Performance analysis of diesel engine running with tyre-derived fuel

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Abstract. In the modern ages, many researches have been conducted to search for alternative fuel. Various source of alternative fuel such as palm, jathropa and rapeseed that are classified as biofuel have been tested to determine its suitability. Besides that, waste product such as waste tyres and plastics also can be processed to yield the alternative fuel. In this paper, performance of a diesel engine operating with tyre-derived fuel (TDF) blended with diesel fuel at several ratios is analysed and compared with diesel fuel. A single cylinder YANMAR TF120M diesel engine is utilized in the experiments where it is operated with constant load exerted to the engine and at variable engine speed ranging from 1200 rpm to 2400 rpm. The performance parameters that was analysed in the paper includes engine power and torque, combustion pressure and exhaust gas temperature. The experimental results show that percentage of TDF blends of 10% in diesel fuel gives significant impact to the engine performance output.

1. Introduction
Diesel engine is one of the favoured type of engine for power generation around the world. This is because diesel engine has advantages over other types of internal combustion such as higher torque, higher thermal efficiency and robustness [1]. Diesel engine usage can be found in many applications such as land transportation, military application, mining and agriculture. Modern diesel engine has improved in terms of new technologies to produce higher engine output with less emission. Improvement in forced induction system, common rail injection system and direct injection system are among examples of modern diesel engine technologies that are available today.

In the modern age, the number of gasoline and diesel vehicles around the globe keeps increasing significantly. It is no exception in Malaysia. According to the statistics published by Malaysia Automotive Association [2], from year 2010 until 2015, more than 600, 000 units of new vehicles including passenger vehicles and commercial vehicles have been registered in Malaysia every year. This large number of motorized vehicles also causes the production of scrap tyres to increase. According to Chong [3], it is stated that Malaysia generates about 150, 000 tonnes of scrap tyres every year. With the increasing number of vehicles in Malaysia, waste tyre production expected to increase. Generally, these scrap tyres are dumped
into open landfills [4]. However, this kind of disposing method will cause hazardous effect to human beings and the environment since waste tyres do not break down easily in the environment [5].

Recycling the scrap tyres to usable products such as liquid fuel is one of the alternative that can be done to reduce scrap tyre problem. These scraps tyres can undergo pyrolysis process as a solution to overcome disposal problem of the waste tyres [6, 7]. In pyrolysis process, the waste tyres are heated in the absence of oxygen to prevent oxidation from occurring [8]. Inert gas such as nitrogen will be passed through the process to avoid the oxidation process from occurring [9, 10]. The thermal degradation of the tyres begins around 350˚C hence, the pyrolysis experiment is commonly done at temperatures ranging between 450 to 700˚C [11]. There are several types of reactors used for the pyrolysis of scrap tyres. The types of bed includes fixed-bed (batch), moving screw bed, rotary kiln, fluidized bed and vacuum bed. Among these types of reactors, the fixed bed reactor is widely used in pyrolysis process studies [9]. From the pyrolysis process, the products obtained at the end of the process include oil, gas and char product or solid [12-14].

The oil obtained from the pyrolysis process is called tyre-derived fuel (TDF). This fuel is claimed by many researchers as able to be used as an alternative fuel for diesel engine [12, 15, 16].

A number of experiments have been conducted to determine the suitability of TDF to be used as an alternative fuel in diesel engine. Bhatt and Patel [17] compared the chemical properties of unblended TDF to Euro IV diesel fuel to investigate the potential of TDF to be used as an alternative fuel. From this study, it was concluded that TDF had comparable value of carbon content, calorific value, nitrogen, sediment, hydrogen and water content as compared to Euro IV diesel. Bhatt and Patel also suggested that TDF could undergo a blending process with diesel fuel to improve the density and viscosity of TDF to be used in diesel engines. However, there are also disadvantages since the properties of TDF such as sulphur content, viscosity and aromatic contents are higher compared to the conventional diesel sample.

Results from another engine testing showed that diesel engine could operate until 90% TDF-diesel blends, as observed by Doğan et al. [18]. In the study, six different fuel blend samples of refined TDF with neat diesel at a specific blending ratio, which are 10% (10% volume of TDF and 90% volume of diesel fuel), 30%, 50%, 70%, 90% and 100% diesel fuel, were tested in the diesel engine. Doğan reported that, the TDF content in diesel fuel did not give significant impact to the engine output such as power, torque, brake thermal efficiency and brake specific fuel consumption as compared to conventional diesel. Additionally, the emission of carbon monoxide, unburned hydrocarbon and smoke opacity decreased while nitrogen oxides emission increased with the increasing amount of TDF blend ratio.

Similar study was conducted by İlkılıç and Aydin [19]. Eight different samples were tested namely 5% (5% volume of TDF and 95% volume of diesel fuel), 10%, 15%, 25%, 35%, 50%, 75% blending ratio and pure 100% TDF. The findings from the study revealed that the torque and power of diesel engine operating with 100% TDF and TDF-diesel blends were lower as compared to diesel fuel. Furthermore, the decrease of the performance parameters is proportional to the increase of TDF blend ratio in diesel fuel. The lowest torque and power output is obtained when 100% unblended TDF is used. Diesel engine also efficiently can operate with TDF blend ratio up to 35% without engine modifications. Other than that, the CO and HC emissions that emitted by the engine are higher when TDF-diesel blends are used compared to diesel fuel. The highest CO and HC emissions occur when 50% TDF, 75% TDF and 100% TDF are used. Thus, 50% TDF, 75% TDF and 100% TDF are not suitable to be used directly in diesel engine due to increased level of CO and HC levels.

More recently here was also a study conducted using 100% unblended TDF that was directly used in large displacement, truck engine as conducted by Pilusa [20]. However, the 100% unblended TDF underwent a refinement process to improve the fuel properties such as kinematic viscosity, cetane number and fuel stability. Results from the engine testing showed that no engine ceasing and knocking occurred when 100% unblended TDF was used. Additionally, the power and torque trend were consistent and comparable to conventional diesel fuel usage. However, the sulphur dioxide (SO₂) emission was significantly higher when 100% unblended TDF was used. The level of sulphur content in 100% unblended TDF was also higher than the recommended limits.

Marínez et al. [21] conducted an experiment to determine the potential of TDF-diesel fuel blend to be used in a light duty, EURO 4 diesel engine under transient operations. There was only one blend ratio that
was used in this study, TDF 5% (5% TDF and 95% diesel fuel). The author stated that the significance of choosing this blend ratio was to keep some critical properties of the blend within the range set in the European Standard EN 590 and to be realistic in the current automotive context. From the engine testing that was conducted, the feasibility of using TDF that blended with diesel fuel to be used in light duty diesel engine without constructive modifications was proven. However, emission issues still need to be considered since the results show that the TDF emissions such as smoke opacity, particulate emission and total specific mass emissions of total hydrocarbon (THC) are higher compared to diesel fuel. Furthermore, reduction of sulphur content in TDF is one major concern to reduce THC and particulate matter emissions.

The purpose of this study is to investigate the performance of TDF blends and diesel fuel in a single cylinder diesel engine on the power, torque, combustion pressure and exhaust gas temperature using a constant load at different engine speeds.

2. Experimental setup and testing details
The schematic diagram for the experimental setup is shown in Figure 1. A direct-injection, single cylinder water-cooled diesel engine (YANMAR TF120M) was employed in this research. The technical data for the engine used is shown in Table 1. The displacement of the engine is 0.638L and the power output for this engine is 10.5HP at 2400 rpm. During the experiment, the engine was tested without any major modification.

The engine was coupled using NBK flexible coupling to a positive displacement gear pump (Hydrome HGP-3F-23) which functioned as a hydraulic dynamometer. The load was controlled using a screw type valve. An air-box was fitted to the engine intake manifold for airflow measurement. The pressure difference inside the air-box and the environment were measured using a Dwyer manometer. Data were taken using a data acquisition system provided by TFX Engineering, which consisted of an in-cylinder pressure sensor and magnetic crank angle sensor. The exhaust temperature, ambient temperature and intake temperature were measured using K-type thermocouples. The thermocouples were placed at exhaust manifold, intake manifold and air measurement unit.

The engine speed parameter was set at five different speeds; 1200 rpm, 1500 rpm, 1800 rpm, 2100 rpm and 2400 rpm. This speed range is chosen based on the standard performance curve of the engine that lies between these speeds ranges. A constant load at 800 psi pressure was exerted to the engine. The engine was set to run at the desired engine speed at the beginning of each setup. Then, the load was exerted to the engine after a stable operating condition was achieved. The data were taken after the load exerted and when the speed measurement remained stable for at least one minute. The engine was run using conventional diesel fuel at the beginning to obtain the base data for comparison.

Three samples with different blend ratio between TDF and diesel fuel were prepared. The blend ratios were 10% (10% TDF and 90% diesel fuel), 30% and 50%. The fuels were prepared through mechanical mixing process using a mechanical mixer. The blended TDF-diesel fuels were labelled as TDF10, TDF30, and TDF50. For TDF blends data measurement, the engine is run with diesel fuel for beginning. After five minutes running on diesel fuel, the valve supplying the diesel fuel to the engine is closed and after a while, the valve for supplying TDF blends into the engine is opened. The engine is left running for at least five minutes before the data is taken to ensure only TDF blends is injected into the combustion chamber. The data measured are engine power, torque, combustion pressure and exhaust gas temperature. The testing procedures is repeated three times to minimize the experimental error.
Figure 1. The experimental setup

Table 1. The YANMAR engine specifications

| Specification          | Value                     |
|------------------------|---------------------------|
| Engine type            | YANMAR TF120M             |
| Number of cylinder     | 1                         |
| Bore x stroke          | 92 x 96 mm                |
| Displacement           | 0.638 L                   |
| Compression ratio      | 17.7                      |
| Injection timing       | 17° BTDC                  |
| Continuous output      | 10.5 HP at 2400 rpm       |

Table 2. Chemical properties of TDF blends and diesel fuel

|                          | Diesel       | TDF10%      | TDF30%      | TDF50%      |
|--------------------------|--------------|-------------|-------------|-------------|
| Density [kg/m³]          | 841.6        | 865.2       | 877.0       | 881.0       |
| Kinematic Viscosity @ 40°C [mm²/s] | 4.0         | 4.1         | 3.8         | 3.8         |
| Flash Point [°C]         | 84.0         | 140.0       | 113.0       | 99.0        |
| Gross Calorific Value [MJ/kg] | 42.5       | 45.2        | 43.4        | 42.9        |

3. Results and discussions

Figure 2 shows the engine power measured at variable engine speeds with constant load exerted to the engine. From the figure, it can be seen that the power output for every fuel sample increases as the engine speed increases. The power produced by the engine from this testing ranges from 4.1 kW to 11.0 kW with the corresponding engine speed from 1200 rpm to 2400 rpm.

From the figure, it can be seen that TDF10% produces the highest power output which is averagely 4.9% higher compared to diesel fuel followed by TDF30% which is 3.0% averagely higher than diesel fuel. TDF50% produce 2.2% higher power output in average compared to diesel fuel. It is also observed that TDF10% produces the highest power output, followed by TDF30%, TDF50% and diesel fuel. The same
trends were also mentioned by İlkılıç and Aydın [19] where the power output decreases as the TDF blend ratio increases. This trend can be related to the gross calorific value of each fuel as shown in Table 2. From the table, it is observed that the calorific values of each TDF blends are higher compared to diesel fuel. When the TDF blend ratio in diesel fuel increases, the gross calorific value decreases. The lower gross calorific value produces a lower amount of energy during combustion process hence producing a lower power output.

Figure 2. Graph of power output at various engine speeds

Figure 3 shows the variation of engine torque versus engine speed for the test fuels. The torque output value varies from 32.3 Nm to 43.7 Nm for all tested fuels for engine speed ranging between 1200 rpm to 2400 rpm. The results show that the torque for every fuel usage increases as the engine speed increases. From the figure, it can be seen that TDF10% marks the highest torque output, which is averagely 4.6% higher compared to diesel fuel followed by TDF30% which is averagely 2.3% higher than diesel fuel. TDF50% produces 2.2% higher torque output on average compared to diesel fuel.

Figure 3 also shows that the TDF blends mark higher torque output as compared to diesel fuel. The phenomenon is due to the level of gross calorific value measured in TDF blends, which is much higher compared to diesel fuel as shown in Table 2. A higher gross calorific value of a fuel will produce a higher amount of energy during the combustion process. From Figure 3, it can be observed that the TDF blends can produce a higher torque output when the fuel is used in diesel engine compared to diesel fuel. This is because the gross calorific value increases when the TDF is blended with diesel fuel. However, as the TDF blend ratio in diesel fuel increases, the gross calorific value decreases as shown in Table 2. The result causes the torque output measured at the engine to also decrease when higher TDF blend ratio is used.
Figure 4. Graph of combustion pressure vs crank angle at 1200 rpm

Figure 4 shows the cylinder pressure curves versus crank angle at a low engine speed of 1200 rpm for all test fuels. Referring to Figure 4, two regions are focused in the graph, which is region A for fuel ignition delay and region B for the combustion peak pressure. Ignition delay area is focused in this paper because as the ignition delay is prolonged, more fuel than necessary will be injected into the combustion chamber before the first fuel particles ignite, causing a large and fast pressure rise at the start of the combustion. This results in a low thermal efficiency and rough-running engine [22]. Higher amount of fuel existing in the combustion chamber when the ignition starts will also cause higher peak pressure. From Figure 4, it can be observed that ignition delay of TDF10%, TDF30% and TDF50% occurs at almost the same crank angle compared to diesel fuel where the ignition starts at approximately 1° bTDC (before TDC). The reason of this trend is caused by the engine speed, which is in a low speed region that enables the combustible air-fuel mixture to form sufficiently between the moments when the fuel is injected into the combustion chamber until the start of combustion. This condition will cause the combustion of TDF fuel blends to occur at almost the same crank angle.

Referring to region B in Figure 4, the peak pressure for diesel fuel is 76.6 bar at 6° aTDC (after TDC) crank angle while TDF10% produces 74.6 bar at 7° aTDC. TDF30% produces 76.8 bar at 7° aTDC, whereas TDF50% produces 78.7 bar at 5° aTDC. From the figure, it can be observed that the peak pressure shows increasing trends with the increase of TDF blend ratio in the diesel fuel. TDF50% shows the highest peak pressure along TDF blends TDF30% and TDF10%. The variations of peak pressure can be related to the fuel density. Since the fuel density increases as the TDF blend ratio increases, more fuel is combusted for the same volume injected into the combustion chamber hence producing higher peak pressure.

Figure 5 shows the cylinder pressure curves versus crank angle at a moderate engine speed of 1800 rpm. It can be observed that the combustion characteristics for each fuel shows a significant difference in terms of the ignition delay and the combustion peak pressure. From the graph, the ignition delay of diesel fuel is the shortest, followed with TDF10%, TDF30% and TDF50%. It can be observed from the figure that the increasing percentage of TDF blend can result in a longer ignition delay. The phenomenon can be related to the density of every test fuel where the ignition delay becomes longer as the density of the test fuels increases. Variations in fuel density determine the spray quality hence affect the air-fuel mixing. Higher fuel density causes greater fuel resistance to the flow. This condition causes poor atomization of the fuel. Poor atomization will cause poor mixing between the fuel and air thus resulting in ignitable air-fuel mixture formed in a long time range, which further effect in ignition delay for each fuel.
It also can be observed from region B that the peak pressure of every fuel increases with the increase of TDF ratio in the diesel fuel. Diesel fuel produces 76.3 bar peak pressure at crank angle of 4° aTDC while TDF10% produces 77.2 bar at 10° aTDC. Meanwhile, TDF30% produces 77.5 bar of peak pressure at 11° aTDC and TDF50% produces 83 bar of peak pressure at 7° aTDC. This trend is due to longer ignition delay of TDF blends compared to diesel fuel. Diesel fuel marks the lowest cylinder pressure, followed by TDF10%, TDF30% and TDF50%. The trend of peak pressure of each fuel can be seen where the peak pressure increases with the increase of ignition delay. Peak pressure is much affected by the level of the fuel density. Higher fuel density will cause more fuel to exist in the combustion chamber thus enabling higher mass of fuel to be combusted. This condition also causes higher peak pressure. Referring to Table 2, the density of each fuel increases as the ratio of TDF increases. With the combination of the above-mentioned factor (ignition delay and fuel density), more fuel is combusted when the ignition starts thus resulting in higher peak pressure.

![Figure 6: Graph of combustion pressure vs crank angle at 2400 rpm](image1)

![Figure 7: Graph of exhaust gas temperature at various engine speeds](image2)

Figure 6 shows the cylinder pressure versus crank angle for each tested fuel at high-speed region, which is 2400 rpm. From the figure, it can be observed that the combustion characteristics (ignition delay and peak pressure) for each fuel shows clear difference compared to each other. Similar trend can also be seen at moderate speed pressure curve as shown in Figure 5. Referring to region 'A', it can be clearly seen that ignition delay increases as the TDF ratio in the diesel fuel increases. Diesel fuel shows shortest ignition delay, followed by TDF10%, TDF30% and TDF50%. It can also be observed from the graph that when the engine speed is increased, the ignition delay of all test fuels is longer in terms of crank angle. Referring to the peak pressure as shown in region 'B', diesel fuel produces peak pressure of 76.8 bar at 6° aTDC while TDF10% produces 78 bar of peak pressure at 7° aTDC. Moreover, TDF30% produces 81 bar of peak pressure at 7° aTDC and TDF50% produces 82.5 bar of peak pressure at 9° aTDC. From the figure, it can be observed that the peak pressure of every test fuel increases as the TDF ratio in the diesel fuel increases.
Diesel fuel yields the lowest peak pressure, followed by TDF10%, TDF30% and TDF50%. It can be seen that the trend of every blended fuel is the same as the moderate speed figure curve. Thus, increasing the blend ratio of TDF in diesel fuel will prolong the ignition delay. This will result in higher peak pressure as a result of rapid pressure rise when more fuel enters the combustion chamber before the ignition starts.

Figure 7 shows the variation of exhaust gas temperature versus engine speed for all test fuels. From the figure, it can be observed that diesel fuel produces the lowest exhaust gas temperature. This is followed by TDF10% which average at 2.1% higher compared to diesel fuel. TDF30% is 3.4% higher compared to diesel fuel in average and TDF50% is 7.9% higher in average compared to diesel fuel.

The trend occurs due to the higher heat release rate of TDF blends that was developed during the premixed combustion phase. As observed in Figure 4, Figure 5 and Figure 6, the ignition delay period increases as the ratio of TDF blends increases. Longer ignition delay causes more fuel to exist in the combustion chamber during ignition delay period, causing a rapid, higher rate of heat release when the combustion occurs. The combustion condition will cause the exhaust temperature to become higher as the ratio of TDF blends in diesel fuel increase. Furthermore, as the engine speed increases, more fuel is injected and combusted in the combustion chamber, thus causing exhaust gas temperature to increase when the engine speed increases.

4. Conclusion
In this study, the engine performance output of a single cylinder diesel engine running with four different samples of fuel is analysed. The samples include diesel fuel, TDF10%, TDF30% and TDF50%. The engine is running at five different engine speeds which are 1200 rpm, 1500 rpm, 1800 rpm, 2100 rpm and 2400 rpm with the constant load 800psi exerted to it. In the paper, the engine power and torque, combustion pressure and exhaust gas temperature was taken and analysed. From the results obtained, several conclusions are made:

1. TDF10% gives highest performance output compared to other TDF-diesel fuel and diesel fuel.
2. The performance output starts to decrease when the TDF ratio further increases.
3. The ignition delay is prolonged when the TDF ratio is increased. The peak pressure also increases when the ignition delay is prolonged.

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Abbreviations
1) aTDC – after top dead centre
2) bTDC – before top dead centre
3) TDF – tyre-derived fuel

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