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A Comparison of the Use of Pyrolysis Oils in Diesel Engine

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ABSTRACT

Creating a sustainable energy and environment, alternative energy is needed to be developed instead of using fossil fuels. This research describe a comparison of the use of pyrolysis oils which are the tire pyrolysis oil, plastic pyrolysis oil and diesel oil in the assessment of engine performance, and feasibility analysis. Pyrolysis oils from waste tire and waste plastic are studied to apply with one cylinder multipurpose agriculture diesel engine. It is found that without engine modification, the tire pyrolysis offers better engine performance whereas the heating value of the plastic pyrolysis oil is higher. The plastic pyrolysis oil could improve performance by modifying engine. The economic analysis shows that the pyrolysis oil is able to replace diesel in terms of engine performance and energy output if the price of pyrolysis oil is not greater than 85% of diesel oil.

Keywords: Pyrolysis; Pyrolysis Oil; Engine Performance; Feasibility Study

1. Introduction

Due to the fossil fuel crisis in past decade, mankind has to focus on developing the alternate energy sources such as biomass, hydropower, geothermal energy, wind energy, solar energy, and nuclear energy. The developing of alternative-fuel technologies are investigated to deliver the replacement of fossil fuel. The focused technologies are bio-ethanol, bio-diesel lipid derived biofuel, waste oil recycling, pyrolysis, gasification, dimethyl ether, and biogas [1]. On the other hand, appropriate waste management strategy is another important aspect of sustainable development since waste problem is concerned in every city.

The waste to energy technology is investigated to process the potential materials in waste which are plastic, biomass and rubber tire to be oil. Pyrolysis process becomes an option of waste-to-energy technology to deliver bio-fuel to replace fossil fuel. Waste plastic and waste tire are investigated in this research as they are the available technology. The advantage of the pyrolysis process is its ability to handle unsort and dirty plastic. The pre-treatment of the material is easy. Tire is needed to be shredded while plastic is needed to be sorted and dried. Pyrolysis is also no toxic or environmental harmful emission unlike incineration [2].

The tire pyrolysis oil and plastic pyrolysis oil have been investigated and found that they both are able to run in diesel engine and the fuel properties of the oils are comparable to diesel oil [3,4]. Both pyrolysis oils are a complex mixture of C_5-C_{20} organic compounds. The tire pyrolysis oil contains a great proportion of aromatics and up to 1.4% sulfur content whereas the plastic pyrolysis oil is able to occur high chlorine content if the plastic is unsorted [5,6]. The assessment in terms of chemical process, production and feasibility study of both pyrolysis oils are done in previous researches [7-9]. There is no research about the use of the oil in terms of cost analysis and potential of fossil fuel replacement.

This research describes a comparison of the use of pyrolysis oils which are the tire pyrolysis oil and plastic pyrolysis oil in the assessment of engine performance, environmental impact, and feasibility analysis. The oils are researched and applied with DI Diesel engine. The sensitivity analysis of the oil price subjected to the oil performance is also distinguished in the research. The oil characteristic and financial data are studied from a commercial plastic pyrolysis and a commercial tire pyrolysis plant in Thailand.

2. Pyrolysis Oil

Feedstock material is the main factor to indicate the properties of the pyrolysis oil. Tire pyrolysis and plastic pyrolysis technologies are the available technologies on the market in Thailand. The feedstock pre-process is one of the main factors to assess the possibility of the technology. The waste tires are collected easily from the scavenger and garage as they are bulky and heavy but only shredding process is required to reduce the size. The waste plastics are collected from scavenger, MSW sorting plant, and landfill area. The weakness of the plastic is the character of the plastic, which is mainly from plastic bag, is small high impurity and bulky. Soring and cleaning is required for plastic process. However, as the purpose of the process is turning waste to energy, the pyrolysis process of tire and plastic is distinguished and compared in this research. Physical and chemical analysis properties of both oils are studied and compared in order to ensure to usage of the oil in diesel engine.

2.1. Plastic Pyrolysis Oil

In the USA, plastic waste approximately 31 million of tons was generated in 2010 which is about 17.45% of total waste by weight as shown in **Table 1** [10]. The percentage of the plastic waste is also similar in Thailand and around the world. As known that plastic is a non-degradable petroleum based product. The old landfill area is found that degradable product is composted, become soil while plastic is still exist. This problem is solved by converting waste plastic to energy by pyrolysis process.

As the petroleum based plastic is the polymeric material, the plastic pyrolysis process is the thermal de-polymerization process in the absence of oxygen which is able to convert plastic into gasoline-range hydrocarbons [11]. The waste plastic used in pyrolysis process is needed to be sorted and cleaned. The Polyethylene (PE) and Polypropylene (PP) which are the main component of the plastic in municipal solid waste are used in the process in order to prevent the contamination of chlorine in the oil [6]. The classified waste plastic is processed from an autoclave pyrolysis reactor. In general, product yields from pyrolysis are varied with temperature. The plastic pyrolysis oil used in this research is processed at 300-500°C at atmospheric pressure for 3 hours. The product output consists of 60-80% pyrolysis oil, 5-10% residue and the rest is pyrolysis gas on weight basis. The plastic pyrolysis oil used in this research is processed from a commercial waste plastic pyrolysis plant in Thailand.

Table 1. Contents of municipal solid waste in the USA year 2010.

Component	Amount (Millions of tons)	Percentage (by weight)
Paper Waste	71.31	40.09%
Glass	11.53	6.48%
Metal	22.41	12.60%
Plastic Waste	31.04	17.45%
Woods	15.88	8.93%
Miscellaneous	25.69	14.44%

2.2. Tire Pyrolysis Oil

In the USA, about 303.2 million of waste tires were discarded in year 2007, while about 60 million of waste tires in Thailand year 2011. Not to mention about the cumulative waste tire in landfill, the problem of tire disposal will be increasing gradually due to the expanding of vehicle market. The tire pyrolysis process converts waste tires into potentially recyclable materials such as flammable gas, pyrolysis oil and carbon black [12]. Although the amount of waste tire is less than the waste plastic, the option of the waste tire conversion is limited.

Tire pyrolysis oil plant has been established around the world in order to produce the substitute liquid fuel for heating purpose as found that the tire pyrolysis oil have a high gross calorific value (GCV) of around 41-44 MJ/kg [13]. Waste tire is needed to be shredded before process. The desulphurization is required in the pyrolysis system to eliminate the sulfur. It was determined that the oil production yield of tire pyrolysis process has a maximum at 350°C and decomposes rapidly above 400°C [13]. The plastic pyrolysis oil used in this research is processed at 300-500°C at atmospheric pressure for 3 hours. The tire pyrolysis oil used in this research is processed from a commercial waste tire pyrolysis plant in Thailand. The product output consists of 35% pyrolysis oil, 56% residue and the rest is pyrolysis gas on weight basis. The amount of the residue is tire wire scrap and carbon black.

2.3. Characteristic of Pyrolysis Oil

Pyrolysis is a complex series of chemical and thermal reactions to decompose or depolymerize organic material under oxygen-free conditions. The products of pyrolysis include oils, gases and char. The pyrolysis oil products in this research are from tire and plastic which are dissimilar in physical properties and chemical properties. The appearance of the tire pyrolysis oil is thick-liquid and dark colour oil whereas the appearance of the plastic pyrolysis oil is grease oil liked and dark colour oil at 30°C (room temperature). They all strong smell due to the high aromatic substance.

As the comparison usage of this research is in diesel engine, the pyrolysis oil from process is a mixture of carbon composition which are C_5-C_{20} in tire pyrolysis oil and C_{10}-C_{30} in plastic pyrolysis oil. The oil requires distillation process to differentiate the diesel-like oil from other compounds. The distillation temperature applied in this research is 180°C. The substance that evaporates before 180°C is taken out. The remaining is analyzed and tested in one cylinder multipurpose agriculture diesel engine. The properties comparison of plastic oil, tire oil and diesel oil is analyzed as shown in **Table 2**.

The proximate analysis was conducted using a thermo-gravimetric analyzer. The elemental determination (carbon, hydrogen, nitrogen and sulfur content) are analyzed by a CHNS Elementary Analyzer. The chlorine content of PVC was determined by improved oxygen bomb combustion – ion chromatography method which is based on the standard method in ASTM D 4208-02. The heating value of all the samples was measured using bomb calorimeter.

The heating value and the flash point of plastic pyrolysis oil is the highest while the other properties are comparable. As the plastic pyrolysis oil is wax form in room temperature, the oil requires pre-heating process before input to diesel engine.

3. Engine Performance Analysis

Engine performance indicates the effects of a fuel in the engine. It shows the trend and possibility of using pyrolysis oil to replace diesel oil without any engine modification. It is necessary to determine break torque (*T*), engine break power (*P*), break specific fuel consumption (*bsfc*), and break thermal efficiency (η_{th}). These several parameters can be obtained by measuring air and fuel consumption, torque and speed of the engine, and heating value of the oil. The performance parameters can be calculated by equations as followed [14].

3.1. Break Torque

Torque is an indicator of the function of break torque calculated by the moment of engine arm connected to weight scale as:

$$T = Fd \tag{1}$$

where *T* is break torque in Nm, *F* is force of engine arm applied to the load in N, and *d* is the distance of engine arm from center of the rotor to the load.

Table 2. Properties of pyrolysis oil.

Property	Tire Pyrolysis oil	Plastic Pyrolysis Oil	Diesel Oil
Heating Value (kJ/kg)	43225.9	46199.12	45814.74
C (%)	84.67	83.79	87
H (%)	10.44	11.36	13
O (%)	4.17	2	-
Cl (%)	n.a	0.03	n.a
S (%)	≤1	-	-
Density @ 30°C (g/cc)	0.924	0.8147	0.7994
Viscosity @ 40°C (cp)	2.69	2.49	1-4.11
Flash Point (°C)	68	100	70

3.2. Engine Break Power

Engine break power (*P*) is delivered by engine and absorbed load. It is the product of torque and angular engine speed where *P* is engine break power in kW, *N* is angular speed of the engine in rpm as:

$$P = \frac{2\pi NT}{60 \times 1000} \tag{2}$$

3.3. Break Specific Fuel Consumption

Break specific fuel consumption (bsfc) is the comparison of engine to show the efficiency of the engine against with fuel consumption of the engine in g/kW-hr where ($\dot{m}_f$) is the fuel consumption rate in g/hr as:

$$bsfc = \frac{\dot{m}_f}{P} \tag{3}$$

3.4. Break Thermal Efficiency

The percentage of break thermal efficiency of the engine (η_{th}) is related to engine break power (*P*) and the total energy input to the engine which is Q_{LHV} lower heating value of fuel in kJ/kg applied to the fuel consumption rate as:

$$\eta_{th} = \frac{P \times 1000}{\dot{m}_f Q_{LHV} \times 3600} \times 100 \tag{4}$$

3.5. Experimental Detail

The characteristics of an engine used this experiment which is a multi-purpose agricultural direct injection diesel engine (Kubota ET-70) are shown in **Table 3**.

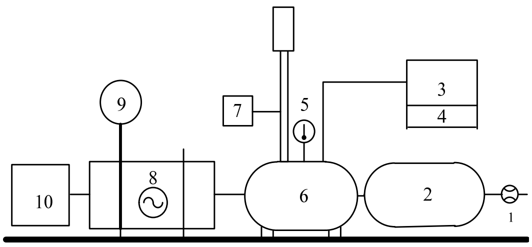
Schematic of the experimental set up is shown in **Figure 1**. The engine equipped with measuring elements including weighing device, manometer, orifice plate, tachometer, thermocouple and black smoke meter at the exhaust. As the experiment was run in constant speed, the torque output from the experiment is measured by the breaking force absorbed by the load. The absorbed load is maximum 7 kW. The pure distilled plastic pyrolysis oil,

Table 3. Engine specification.

Engine Specification	Kubota ET70
Bore X Stroke	78 mm. X 84 mm.
Swept Volume /Cylinder	401 cc.
Compression Ratio	23.5:1
Max.Torque @1800 rpm	22.56 Nm
Max. Output, HP/rpm	7 (5.15)/2200
Rated. Output, HP/rpm	6 (4.41)/2200

distilled tire pyrolysis oil and diesel oil were tested in this experiment.

The experiments were conducted by starting engine with the blended testing fuel. The operating conditions were set at a rated engine speed 1500 rpm. Loads were applied from 500 W and stepped up until reached the maximum load. The air box and orifice plate flow meter are applied for air flow measurement. Fuel consumption is measured from the differential of the fuel in time. A chromel-alumel thermocouple was installed to measure the exhaust gas temperature. The engine was run for 5 minutes to reach the steady state of test condition before collecting data. At the end of the test, the engine was run with diesel fuel for sometime to flush out from the engine.



1. Orifice Plate *2. Air box*
3. Fuel Tank *4. Weighing Device*
5. Tachometer *6. Engine*
7. Black Smoke Meter, Thermocouple 8. Generator
9. Torque Meter 10. Load

Figure 1. Schematic of the experimental setup.

3.6. Engine Performance Result

The experimental result of the engine performance shows the opportunity of using pyrolysis oil in diesel engine. The variation of the break thermal efficiency with the break power shows that the trend of thermal efficiency performance of the tire pyrolysis oil and plastic pyrolysis oil are comparable to diesel oil. The tire pyrolysis oil offers higher efficiency in the medium load while the plastic pyrolysis offers slightly lower efficiency. The maximum load production from plastic pyrolysis oil is the lowest which is 3,064 W where as the tire pyrolysis oil produces 3,282 W and diesel produces 3,500 W as shown in **Figure 2**. The trend lines of the plastic pyrolysis oil and diesel oil are similar in linear line unlike the tire pyrolysis oil which is in parabolic curve.

It shows that the tire pyrolysis oil consists of aromatics and complex compound which reflected in high efficiency in the medium load. The variation of the break specific fuel consumption with the break power in **Figure 3** is also shown that both of the pyrolysis oil is applicable to use in diesel engine. The plastic pyrolysis oil offer the lowest break specific fuel consumption at 294 g/kW-hr with maximum break power at 3,064 W. As diesel engine is designated to apply with diesel oil, some

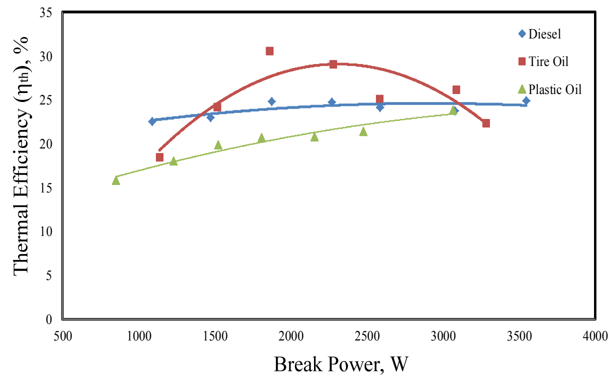


Figure 2. The variation of the break thermal efficiency with the break power.

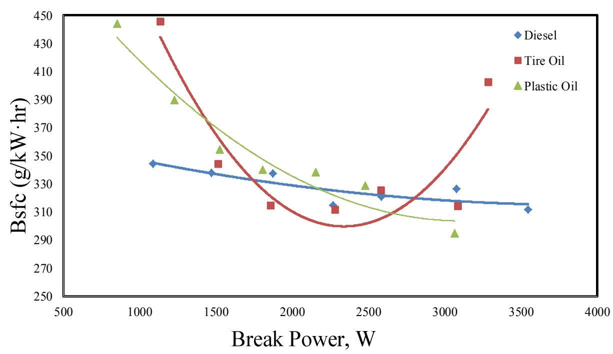


Figure 3. The variation of the break specific fuel consumption with the break power.

properties in tire pyrolysis and plastic pyrolysis such as density and viscosity might cause the less efficiency and the limitation in combustion condition.

The engine exhaust gas temperature for plastic pyrolysis oil varies from 120℃ at low load to 225℃ at full load where in case of tire pyrolysis oil varies from 119℃ at low load to 295℃ at full load and in case of diesel oil varies from 119℃ at low load to 312℃ at full load. The experiment shows the combustion of diesel oil deliver higher heating rate due to the ignition delay condition. However, the performance of the use of plastic pyrolysis oil could be enhanced by modifying the injection timing of the engine [15].

Exhaust soot was measured in Bosch Smoke Units (BSU) by a Bosch smoke meter. The smoke opacity of the plastic pyrolysis oil is the highest which is varies from 18% at no load to 97% at full load. The tire pyrolsis oil is slightly higher than the diesel oil as fuels with higher aromatics exhibit higher NOx and smoke at full load [16]. The smoke opacity varies from 11% at no load to 84% at full load for Diesel where as for tire pyrolysis oil varies from 15% to 95%. The result reflects that the best oil for engine is diesel oil. The plastic pyrolysis is the lowliest while the tire pyrolysis is acceptable for the engine use without modification.

4. Economic Analysis

Comparison of the use of two types of pyrolysis oils are cannot be completed if the economic analysis concerning the cost and sensitivity. Fuel costs are estimated regarding the information from pyrolysis plant in Thailand. The currency unit used in this research is in Thai Baht.

4.1. Fuel Production Cost Analysis

The investment and expenses of these two pyrolysis plants are concerned and analyzed to estimate the production cost of respectively oil as shown in **Table 4**. Though the core technology of each plant is similar, the characteristics of feedstock and product are slightly different. It is assumed that the feedstock input is 6 tons per day. Plastic used is waste plastic from landfill site and tire used is collected from garages.

Sorting system of plastic pyrolysis plant carry out higher capital cost and feedstock expense but in return, the amount of oil production is higher. The tire pyrolysis plant require only shredding process but in return, it produce less amount of oil compare to the same amount of feedstock as the tire contains tire wire and high carbon residue. The cost of plastic oil is slightly lower than tire oil due to the production amount.

4.2. Energy Cost and Sensitivity Analysis

The fuel cost analysis is done under financial assumption which is not concerning about efficiency output of oil.

Table 4. Pyrolysis oils cost estimation.

Type of Cost	Unit	Plastic Oil	Tire Oil
Total Capital Cost	Baht	9,000,000	6,000,000
Capital cost	Baht/Day	24,658	16,438
Expenses:			
Feedstock Expenses	Baht/Day	30,000	8,000
Operation Expense	Baht/Day	3,000	1,500
Maintenance Expenses	Baht/Day	1,000	440
Labor Expense	Baht/Day	3,000	2,000
Utilities Expense	Baht/Day	1,000	1,000
Taxes, Insurance	Baht/Day	450	200
Total Expenses	Baht/Day	38,450	13,140
Profit 30%	Baht/Day	11,535	3,942
Total production	**Baht/Day**	**74,643**	**33,520**
Oil production	Liter/Day	4,500	2,000
Production cost	**Baht/Liter**	**16.59**	**16.76**

The cost might not applicable to all situations as the engine performance result shows the diverse of efficiency. Therefore, the indicator that is applicable to all situations to predict the use of oil in terms of economic analysis should be energy cost consumption per power output as:

$$\varphi_E = bsfc \times \left(\frac{Cost_{PO}}{\rho_{PO}} \right) \quad (5)$$

where φ_E is the cost of energy consumption per power output in Baht/kW-hr, ρ_{PO} is the density of calculating oil. Equation (6) shows the cost of energy compared regarding to the efficiency.

The energy consumption cost indicates that the use of both tire pyrolysis oil and plastic pyrolysis oil is economically comparable to diesel oil. Though the engine performance is lower, the cost of fuel is significantly lower as shown in **Figure 4.**

However, the sensitivity analysis of the fuel cost is done and it is found that the both pyrolysis oil is suitable to use as diesel replacement in terms of engine performance and economic analysis as long as the price of pyrolysis is less than 85% of diesel oil price.

5. Conclusions

The use of plastic pyrolysis oil and tire pyrolysis oil in diesel engine in the aspect of technical and economical is compared and found that both of the oils are able to replace the diesel oil.

Though the plastic pyrolysis oil offers lower engine performance, the plastic waste amount is enormous and it needed to be process to reduce the environmental problems. Moreover, the engine can be modify follow the combustion condition of plastic pyrolysis oil. The waste plastic used in the process must be PE or PP in order to protect the contamination of chlorine in the oil.

Tire pyrolysis offers comparable efficiency to diesel oil in medium to high load but it has been question on the desulfurization process. Therefore, the development of the tire pyrolysis oil is depending on the cost of desulfurization process. Although the tire pyrolysis oil offer

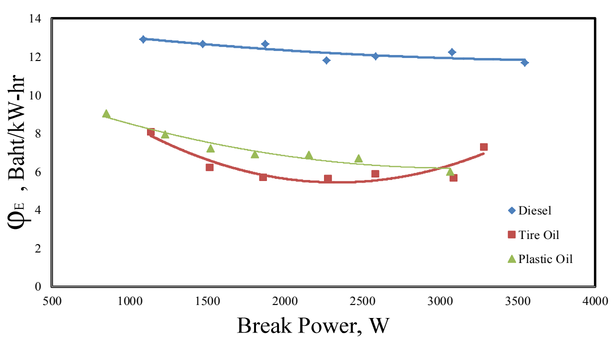


Figure 4. The variation of the energy cost consumption per power output with the break power.

better quality than plastic pyrolysis oil, the amount of waste tire is minimal compare to plastic waste and the oil production is less. Additionally, by product of the tire pyrolysis plant carbon residue and tire wire from waste tire, the plant entrepreneur need to find an opportunity to process these by products due to the amount of the by product is correspondent to the oil product.

Turning waste to energy is not only financial profitable but it also environmental friendly business which the government should offer a strong policy to encourage the entrepreneur to invest in the waste to energy business.

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