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Study of a diesel engine performance with exhaust gas recirculation (EGR) system fuelled with palm biodiesel

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Abstract

The increase in world population leads to the growth in energy demand. The primary sources of this energy come from the combustion of fossil fuel which producing oxides of nitrogen and other harmful greenhouse gas emission. However, biodiesel offers a solution as an alternative fuel for internal combustion engine but higher in NOx emission. Exhaust gas recirculation (EGR) system is used to lower the NOx emission. This paper focuses on determining the effect of EGR and palm biodiesel on fuel consumption (SFC), exhaust gas temperature (EGT) and exhaust emissions (NOx, CO, UHC, and CO_2). Experimental works using a multi-cylinder diesel engine with EGR and simulated works using Diesel-RK were performed at a constant engine speed of 2500 rpm in full load condition. The results showed that, from the simulated and experimental works, palm biodiesel significantly increased fuel consumption, increased NO_x and slightly decreases in other emissions including CO_2, CO, and unburned hydrocarbon (UHC). However, the use of EGR shows a significant reduction in the NOx emission and exhaust temperature but increases in fuel economy, CO, CO_2, and UHC emissions.

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Keywords: Diesel engine; exhaust gas recirculation (EGR); engine performance; exhaust emission; palm biodiesel;

1. Introduction

Renewable and alternative fuels from sustainably available feedstock sources have been the vital subject of research in recent years for replacing current petroleum fuels. These alternate fuels are suggested for opposing the adverse effects contributed by the present use of petroleum fuels in transportation and power generation [1, 2].

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Harmful gasses such as NOx and CO are emitted by the petroleum fuels which cause severe effects to the human health and environment [3]. Interestingly, these substitute fuels are mainly produced from edible and non-edible oils, originated from living feedstocks [4, 5]. Therefore, numerous studies on biofuels including biodiesel have been conducted regarding performance and emission characteristics of diesel engines with partial or complete replacement with the petroleum fuels [6, 7]. Biodiesel or methyl ester is originated from monoalkyl esters of long chain fatty acids which mainly produced from edible and non-edible oils of plants and animal fats [8]. Due to the molecular similarities between biodiesel and petroleum-based diesel and able to be used directly or partially without any engine modification, this substitute fuel secures possible high chances in replacing the current fuel in the future. However, biodiesel has drawbacks such as higher density and viscosity. Through transesterification process, the higher viscosity is reduced to achieve a closer value with petroleum diesel whereas cetane number and heating value are preserved. In general, the combustion of biodiesel in diesel engines contributes lower carbon monoxide (CO), unburned hydrocarbon UHC), particulate matters (PM) and smoke emission while conversely emits higher oxides of nitrogen (NOx). Many experimental works can be conducted to investigate the effect of EGR on a different type of fuels such as biodiesel based on the engine performance, combustion and emission characteristics [9, 10]. Previous research work results [10-13] significantly disclosed that EGR in modern engines is one of the most efficient methods for reducing NOx emissions. On the other hand, despite experimental works require a possible cost, time and manpower, there are some proposed approaches including numerical simulation and modeling methods [14, 15]. One of the engine simulation software that proposed is Diesel-RK software that purposely for the calculation and optimization in the internal combustion engines. The software, Diesel-RK is a multi-zone, full cycle, 1-D engine simulation software, which established by Razleytsev, Andrey Kuleshov, and others at Bauman Moscow State Technical University (BMSTU) and is still developed until the present day [16, 17]. It is designed to simulate and optimize the thermodynamic working processes of two and four stroke engines that covered all kinds of air boosting including turbocharging [18].

Since the comparison for both EGR and normal modes is required for the fuel testing, both experimental work and numerical investigation are needed to determine and analyze the effect of EGR on different fuels at different engine operating modes [19-21]. This aim of this paper is to identify the palm biodiesel characteristics and mineral diesel as a reference fuel regarding specific fuel consumption (sfc), exhaust gas temperature (EGT) and emissions of NOx, CO, CO2 and unburned hydrocarbon (UHC) in the experimental and simulated study operating with EGR. The test for both fuels is conducted at a constant engine speed of 2500 rpm in full load condition.

Nomenclature

EGR	exhaust gas recirculation
NOx	oxides of nitrogen
CO	carbon monoxide
CO_2	carbon dioxide
UHC	unburned hydrocarbon
EGT	exhaust gas temperature

2. Methodology

In the present work, palm biodiesel and mineral diesel were purchased from Mission Biofuels Sdn. Bhd and a commercial petrol station. Palm biodiesel is produced by a transesterification process which using KOH as alkali catalyst and methanol as alcohol. Then, the purchased palm biodiesel was analyzed for the fuel properties at UMP Central Lab according to the manufacturer standard. The important properties of palm biodiesel and mineral diesel are listed in Table 1 correspondingly.The experimental work was performed using a four-stroke, four cylinder diesel engine with EGR type diaphragm as shown in Fig. 1. This engine is a naturally aspirated (NA) diesel engine with a bore of 82.7 mm, stroke 93 mm and a compression ratio of 22.4:1. The engine is an air-cooled with the maximum power was 64.9 kW at 4500 rpm. More details are listed in Table 2. Test engine is directly coupled to an eddy-current brake *ECB* dynamometer and controlled using a Dynalec load controller.

Table 1 Properties of diesel and palm biodiesel

Property	Method	Unit	Diesel	Palm biodiesel (B100)
Heat value	-	MJ/ kg	45.28	41.3
Cloud point	ASTM D 2500	°C	18	13
Density @ 15°C	-	kg/m^3	853.8	867
Flash point	ASTM D 92	(°C)	93	165
Pour point	ASTM D 97	(°C)	12	7.0
Cetane Number	-		54.6	67

Table 2 Specifications of the test engine

Description	Specification
Number of cylinders	4 in-line
Combustion chamber	Swirl chamber
Total displacement cm	1.998 cc (121.925 cu in)
Cylinder bore mm x Piston stroke mm	82.7 x 93
Bore/stroke ratio	0.89
Compression ratio	22.4:1

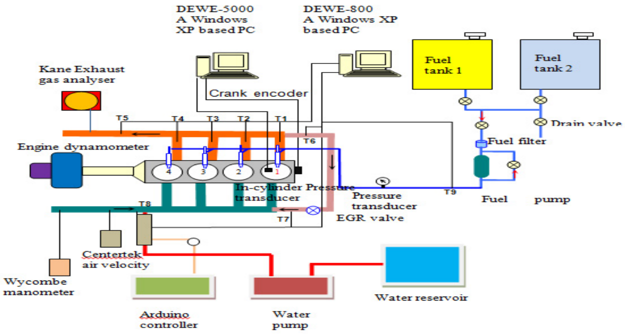

Fig. 1 Engine test set up

2. Results and Discussion

3.1 Effect on Performance and Combustion Characteristics

The performance and emission parameters are compared for palm biodiesel and mineral diesel under EGR and normal modes in the experimental works and numerical study at same test conditions. The full load condition is chosen since the point is achieved minimum air-fuel ratio with maximum smoke emission. This condition provides more significant differences when comparing different fuels at similar test condition. In understanding the effect of EGR on engine performance, the brake specific fuel consumption (BSFC) and exhaust gas temperature (EGT) were measured and calculated at full load condition with a constant engine speed of 2500 rpm.

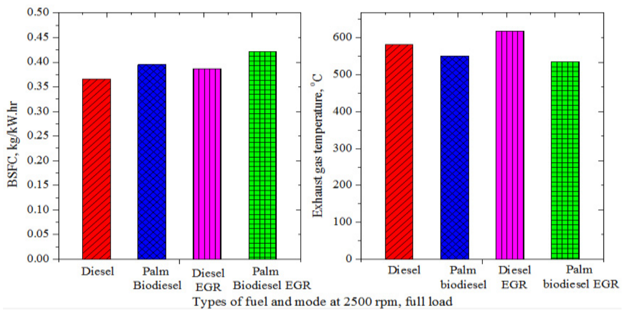

Fig. 2 BSFC and exhaust gas temperatures for test fuels at constant engine speed and full load

Table 3 Average values and % changes in BSFC and exhaust gas temperature (EGT)

Types of fuel and mode	BSFC (kg/kW.hr)	Exhaust gas temperature, EGT (°C)	% change in BSFC	% change in EGT
Diesel	0.3661	550.5		
Palm biodiesel	0.395	581.3	7.9	5.6
Diesel + EGR	0.387	534.9	5.7	-2.8
Palm biodiesel + EGR	0.4721	572.0	19.5	-1.6

The BSFC, exhaust gas temperature (EGT) and percentages of BSFC and EGT at different test fuels and modes were listed in Table 3. It is shown in Fig. 2 that the test fuels with EGR posses higher BSFC with lower EGT than test fuels at normal modes. The increase in BSFC was understandable since the power loss occurs in the cylinder during the testing as well as the lower heating value of palm biodiesel. The presence of lower oxygen content of intake air in the cylinder also contributes the decrease in power and torque for the test fuels when operating with EGR since EGR operation requires exhaust gasses mixing with fresh air intake recirculate in the cylinder. Lack of oxygen content possibly leads to the combustion inefficiency and incomplete burning of the fuels. Therefore, the engine is required to consume more fuel to achieve the same power at the constant full load. The experimental results are similar to those simulation results predicted by Diesel-RK simulation software. Average values and % changes in exhaust gas temperature (EGT) of both fuels operating under EGR and normal modes are shown in Fig. 2 and Table 4. It is obtained from the study that palm biodiesel produces a 5.6% higher exhaust gas temperature than mineral diesel. This effect is due to the higher excess oxygen content in methyl ester that leads to improved combustion efficiency with higher cylinder temperature [7]. In the case of EGR mode, it is found that the exhaust gas temperatures for mineral diesel and palm biodiesel are 2.8% and 1.6 % lower than normal modes. Similar finding noticed with the results obtained by Rajesh Kumar et al. [8]. Their studies also concluded that most different types of fuel produce lower exhaust gas temperature significantly with EGR mode at various speeds and loads. The decrease in the exhaust gas temperature may be associated with the exhaust gasses recirculate and combine with the fresh air charge in the intake manifold [9]; eliminating the enriched oxygen content, then swirl back in the cylinder to be burned again. This condition will increase the incomplete fuel burning rate as lack of excess oxygen burns with fuel which attributes to lower thermal efficiency and more fuel to be consumed.

3.2 Effect on Emission Characteristics

The exhaust emissions were compared to mineral diesel and palm biodiesel under EGR and normal modes at full load condition with a constant engine speed of 2500 rpm. Exhaust emissions include oxides of nitrogen (NOx), carbon monoxide (CO), carbon dioxide (CO_2) and unburned hydrocarbons (UHC) were measured during the testing. An increase in cylinder temperature is mainly attributed to the higher formation level of NOx emission [10]. However, two additional conditions contribute to the NOx formation which more oxygen content in the fuel and the reactions occur in the residence time. Since palm biodiesel is used for the testing, the listed conditions are a favor to the biodiesel combustion as compared to mineral diesel. Hence, palm biodiesel combustion contributes higher NOx emission than mineral diesel. This consequence is mainly attributed higher oxygenated nature content in methyl ester, which leads to higher oxidized flammable combustion in the cylinder and increases exhaust temperature simultaneously. Also, the higher oxygen content in biodiesel may be associated with the early injection timing in the combustion due to the difference in the compressibility of the different fuels in the cylinder.

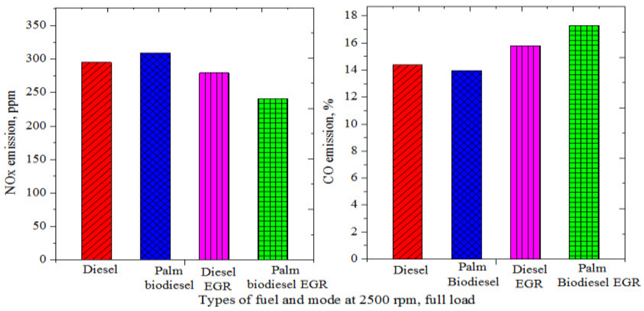

Fig. 3 Formation levels of NO_x and CO emission with engine speed for test fuels

Table 4 Average values and % changes in NOx and CO emissions

Types of fuel and mode	NOx (ppm)	CO (%)	% change in NOx	% change in CO
Diesel	295	14.4	-	-
Palm biodiesel	309	13.9	4.7	-3.5
Diesel + EGR	279.2	15.8	-5.4	9.7
Palm biodiesel + EGR	241.02	17.3	-22.0	24.5

Fig. 3 presents the NOx emission results and Table 4 lists the average values and % changes of NOx emissions for the test fuels operating with EGR and normal modes. It is found that palm biodiesel produced a 4.7% higher NOx emission than mineral diesel under normal mode. However, lower NOx emissions were achieved when EGR mode is employed for mineral diesel (5.4%) and palm biodiesel (22%). In general, the use of EGR system tends to reduce NOx emissions due to the rise in total heat capacity of the exhaust gasses, which lessens the elevated peak temperature. It is found from the results that NOx emissions are reduced significantly with the EGR employment due to the presence of inert gas (CO_2). This inert gas absorbs energy released by combustion and replaces the enriched oxygen content in the cylinder. As a result of a reduction in temperature and oxygen, the achieved NOx emissions for both fuels reduce significantly.

The average and percentage change in CO emissions for both fuels with EGR and normal modes are shown in Fig. 3 and Table 4. For palm biodiesel, the CO emission is lesser than for the mineral diesel because of a complete burning is occurred inside the cylinder due to the more availability of the oxygen content in palm biodiesel as compared to mineral diesel. The excess oxygen content in palm biodiesel supplies the necessary oxygen to convert CO to CO_2. However, it is obtained from the results that 9.7% and 24.5% increase in the CO emission for mineral diesel and palm biodiesel when employed EGR at full load. CO emissions percentage is increased for both fuels with EGR mode due to the insufficiently supplied oxygen in the inlet charge that mixing with recirculating exhaust gas, which causes incomplete fuel burning.

3.3 Comparison of Results

This section discusses the results obtained from the experimental and simulated works for both fuels in two different modes; normal and EGR. A slight difference for fuel economy, exhaust gas temperature, and emissions of NOx, CO, CO_2 and UHC in both works was recorded. The results are compared to full load condition with a standard compression ratio of 22.4. Table 6 presents the difference between these results

Table 6 Comparison of experimental results with Diesel-RK software results for mineral diesel and palm biodiesel

% Change in parameter	Experimental results (%)				Diesel-RK results (%)				Difference (%)			
	MD	PB	MD+ EGR	PB+ EGR	MD	PB	MD+ EGR	PB+ EGR	MD	PB	MD+ EGR	PB+ EGR
BSFC		7.89	5.7	19.5		6.2	6.5	3.0	1.6	-1.7	0.7	-16.5
EGT		5.6	-2.8	-1.6		4.6	-1.7	-1.5	26.3	-1.0	1.1	0.1
NOx		4.7	-5.4	-22.0		17.7	-5.1	-18.9	3.4	13.0	0.2	3.1
CO		-3.5	9.7	24.5		-7.6	5.1	26.0	9.7	-4.1	-4.7	1.6
UHC		-2.4	1.8	47.8		-8.8	8.4	35.6	7.8	-6.3	6.6	-12.1
CO2		-0.7	22.5	11.3		-2.9	14.2	4.4	15.4	-2.2	-8.4	-6.9

*MD - Mineral diesel **PB – Palm biodiesel

4. Conclusion

The reported work had concluded some significant findings during the test fuels, mineral diesel and palm biodiesel operated with two different modes (EGR and normal) in a diesel engine at full load at 2500 rpm. The findings concluded as follows:

i. Increases in fuel economy are obtained with the use of palm biodiesel and EGR employment at the specific engine speed.
ii. The decreases in the exhaust gas temperature are obtained when the EGR is employed for both test fuels.
iii. NOx emission is reduced significantly when the EGR is applied with increases in CO and UHC emissions are obtained for both test fuels.

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