Engine Performance and Economic Impact Study of Diesel-Like Tire Pyrolysis Oil

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Abstract: - Depletion of fossil fuel influences the development of renewable energy and alternative fuels. Pyrolysis oil from waste tire studied in this research to apply with one cylinder multipurpose agriculture diesel engine. The engine performance and economic analysis are investigated by blended the commercial diesel in Thailand and diesel-like tire pyrolysis oil into 50, 75, and 100 % by volume. This research presents the performances of engine which are break torque, engine break power, break specific fuel consumption, and thermal efficiency, cost comparison of blended oil in engine. This research is done under the DTPO production value in Thailand and without engine modification. 100% DTPO is the most cost effective point as 0.2 US$/kW-hr. with the load 2500W while the diesel oil offer 0.38 US$/kW-hr. The result shows that the 75% DTPO affects the highest efficiency comparable to 100% DTPO in medium load also offer smoother condition for engine and nozzle.

Key-Words: - Pyrolysis; Diesel-like tire pyrolysis oil; Engine Performance

1 Introduction

Increasing of energy demand and oil depletion situation encourage the development of renewable energy and alternative fuel technology. Pyrolysis process becomes an option of waste-to-energy technology to deliver bio-fuel to replace fossil fuel. The availability and demanding of alternate fuels from municipal solid waste (MSW), wood, agricultural waste, sewage sludge, and waste tire, is growing. Focusing on the tire waste material, 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. As tires are not easily degradable in landfill and they can create high pollution emission when they burned, waste management is needed [1]. 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.

Tire pyrolysis has been investigated for more than 20 years. The process converts waste tire into potentially recyclable materials such as flammable gas, pyrolysis oil and carbon black [2]. Composition of the oil depends on reactor design and operating condition. 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 [1]. Desulfurization process is needed for tire oil pyrolysis as the high concentration of sulfur in pyrolysis oil leads the emission of SO_2 and sulfate particular matter. The economic analysis of the fuel cost analysis is done to reflect the potential of the market [3,4]. The use of tire pyrolysis oil in diesel is investigated and found that reducing the aromatic content and viscosity would improve the oil usage in diesel engine [5]. Therefore, the tire pyrolysis oil was distilled between 150-200°C and investigated performance and emission with diesel engine. Murugan et al. [6] found that the diesel engine is able to use up to 90% of distilled tire pyrolysis oil and 10 % of diesel. However, the acceptance of technology has been limited by the market value of the produced oil. The economic analysis of the tire pyrolysis oil in term of engine usage replacing fossil fuel is lacking, though it has been known that the process causes not only the value added to waste tire process but also the reduction of fossil fuel consumption.

This paper presents the engine performances, and economic analysis in terms of cost of fuel compare with energy output in kilowatt-hour applying blended various compositions of diesel-like tire pyrolysis oil (DTPO) and diesel oil in agriculture diesel engine in order to predict the behavior of cost in each blended oil.

2 Tire Pyrolysis

Pyrolysis is a complex series of chemical and thermal reactions to decompose organic material under oxygen-free conditions. The products of pyrolysis include oils, gases and char.

For tire pyrolysis oil, it has been reported that the tire pyrolysis oil is a complex mixture of organic compounds of 5-20 carbons with high proportion of aromatics [7].

In general, product yields from pyrolysis are varied with temperature. Chang et al. [8] determined that the oil production yield of tire pyrolysis process has a maximum at 350°C and decomposes rapidly above 400°C. The pyrolysis oil used in this research is processed from a batch pyrolysis reactor with desulfurization process. The capacity of the system is 6 tons of waste tire input per batch at the temperature range 350-400°C. The tire pyrolysis oil is distilled and distinguished into 3 kinds of substances, gas and light oil (C_6-C_{14}), diesel-like oil (C_{14}-C_{19}), and heavy oil (C_{19}-C_{35}) as shown in Fig. 1.

Diesel-like oil in this research is distilled at temperatures between 250-340°C respect to the distill temperature of diesel oil in order to optimize the efficiency of the engine. The basic properties of diesel-like oil were analyzed and compared to diesel fuel, as given in Table 1.

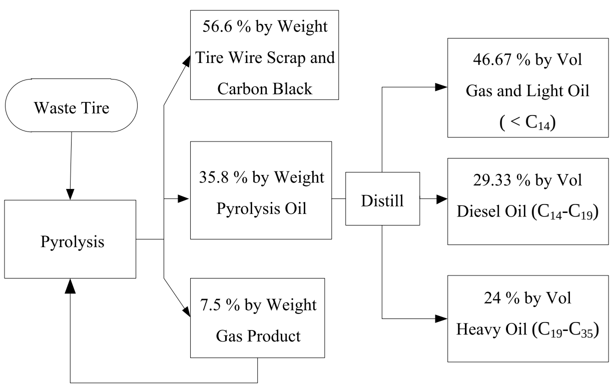


Figure 1. Average production yield of tire pyrolysis process.

Table 1. Comparison of diesel-like tire pyrolysis oil with diesel oil.

Fuel	Heating Value kJ/kg	C (%)	H (%)	O (%)	N (%)	S (%)	Flash Point (°C)	Viscosity at 40 °C (cp)
DTPO	43225.9	84.67	10.44	4.17	0.7	0.02	68	2.69
Diesel	46400.0	87	13	-	-	-	62	1-4.11

3 Methodology

3.1Engine Performance

Engine performance is the main parameter to observe the characteristic of various fuels in the engine. Experimental result indicates the behavior of the engine using diesel-like tire pyrolysis oil in different blended.

It shows the trend and possibility of using diesel-like tire 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 [9, 10].

3.1.1 Break Torque

Torque is an indicator of the function of break torque calculated by the moment of engine arm connected to weight scale which is given in (1).

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

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.

3.1.2 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.

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

3.1.3 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 in (3).

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

3.1.4 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 in (4).

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

3.2 Economic Impact

3.2.1 Energy Cost Analysis

The economic impact assessment in this research is done in the approach of energy cost analysis. As engine performance is the main parameter to observe, the cost analysis is the comparison of cost in terms of energy consumption against power output. It can be calculated as in (5).

$$C_E = bsfc \times \left[\left(\frac{\Gamma_D}{\rho_{Diesel}} \times C_{Diesel} \right) + \left(\frac{\Gamma_{DTPO}}{\rho_{DTPO}} \times (C_{DTPO}) \right) \right] \quad (5)$$

Where C_p is the cost of energy consumption per power output in US$/kW-hr, Γ_D is the ratio of diesel blended in fuel and Γ_{DTPO} is the ratio of diesel-like tire pyrolysis oil in fuel. ρ_{Diesel} is density of diesel fuel, equaled to 830 kg/liter while ρ_{DTPO} is density of diesel-like tire pyrolysis oil, equaled to 871 kg/liter [6]. C_{Diesel} is the cost of diesel (1 US$ per liter). C_{DTPO} is the cost of distilled tire pyrolysis oil (0.6 US$ per liter). All costs in this study based on Thailand cost and converted to US$ at the average exchange rate in 2012 were ฿30 Baht = $1 USD.

However, the cost of pyrolysis oil is varied on the material cost, capital cost, labour cost and electricity cost of the location [11,12].

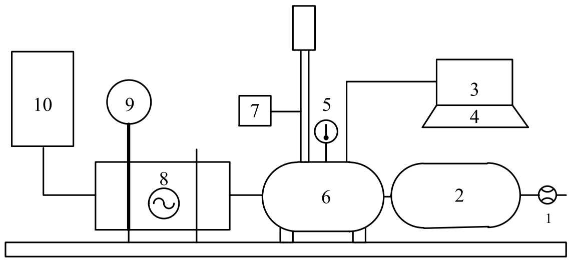
4 Experimental details

The engine specification, schematic of the engine measurement, engine operating condition and experimental results will be described in this part.
A multi-purpose agricultural direct injection diesel engine (Kubota ET-70) is used for the experiment. The engine characteristics are shown in Table 2.

Schematic of the experimental set up is shown in Fig. 2. 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.

Table 2. Engine Specification

Engine Specification	Kubota ET70
General Details	four stroke, CI, water cooled, single cylinder
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



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 2. Schematic of the experimental set up

The absorbed load is produced by a set of 5x100W light bulbs and 13x500W light bulbs connect in series together in order to vary the absorbed load.

Commercial diesel oil in Thailand blended with diesel-like tire pyrolysis oil into 50, 75, and 100 volume percentages were used in the 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 power output is measured by the watt meter which is lower than the load regarding to the efficiency of the generator. The air box is applied to stabilize the air flow into the engine as the air box volume is 500 times the volume of the engine cylinder. Orifice plate flow meter is 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. Smoke opacity was measured in Bosch Smoke Units (BSU) by a Bosch smoke meter. At the end of the test the engine was run with diesel fuel for a while to flush out from the engine.

5 Experimental Results

5.1 Engine Performance

The experimental result shows the potential of replacing diesel fuel with diesel-like tire pyrolysis oil. According to the test result, it was found that the maximum power load of engine using diesel-like tire pyrolysis oil was slightly lower than diesel. The torque output, bsfc, and thermal efficiency of the blended oil seems to be more fluctuated while the diesel is more stable.

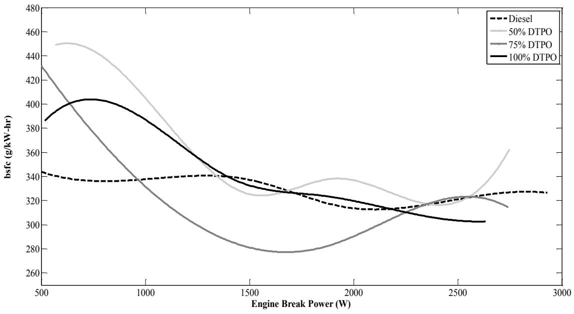


Figure 3. Variation of brake specific fuel consumption with engine brake power.

The comparison of brake specific fuel consumption (bsfc) with engine brake power is shown in Fig. 3. It was found that the bsfc for Diesel at maximum load is 311.83 g/kW-hr while with 50%, 75% and 100% DTPO, it is 381.58 g/kW-hr, 402.67 g/kW-hr, and 406.82 g/kW-hr respectively. The bsfc of diesel fuel trend line seems to be linear and slightly decrease with higher loads unlike the blended diesel-like tire pyrolysis oil. The bsfc of blended diesel-like tire pyrolysis oil trend lines are swing in parabolic curve which have minimum fuel consumption at medium loads. The behavior is obvious since the 75% DTPO leads the lowest fuel consumption which is 281.5 g/kW-hr while diesel fuel consumes 314.75 g/kW-hr at the engine break power of 2000 W. The 100% DTPO offer low fuel consumption as 288 g/kW-hr at the engine break power of 2500 W. This may due to the long chain of hydrocarbons in blended fuel release higher energy in the combustion process affects the higher efficiency at the higher load.

As the diesel-like tire pyrolysis oil contains wide range of hydro- carbon compositions and aromatic content, it causes the instability of efficiency in engine while the efficiency of the diesel fuel is constant due to the additive and distillation process.

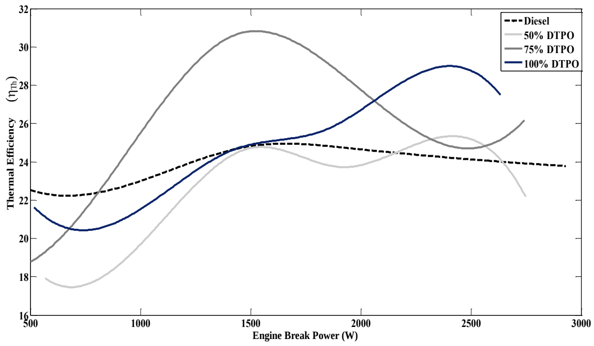


Figure 4. Variation of thermal efficiency with engine brake power.

Therefore, the performance of the engine is not performs in linear curve and predict the trend regarding to the heating value of the oil.

The thermal efficiency is resulting similar trend as the bsfc as shown in Fig. 4. The highest efficiency is the 75% blended oil in medium load and the 100% diesel-like tire pyrolysis oil in high load. At the engine break power 1,500 W, the highest thermal efficiency is 30.64 % at the operating condition of 75% DTPO. Though it can be seen that the 100% DTPO tend to performs better in the higher load, the maximum load produced of DTPOs are lower than diesel oil proportionally. The 100% DTPO is able to produce maximum load 2,818.75 W while the diesel oil can produce 3,414 W. These results reflect the quality of DTPO in terms of the power output regarding to the heating value of the oil and the instability of the DTPO regarding to the fluctuation of the results.

The black smoke of the blended oil which is indicated by percentage of the smoke opacity is slightly higher than the diesel oil as fuels with higher aromatics exhibit higher NOx and smoke at full load [13]. The smoke opacity varies from 11% at no load to 84% at full load for Diesel. For the 100% DTPO, it varies from 15% to 95%.

Regarding to the smoke opacity standard in Thailand, the percentage of the smoke opacity should not reach 50%, both DTPO and diesel oil should not run at the maximum load. The suitable point to run the engine due to the opacity rate is not over 2,500 W

5.2 Fuel Cost Analysis

In terms of economic analysis, the comparison of the cost of fuel consumption per kW-hr is shown in Fig. 5 in order to compare the cost by the energy output.

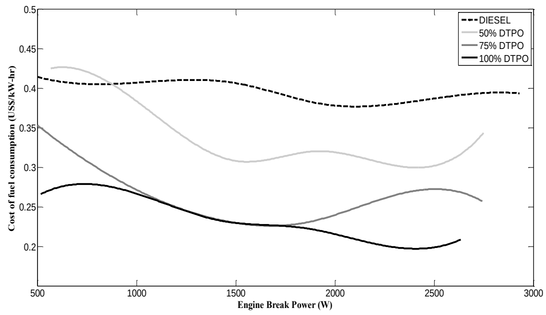


Figure 5. Variation of cost of fuel consumption with engine brake power.

As the cost of diesel-like tire pyrolysis oil is approximately 60% of diesel fuel, the higher blended ratio is the more cost effective while the cost of diesel compare with energy output is constant at about 0.39 US$/kW-hr. 100% DTPO is the most cost effective point as 0.2 US$/kW-hr. with the load 2500W while the diesel oil offer 0.38 US$/kW-hr.

During the load of 1,000 and 1,500 W, the 75% DTPO offer the cost of fuel comparable to 100% DTPO due to the high performance of the engine which is 0.23 and 0.22 US$/kW-hr respectively. The result shows that the use of DTPO in any blend is not suitable for low load condition as the high fuel consumption low torque and not cost efficient.

6 Conclusion

In the presented study, it is found that the diesel-like tire pyrolysis oil is able to replace diesel oil in small engine. As the diesel-like tire pyrolysis oil contains wide range of hydro- carbon composition and aromatic content, it causes the instability of efficiency in engine. The long chain of hydrocarbons in blended fuel affects the higher efficiency at the higher load while the efficiency of the diesel fuel is constant due to the additive and distillation process.

At the medium load, 1,000-1,500 W, the brake specific fuel consumption of the 75% DTPO is the lowest while the thermal efficiency is the highest and the cost is comparable to the 100% DTPO.

Although the engine performance of blended DTPO is comparable to the diesel oil, the gum from the DTPO causes the dirtiness to the engine. The nozzle engine oil and oil filter have to be checked and cleaned regularly. The higher blend is the more dirt. User is strictly have to flush out the DTPO from the engine otherwise the engine is not able to run in the next day due to the gum.

It can be concluded that the 75% DTPO is the optimum point to use the diesel-like tire pyrolysis oil in a small engine. Using 75% blended increase 25% of efficiency from the diesel fuel and 45% of fuel cost reduction per kW-hr. Moreover, 75% DTPO oil behave more friendly to the engine.

Finally, this study exhibit that tire pyrolysis oil is potentially an alternative fuel for agriculture purpose engine. Promoting pyrolysis oil is not only reducing fossil fuel use and support recycle business, it also increase the direct and indirect income of local people and reduce logistic cost of fuel delivery.

7 Acknowledgments

The authors would like to acknowledge Thailand Institute of Scientific and Technological Research for their technical supports. The research was conducted by researchers in the pyrolysis research group, in support of Rajamangala University of Technology Phra Nakhon.

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