text{ liter/min}$.

3.5 Complete Pyrolysis Unit

Assembly of various components of pyrolysis unit was the most important task for better performance of the plant. At first a concrete slab supported by four pillars was placed inside underground holes as base of the pilot plant. Then the furnace was made on concrete slab by using fire bricks. Two burners were connected at the bottom of the furnace. Then reactor chamber was placed on the furnace supporting with two mild steel rods. Then the insulated side walls were placed around the reactor. A cover plate was attached at the top of furnace. Two fixed parts of side wall were attached with the exhaust pipes and other two portable parts were connected with fixed parts by means of nut-bolts. Then a gas flow line with a gate valve was connected to the fractionating column. The purpose of fractionating column was to separate the heavy compounds from volatiles and gases. Thus the proper flow of gases through the pipe lines was maintained by separating the heavy compounds of higher density as well as higher viscosity. The fractionating column was attached with vertical condenser. The vertical condenser was connected with horizontal condenser. A digital pyrometer probe was inserted into the reactor through cover plate. Fractionating column and the gas pipe lines were supported by metallic stand and insulated by insulating material named glass wool having a thickness of 3 cm. Finally a hole was made to place the liquid collector at the outlet of the horizontal condenser. Fig. 2 shows the flow diagram and photograph of the completely assembled pilot scale pyrolysis unit, respectively.

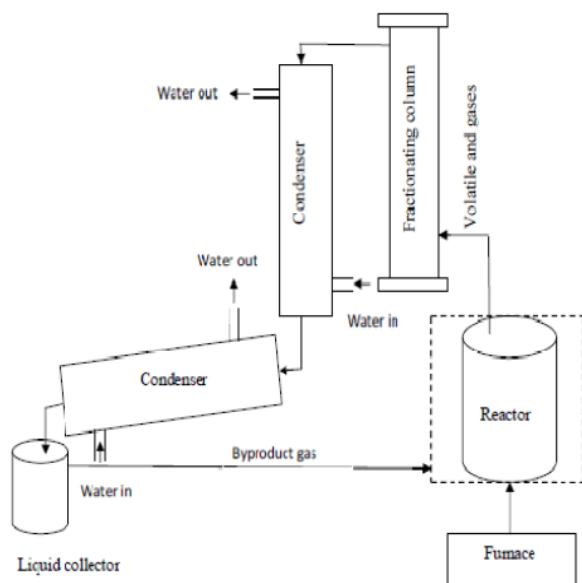


Fig. 2: Flow diagram of pyrolysis unit

3.6 Operation of the Pilot Plant

Dry and weighted feed materials were taken into the

reactor for pyrolysis experiments. Then the reactor feeder was closed by cover plate with steam gasket to ensure leak proof of gases. For reactor heating furnace was started to burn by means of compressed air and fuel. The pyrometer prob was inserted into the reactor to measure the reactor inside temperature. The gas flow line from reactor to condenser was fully opened. To condense the volatile, cooling water was supplied through the condensers. Finally the condensed liquid was collected into liquid collector and non condensable gases were released into atmosphere. The whole operational procedure for the complete pilot scale pyrolysis plant is presented by a flow chart in Fig. 3.

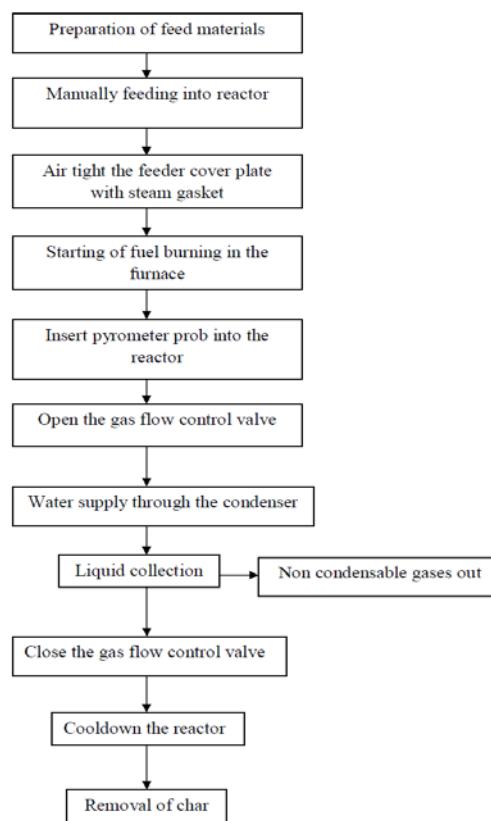


Fig. 3: Operational procedure for the pilot plant

3.7 Heating and Cooling Operation

The heating and cooling operation is very important factor for pyrolysis plant. The reactor and furnace was designed in such a way that the produced heat was transferred into reactor chamber quickly and uniformly. Initially reactor temperature was 30°C . Then after every 10 minutes, temperature reading was recorded during heating and cooling of the reactor. The reactor was heated at an increasing rate up to first 100 minutes of running operation. Then the next 80 minutes was maintained at constant temperature near about $430^\circ\text{C} (\pm 10^\circ\text{C})$. Then the portable parts of the insulated side wall of furnace were removed for cooling purpose. Next 180 minutes was taken as cooling period where temperature decreased to 50°C . The total time for the reactor heating and cooling operation of the pilot plant was 360 minutes. Temperature distribution during the reactor heating and cooling operation is presented in Fig. 4.

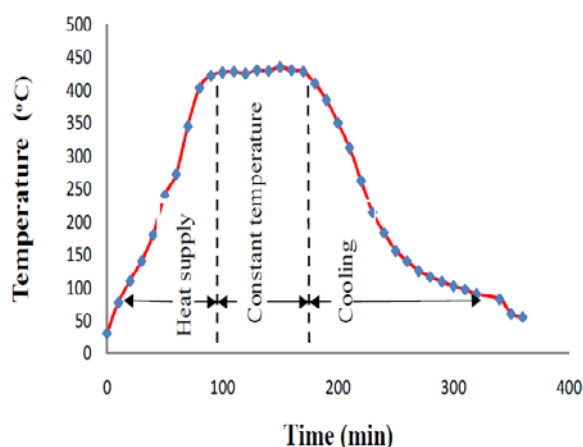


Fig. 4: Temperature distributions during reactor heating and cooling operation

4. RESULTS AND DISCUSSION

4.1 Pyrolysis Products from the Pilot Plant

In tire pyrolysis system three products were obtained, liquid, char and gases. Pyrolytic liquid was the main products in pyrolysis process. Char and gases were two by-products having high gross calorific value which may be used as fuel for reactor heating purpose. A total of four successful runs were carried out by using prepared tire waste samples. The product distributions obtained from the pilot plant experiments are presented in Table 2.

Table 2: Product yields distribution of pilot plant tire pyrolysis for variation of running time

No of obs	Running time (min)	Tire feed (kg)	Product yields (wt %)		
			Liquid	Char	Gas
1.	170	35	48.5	37.7	13.8
2.	180	35	48.4	38.1	15.3
3.	190	35	49	38.3	12.7
4.	200	35	46	37.5	16.5

The table shows that average running time for the plant was 188 minutes and enabling average product yields: liquid 48 %, char 38 % and gases 14 %.

From the previous study, it was found that the liquid production in laboratory scale was slightly higher than pilot plant. For a particle feed size 10 x 2 x 1 cm, the maximum liquid, char and gas production was found of 57, 26 and 17 wt %, respectively at an operating temperature 475°C. The comparison of product yields distribution obtained from pilot plant and laboratory studies are presented in Fig. 5.

4.2 Comparison of Pyrolysis Liquid with Petroleum Products

The properties of pyrolytic liquid are very important to identify the nature of that oil. A few properties of pyrolytic liquid were much closer to petroleum products. The comparison of properties among pyrolytic liquid and petroleum products is presented in Table 3.

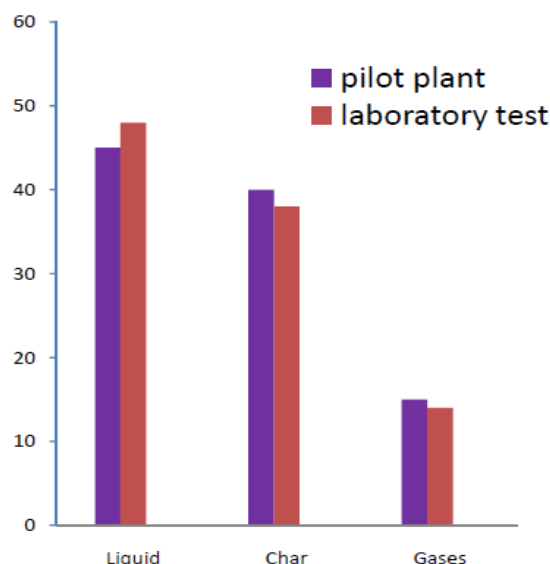


Fig. 5: product yields distribution of pilot plant compared to laboratory study

Table 3: Comparison between pyrolytic liquid and petroleum products

Properties	Pyrolytic liquid	Diesel	Furnace oil
Density (kg/m ³)	950	840	930
Viscosity (cSt)	4.0	2.8	6.2
HCV (MJ/kg)	42	44.8	46

The above table shows that the higher calorific value of pyrolytic liquid is much closer to commercial diesel fuel, but the density and viscosity is slightly higher than that of diesel fuel.

5. CONCLUSION

The solid waste tires are converted into liquid product by batch type fixed bed pyrolysis system. The main objectives of this type of project are to improve the production rate and simplify the system during large production. Hence the reactor was designed such that it contains enough feedstock and proper heat transferred to it for maintaining maximum liquid production. The reactor was designed vertically so that feeding and char removing were easier due to gravity action. The reactor was placed inside the furnace containing two portable parts. These parts were maintained faster cooling of reactor naturally. A few trial runs have been carried out at various operating condition for the maximum liquid production. The maximum liquid yield for tires was found to be 49 wt %, of feed. The characterization study of liquid product was compared with other fuels. It was found that some properties were much closer to diesel fuels and other conventional fuels. In the conclusion, it may be said that the pyrolysis liquid from tires may be better substitute of conventional fuels.

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