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EXPERIMENTAL STUDIES OF DIESEL ENGINE OPERATING ON DIESEL-TIRE PYROLYSIS OIL BLENDS

The article presents the experimental test results of diesel engine efficiency operating on diesel fuel and tire pyrolysis oil blends. The aim of the work was to study the performance efficiency and emissions of a diesel engine fuelled with blends of diesel fuel (DF) and tire pyrolysis oil (TPO) at a constant engine speed and various load modes. For experimental research diesel engine "ORUVA F1L 511" was used. Diesel fuel and its blends TPO10 and TPO20 with tire pyrolysis oil were used for the research. During the test, the engine's hourly fuel consumption, volumetric air consumption, engine torque, emissions and smoke opacity were measured. In the studies, it was found that the highest brake specific fuel consumption was obtained when the engine was running on a fuel blend TPO20 of diesel and tire pyrolysis oil. At full load, TPO10 and TPO20 fuel blends resulted in 3.6 % and 4% lower engine brake thermal efficiency compared to the diesel engine, respectively. In the same mode, using a blend of diesel fuel and tire pyrolysis oil TPO10, the engine generated the highest total emissions of nitrogen oxides. At full load, the highest carbon monoxide CO emissions were obtained with the TPO20 fuel blend (745 ppm), and the lowest with diesel fuel (646 ppm). When the engine was operating at full load, the TPO20 fuel blend, generated 25.5 % less smoke opacity than the diesel fuelled engine.

Key words: diesel fuel, tire pyrolysis oil, engine efficiency, emissions, smoke opacity.

INTRODUCTION

Currently, the world is facing a multitude of challenges related to energy. The most prominent issues include rapidly growing energy demand not only in developing but also in emerging countries, increasing dependence on fossil fuels in the global energy sector, and continuously rising concentration of greenhouse gases, leading to the universal impact on climate change. Tightening environmental regulations prompt the search for new ways to reduce the emission of these gases across various sectors. The expansion of transportation means increases the consumption of energy resources. In the European Union (EU), up to 26% of greenhouse gases are emitted in the transport sector. Considering these circumstances, scientists worldwide are actively searching for alternative and renewable energy sources that could be utilized in the transportation sector.

Converting waste into fuel holds immense potential as an alternative fuel, which could reduce the global waste burden. The disposal of used tire waste, by dumping it into landfills, poses a significant threat to the environment and human health. Every year, 1 billion used tires are discarded worldwide. Only 15 – 20 % of tires are reused, while the remaining tire waste becomes part of the environment [3]. Approximately 24 thousand tons of used tires are collected annually in Lithuania. Some of the used tires are left in the environment or in illegal landfills.

Recycling used tires is beneficial on several fronts: firstly, recycling reduces the amount of waste and protects nature from unnecessary landfilling; secondly, it increases the amount of secondary raw materials, contributing to the creation of a sustainable production and consumption model. Tires have high energy value, so they can be recycled into various aggregate state fuels: oil, carbon, and gas [4]. The waste of used tires are recycled into fuel by pyrolysis, which is burned in an inert atmosphere [1]. During the pyrolysis process of used tires, a liquid product is obtained: tire pyrolysis oil (TPO). Waste-based tire pyrolysis oil (TPO) can be a promising solution to replace the bio-proportion of diesel fuel. Since it is made from waste tires, it is also an optimal solution for recycling waste [8].

The physical and chemical characteristics of fuels, such as cetane number, viscosity, density, lower heating value, C/H ratio, oxygen content, influence the combustion process of diesel engines. The properties of fuels with different compositions effect on engine performance, emissions, and smoke opacity production differently. Although numerous chemical and physical properties of TPO closely resemble those of diesel fuel (Table 1), some differences significantly affect fuel injection, atomisation, the air-fuel mixing rate in the cylinder, combustion process, and consequently, emissions of harmful exhaust gases. Most scientists argue that TPO could be an excellent alternative fuel; however, using pure pyrolysis oil of used tires may pose challenges due to its low cetane number, high sulphur content, and high viscosity [3]. Nonetheless, the cetane number of TPO is lower at 39.94, compared to the 51.4 diesel fuel (DF). This disparity could potentially lead to autoignition issues, particularly when operating with blends of DF and TPO under light engine loads and speeds. A high sulphur content increases emission. More viscous fuels poorly atomize and distribute in the combustion chamber. Due to the influence of the physical and chemical properties of fuels, the comparative effective on fuel consumption, engine performance, emissions, and smoke production vary [2].

Pinto et al. [8] conducted analysis of blends containing traditional diesel, different amounts of pyrolysis oil from used tires and biodiesel from waste cooking oil has been proposed herein, with the aim of investigating the feasibility of using them in a diesel engine and analysing their emissions and power in comparison with traditional diesel fuel. Tests were carried out using a single-cylinder diesel engine with a maximum rated power of 5.6 kW and its emissions were measured with a gas analyser. The results revealed that using small amounts of tire pyrolysis oil in the blends (up to 5%) leads to a very small decrease in brake thermal efficiency (BTE) while emitting fewer CO and NOx pollutants, when compared to neat diesel. However, adding higher quantities of tire-pyrolysis oil causes a notable loss in BTE while increasing CO, decreasing NOx and emitting considerably more sulphur. Finally, replacing portions of diesel with biodiesel in diesel-tire pyrolysis oil blends decreased CO, but at the cost of increasing NOx emissions [8].

Kondor et al. [9] investigated different low-volume-percent tire pyrolyzed oil blended with diesel. The aim of research was to investigate the effect of low volume percentage TPO on performance and emissions on a light-duty diesel engine. Authors noted that until full engine load, the brake-specific fuel consumption increased. At low speed and low load, the TPO had a 16% higher emission value. With the increased engine loads, the HC emissions decreased. At 100% load, it was 42% lower than regular diesels. The NOx emissions increased. The reason for that might be the lack of oxygen. CO emissions increased in all investigated measuring points [9].

World scientists are extensively researching the possibilities to use alternative fuels, but there is no unanimous opinion how the physical and chemical properties of the different compositions fuels effect on the diesel engine performance, fuel system elements, and emission characteristics. The aim of the study is to investigate the performance and emission characteristics of a diesel engine fuelled by blends of diesel fuel and tyre pyrolysis oil.

OBJECTS, EXPERIMENTAL APPARATUS AND METHODOLOGY OF THE RESEARCH

The test results reflecting the comparative changes in the performance efficiency and emissions of the exhaust occurring due to its transition from diesel fuel to operation on diesel fuel-tyre pyrolysis oil blends prepared by mixing in various proportion (by volume). The fuel blends PPO10 and PPO20 were prepared by mixing 90 vol % DF/10 vol % TPO and 80 vol % DF/20 vol % TPO, respectively. The properties of the tested fuels are presented in Table 1.

Table 1 – Properties of the tested diesel fuel and tire pyrolysis oil

Property parameters	Fuel test methods	TPO	DF
Density at 15 C, kg/m^3	EN ISO 12185:1999	917	832,7
Kinematic viscosity, mm^2/s	EN ISO 3104+AC:2000 at 40 °C	3,77	2,13
Flash point (FP), °C	EN ISO 2719:2000	43	57
Stoichiometric air–fuel ratio, kg/kg	-	13,46	14,5
Low calorific value, MJ/kg	EN ISO 8217:2012	40,49	43
Cetane index	EN ISO 5165:1999	39,94	51,4
Carbon (%)		86,68	86,13
Hydrogen (%)		10,49	13,87
Oxygen (%)		1,29	–
Nitrogen (%)		0,48	–
Sulfur (%)		0,84	–

Experimental research was carried out in the fuel equipment-testing laboratory of the Department of Mechanical, Energy and Biotechnology Engineering at the Faculty of Engineering of Vytautas Magnus University - Agricultural Academy.

Table 2 – Engine FL 511 specifications

Type	Deutz F1L 511
Operating principle	4 strokes
Number of cylinders	one cylinder
Bore, mm	100
Stroke, mm	105
Swept volume, cm3	825
Compression ratio	17
Injection timing advance in CADs BTDC	24°
Maximum power (at 3000 rpm), kW	12.8 ±5%
Injection pressure, bar	175
Fuel consumption, g/kW·h	255 ±5%
Rated speed, rpm	3000
Engine weight, kg 135	135

For stroke, one-cylinder, direct injection, air cooled, "ORUVA FL 511" diesel engine was used for these experiments. Technical characteristics of the experimental engine are listed in Table 2. Load characteristics of an engine were taken when operating at gradually increasing load and constant engine speed of 2000 rpm at which an engine maximum torque develops.

Torque of an engine was measured with a magnetic powder brake dynamometer PT40M (0 – 60 N·m) with a definition rate of ±0.5 N·m and rotation speed with the mechanical tachometer (150 – 3000 rpm) with an accuracy of ±0.5% of the measured value. The air mass consumption was measured with the turbine type gas meter CGT-02 (10 – 100 m^3 /h) with an accuracy of ±1% of the measured value, and fuel mass consumption by using electronic scale SK - 1000 with an accuracy of ±0.5%.

Emissions of nitric oxide (NO), nitrogen dioxide (NO_2), carbon monoxide (CO) in parts per million (ppm) and carbon dioxide (CO_2) in vol% were measured with electrochemical cells installed in Testo 350 XL flue gas analyser. Total NO_x emissions were determined as a sum of both NO and NO_2 pollutants with an accuracy of ±5 ppm.

Exhaust smoke measured with a Bosch RTT 110 opacity meter with an accuracy of ±0.1% in a scale range of 0 – 100 %. The measuring rages of apparatus used, accuracies of the measured experimental data of engine performance and exhaust emission parameters and the uncertainties of the calculated test results (power, fuel consumption etc.) are listed in Table 3.

Table 3 – The accuracy of the measured engine performance and emission parameters and the uncertainty of the computed experimental results

Parameter	Measuring range	Accuracy
Torque	0 – 60 N·m	±1.5 %
Speed	150 – 3000 rpm	±0.5 %
NO	0 – 3000 ppm	5 %
NO_2	0 – 500 ppm	5 %
CO	0 – 10000 ppm	5 %
CO_2	0 – 50 %	1 %
Smoke density	0 – 100 %	1.5 %
Engine power output		±1
Fuel mass flow rate		±0.5
Brake specific fuel consumption		±1.5
Brake thermal efficiency		±1.5
Air flow rate		±1

To improve the reliability of the measured data the tests have been repeated no less than three times.

RESULTS AND DISCUSSION

Changes in the combustion process have influence on engine's economy parameters: brake specific fuel consumption (bsfc) and brake thermal efficiency (η_e). The dependency of brake specific fuel consumption on engine load when the engine operates on the tested fuel blends is presented in Figure 1. As seen, under the same engine operating conditions, the brake specific fuel consumption was higher when the engine operated on TPO blends. This can be explained by the lower calorific value of the tested fuel blends, which requires a larger fuel portion to produce the same engine power. At full load, when the engine operated on TPO10 and TPO20 fuel blends, the brake specific fuel consumption increased by 4.4 % and 5.5 %, respectively, compared to diesel fuel (DF).

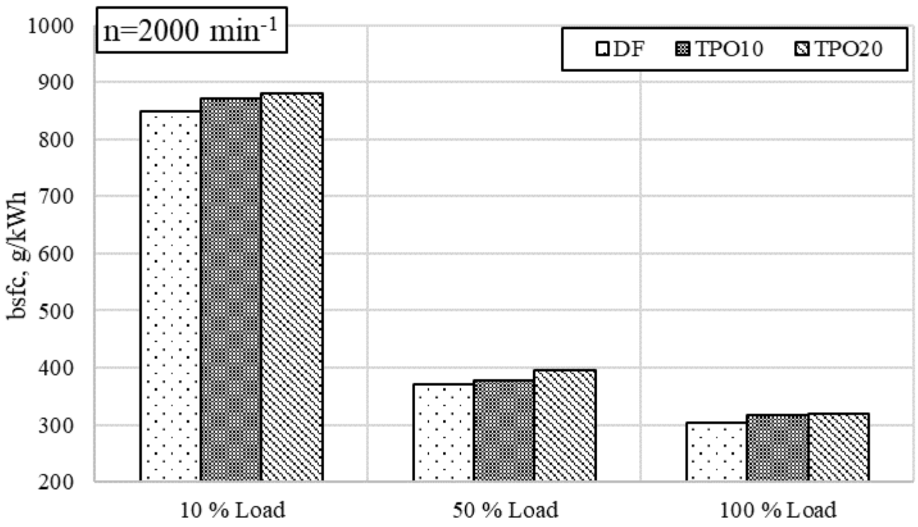

Fig.1 – Brake specific fuel consumption (bsfc) dependence on engine load when engine was running on diesel fuel and its blends with tire pyrolysis oil

Fig. 2 shows the dependency of the brake thermal efficiency on engine load when the engine operates on diesel fuel and its blends with tire pyrolysis oil. The graph shows that, across all load regimes, the highest brake thermal efficiency was obtained when the engine was fuelled on pure diesel fuel. At full 100 % engine load, using TPO10 and TPO20 fuel blends, the brake thermal efficiency decreased by 3.62 % and 4 % respectively, compared to the engine running on diesel fuel. The decrease of the brake thermal efficiency in this case can be explained by the fact that is the mostly affected by their reduced cetane number of TPO as the latter suppresses the auto ignition and combustion processes in the cylinder.

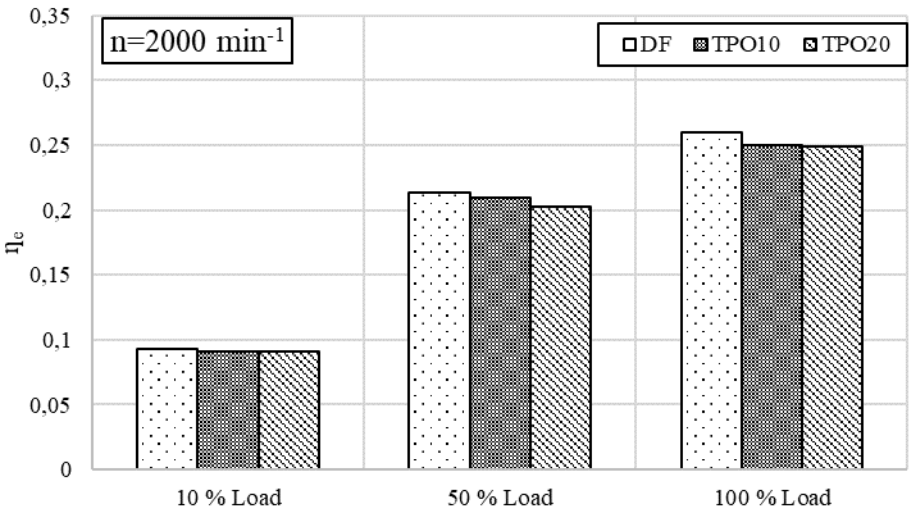

Fig. 2 – Brake thermal efficiency (η_e) dependence on engine load when engine was running on diesel fuel and its blends with tire pyrolysis oil

Nitrogen oxides are produced at elevated temperatures outside the flame front, where free nitrogen atoms react with excess oxygen in the combustion chamber through a complex chain reaction. The overall nitrogen oxides emissions during combustion are predominantly influenced by the maximum process temperature, as the reaction is endothermic and not directly associated with the combustion processes of the fuel mixture. As columns in |Fig. 3 show the amount of total nitrogen NOx emissions increased with increasing engine load for diesel fuels and the fuel blends tested. When the engine operated under low engine load, the highest amount of nitrogen oxides was generated when fuelled by diesel fuel. At the same engine load, using a TPO20 fuel blend resulted in a 6.8 % lower nitrogen oxide emission compared to using diesel fuel. From the graphs, it can be observed that at full load, the maximum nitrogen oxide emission value (2094 ppm) is obtained when the engine is running on TPO10 fuel blend. Significant influence on the formation of NOx emissions has two parameters a - high gas temperature in the cylinder and a longer duration of the self-ignition period. Fuels with a longer self-ignition delay period are characterized by a higher maximum of heat release rate. As a result, the temperature in the cylinder increases [7]. On the over hand a higher amount of aromatic substances increases the quantity of nitrogen oxides [6].

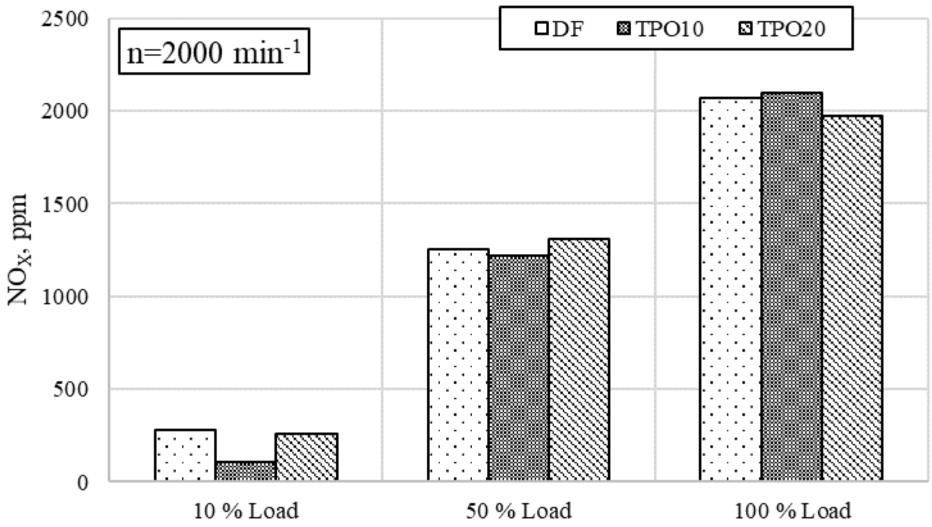

Fig. 3 – Nitrogen oxide emissions (NOX) dependence on engine load when engine was running on diesel fuel and its blends with tire pyrolysis oil

The dependencies of carbon monoxide (CO) emission on engine load are shown in Fig. 3.

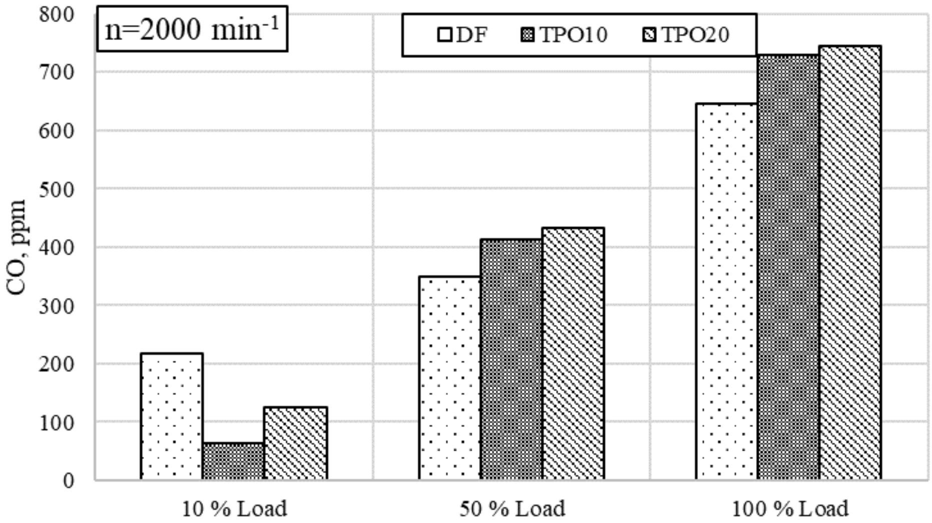

Fig.4 – Carbon monoxide (CO) emissions dependence of engine load when engine was running on diesel fuel and its blends with tire pyrolysis oil

When the engine operated under low load, the highest carbon monoxide (CO) emission was obtained when fuelled by diesel fuel. At average engine load, the carbon monoxide (CO) emission was higher when using a TPO20 fuel blend. At full engine load, using fuel blends of diesel fuel and tire pyrolysis oil (TPO10 and TPO20) carbon monoxide emissions increased in a 12.8 % and 15.3 % in, respectively, compared to the results obtained from testing diesel fuel (DD). The authors of other articles explain the increase of CO emissions by the lower cetane number in TPO fuel. For this reason, the combustion may be delayed and fuel may not burn completely in the combustion chamber [5].

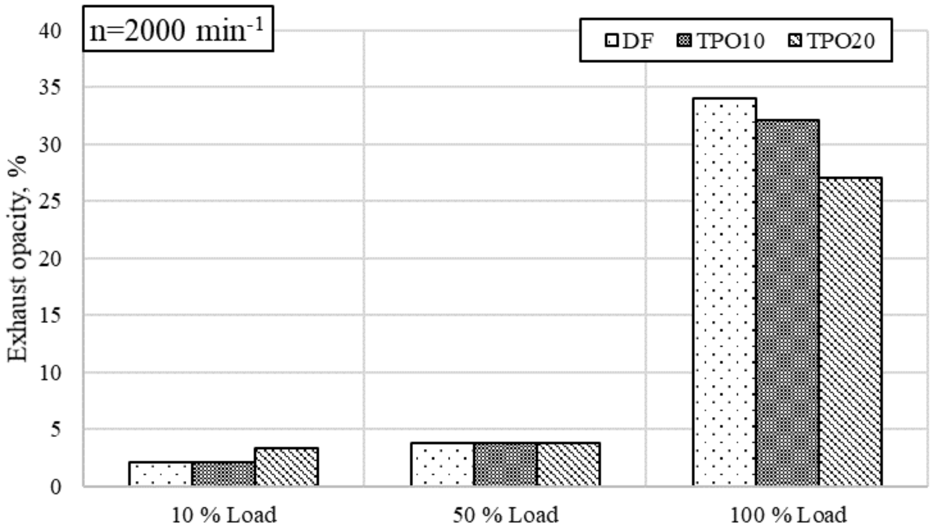

Fig.5 – Smoke dependence on engine load when engine was running on diesel fuel and its blends with tire pyrolysis oil

The soot formation is able to progress at local locations in the fuel-saturated combustion chamber during pyrolysis of hydrocarbons. The smoke opacity of diesel engines depends on the cetane number of the fuel, the chemical composition, the amount of aromatic hydrocarbons, the fuel injection and the quality of the combustible mixture, the diffusion process in the chamber and the complex mechanism of soot particle formation and their combustion burn reaction rate. The graphs in figure 5 show dependencies of smoke opacity on the exhaust of engine load when engine was running on diesel fuel and its blends with tire pyrolysis oil. It was observed that engine load has the most impact on smoke opacity. It can be seen that when the engine operates under low load, the lowest smoke opacity was obtained when the engine was fuelled on PPA20 fuel blend. At full load, using fuel PPA10 and PPA20 blends, smoke opacity decreased by 5.9 % and 25.5 % respectively, compared to an engine working on mineral diesel. It is evident that smoke opacity of the exhaust is influenced by the different physical and chemical properties of the fuels.

CONCLUSIONS

1. The lowest brake specific fuel consumption was obtained when the engine was running on diesel fuel and at a low (10 %) load. At full engine load (100 %), the highest (320.3 g/kW·h) brake specific fuel consumption was obtained with the engine running on the TPO20 fuel blend.

2. At an average engine load (50 %), using the TPO20 fuel blend resulted in a 5.4 % lower brake thermal efficiency compared to the engine running on diesel fuel.

3. At low engine load (10 %) and using the TPO20 fuel blend, the nitrogen oxide emissions were lower by 6.8 % compared to the diesel fuel.

4. When the engine is operating at the medium engine load (50 %), the highest carbon monoxide emissions were obtained from the engine running on the PPA20 fuel blend (433 ppm), and the lowest (349 ppm) from the diesel fuelled engine.

5. When using the PPA20 fuel blend at the full engine load (100 %), the smoke opacity was reduced by 25.5 %, compared to the diesel fuel.

The optimal ratio of the TPO blends on diesel fuel depends on many factors, such as the engine, injection system, injection pressure, the shape of the combustion chamber, the way the combustion mixture is prepared, and other factors. The influence of these factors can be determined by experimental studies, depending on the specific situation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data will be made available on request.

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