THE EFFECT OF BIOFUEL ON THE EMISSION OF EXHAUST GAS FROM AN ENGINE WITH A COMMON RAIL SYSTEM

PIOTR ŁAGOWSKI[1]

Abstract

The paper presents the results of experimental tests of a FIAT MultiJet 1.3 SDE 90 PS engine equipped with a common rail system, running at full load operation at rotational speeds of n=1,000, 2,000, 3,000 and 4000 rpm, carried out on a dynamometer stand. During the tests, the engine was supplied with diesel oil and rape oil fatty acid methyl esters (FAME) in the following proportions: B30 (70% diesel oil and 30% FAME) and B70 (30% diesel oil and 70% FAME). This paper presents an assessment of the effect of the additions of rape oil fatty acid methyl esters to diesel oil on the unit fuel consumption and the emission of the following harmful exhaust gas components: nitrogen oxides, hydrocarbons, carbon monoxide, particulates and carbon dioxide. The fuel consumption was measured using a AVL 730 Dynamic Fuel Consumption fuel dosimeter. The measurements of the concentrations of the above-mentioned harmful exhaust gas components were performed using a MEXA-1600 DEGR analyser manufactured by Horiba, while particulate emissions were measured with a MEXA-1230PM analyser manufactured by Horiba.

Keywords: self-ignition engine; common rail system; biofuel; exhaust gas toxicity

1. Introduction

The threat of global warming caused by the environmental emissions of greenhouse gases has led to the increasing utilisation of renewable energy sources [20]. The main sources of greenhouse gases are the products of the combustion of fossil fuels. Striving for the reduction of greenhouse gas emissions has resulted in the search for new energy sources. Some of these energy sources are renewable fuels [18, 29]. The Directive of the European Parliament and of the Council 2009/28/EC of 23 April 2009 recommends the use of biofuels, which reduce the emissions of harmful exhaust gas components by 35% compared to exhaust gas from the combustion of plant-origin fuels. An adverse effect of using biofuels is an increase in the emissions of nitrogen oxides [4, 26]. However, substituting diesel oil with biofuel can contribute to a reduction in the emissions of particulates, carbon dioxide and hydrocarbons [25, 28, 30]. Automotive self-ignition engines can be supplied with higher fatty acid esters of oils of either plant or animal origin [3, 21, 22]. For the production of biofuels, easily accessible agricultural raw materials are most often used [27]. These include rape, soya, sunflower, corn, palms, beets and sugar cane [1, 10,12]. This paper reports the results of tests carried out on an engine supplied with methyl esters of rape oil fatty

[1] Kielce University of Technology, Department of Automotive Engineering and Transport, Al. Tysiąclecia Państwa Polskiego 7, 25-314, Kielce, Poland, e-mail: p.lagowski@tu.kielce.pl

acids, in which oleic acid and linoleic and linolenic acids constituted a vast majority [31, 13, 14]. The participation of the above-mentioned fatty acids in the fuel substantially influences the physicochemical properties of the FAME biofuel. The methyl esters of fatty acids of either plant or animal origin can be used for feeding self-ignition engines, as their properties are similar to those of diesel oil [8, 11, 16]. From an ecological point of view, a big advantage of esters compared to hydrocarbon fuels is that they are biodegradable. They have a low content of sulphur and are harmless to the human natural environment. Moreover, their cetane number is similar to that of diesel oil. Fatty acid esters have also their drawbacks, which include: poorer low-temperature properties, a tendency for absorbing water, an increased likelihood of fouling spray nozzle tips and combustion chamber elements with carbon deposits, a decrease in the engine's power, an increase in the hourly fuel consumption and an increase in the nitrogen oxide emissions. Investigations are currently being conducted in many research and development and scientific centres with the aim of assessing the effect of biofuel on the combustion process and, as a consequence, on the emissions of harmful exhaust gas components [2, 9, 7]. A negative factor that is associated with the combustion process is exhaust gas emission [17, 23]. Knowledge of the elementary composition of the fuel allows the determination of the elementary composition of the exhaust gas, which is indispensable for the assessment of the engine's operation in the environmental aspect. It enables the determination of the most advantageous and disadvantageous operation conditions of the engine in terms of its harmful environmental impact, and makes it possible to search for methods to minimise this impact.

The emissions of harmful and toxic exhaust gas components depend on the design and adjustment factors and the technical condition of the engine, as well as the quality of engine oils and fuels used in the operation of the engine [6, 19]. Additionally, engine running conditions have a great effect on the emissions. The basic components can be classified into three groups: the first group includes the products of the incomplete combustion process, i.e. carbon monoxide, hydrocarbons, aldehydes and particulate solids. The second group comprises the products of oxidation of air nitrogen and inorganic additives contained in the fuel and lubricating oil, i.e. nitrogen oxides, sulphur oxides and lead compounds. The third group includes nontoxic components and complete combustion products, i.e. hydrogen, carbon dioxide, water, nitrogen and oxygen.

2. The object of investigation and control and the measuring apparatus

The object of investigation was a FIAT MultiJet 1.3 SDE 90 PS diesel engine. The engine was furnished with a common rail feed system. During testing, the engine was running at the full load operation and at rotational speeds of n=1,000, 2,000, 3,000 and 4,000 rpm and was supplied with diesel oil and mixtures of diesel oil with rape oil fatty acid methyl esters in the following proportions: B30 (30% fatty acid methyl esters and 70% diesel oil); B70 (70% fatty acid methyl esters and 30% diesel oil) and 100% FAME. The technical specification of the engine is given in Table 1.

Tab. 1. The basic technical specification of the MultiJet1.3 SDE 90 PS engine

Parameter	Value
Cylinder arrangement	vertical – in–line
Number of cylinders, c	4
Injection type	Direct multi-stage fuel injection
Cylinder operation order	1 – 3 – 4 – 2
Compression ratio	17.6:1
Cylinder bore	69.6 mm
Piston stroke	82 mm
Engine cubic capacity	1,251 cm^3
Maximum engine effective power	66 kW at 4000 rpm
Maximum engine torque	200 N·m at 1750 rpm
Idling rotational speed	850±20 rpm

The fuel consumption was measured with an AVL 730 Dynamic Fuel Consumption fuel dosimeter. The measurements of the concentrations of harmful exhaust gas components (nitrogen oxides NOX, hydrocarbons HC, carbon monoxide CO and carbon dioxide CO_2) were performed using a MEXA-1600 DEGR analyser manufactured by Horiba. The particulate emissions were measured with a MEXA-1230PM analyser by Horiba. This analyser enables the separate and simultaneous measurement of two particulate solid components: soluble organic fraction (SOF) and soot.

Table 2 summarises the physicochemical properties of diesel oil and rape oil fatty acid methyl esters (FAME).

Tab. 2. Basic physicochemical properties of commercial diesel oil and rape oil methyl esters [15, 24]

Parameter	Diesel oil	FAME
Density at a temperature of 15°C, kg/m^3	833.4	883.1
Calorific value, MJ/kg	43.2	36.7
Kinematic viscosity at a temperature of 40°C, mm^2/s	2.596	4.55
Cetane number	51.0	51.3
Cloud point, °C	-10	-6
Cold filter plugging point, °C	-29	-22
Ignition point, °C	63.5	above 111
Sulphur content, mg/kg	8.3	6.4
Water content, mg/kg	84	180
Particulate contents, mg/kg	7.3	18
10% v/v fuel distilling off	215.3	318.0
50% v/v fuel distilling off	280.2	356.2
90% v/v fuel distilling off	341.7	370.4
95% v/v fuel distilling off	354.4	372.1

3. Testing results

The paper presents an assessment of the effect of the additions of rape oil fatty acid methyl esters to diesel oil on unit fuel consumption and the emission of the following harmful exhaust gas components: nitrogen oxides, hydrocarbons, carbon monoxide, particulates and carbon dioxide. Figure 1 illustrates the brake specific fuel consumption for the engine running at the full load operation at rotational speeds of n=1,000, 2,000, 3,000 and 4,000 rpm, and supplied with diesel oil, FAME fuel and the mixtures B30 and B70.

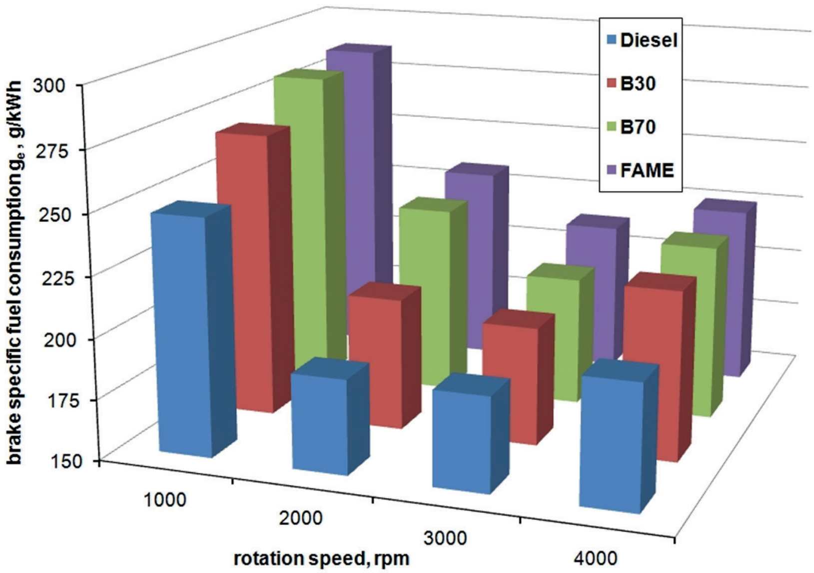

Fig. 1. Unit fuel consumption for the engine running at full load operation

For the engine running at full load operation, the largest unit fuel consumption was obtained when the engine was supplied with pure diesel oil. With increasing volume fractions of rape oil fatty acid methyl esters to the diesel oil, the unit fuel consumption increased. The highest unit fuel consumption was obtained for the engine supplied with pure rape oil fatty acid methyl esters. This increase is primarily due to the lower calorific value of the esters. It might also result from the different physicochemical properties of the fuels. For the engine furnished with the common rail high-pressure injection system and supplied with diesel oil, FAME and the mixtures B30 and B70, the latter are poorer atomized during the injection process, compared to diesel oil. This is due to the greater density and kinematic viscosity of the FAME fuel. Previous research [5] showed that the addition of rape oil fatty acid methyl esters to diesel oil resulted in an increase in the mean droplet diameter SMD (Sauter mean diameter). Increasing the diameter of a droplet causes the droplet to need more time to be heated up, evaporated and diffused with the air. Injected droplets are larger and there may not be sufficient time for their evaporation and the mixing of the fuel vapour with the air. Therefore, the air-fuel mixture is less well prepared for combustion. The quantity of released heat has a fundamental influence on the obtainable effective power of the engine. The less the released heat, the smaller the obtained power.

Figure 2 illustrates the emissions of nitrogen oxides, NOX, for the engine running at the full load operation at rotational speeds of n=1,000, 2,000, 3,000 and 4000 rpm, and supplied with diesel oil, FAME and the mixtures B30 and B70.

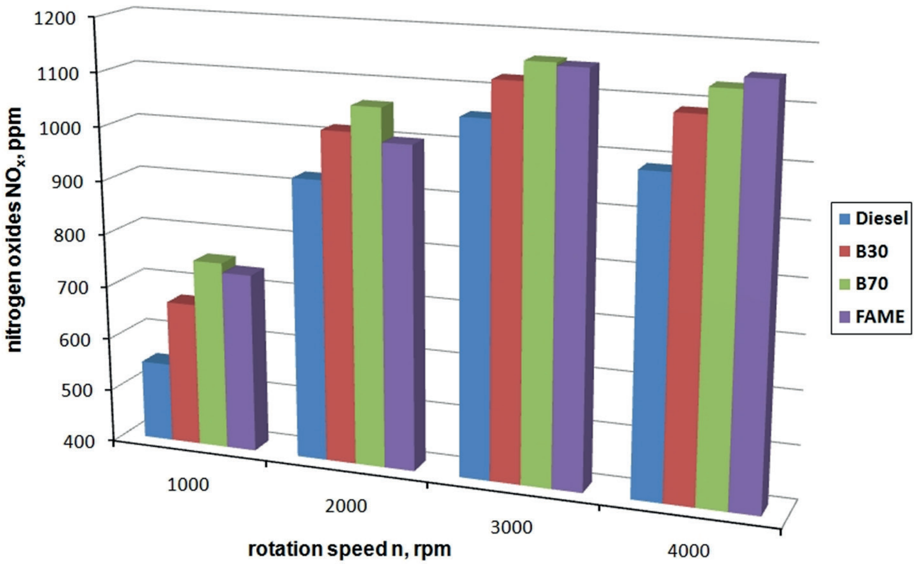

Fig. 2. Nitrogen oxide emissions for the engine running at full load operation

Lower nitrogen oxide emissions were obtained for the engine supplied with diesel oil compared to the engine fed with pure rape oil fatty acid methyl esters (FAME) and their mixtures. This might result from the greater heat release intensity for the engine supplied with diesel oil with the addition of methyl esters. This is due to the elementary composition of the fuels. The FAME fuel contains more oxygen molecules compared to diesel oil. Therefore, the combustion process proceeds faster, and the temperature increase in the cylinder is more rapid and higher compared to the diesel oil-fed engine. The higher maximum temperatures in the cylinder contributed to higher nitrogen oxide emissions for the engine supplied with diesel oil with the addition of rape oil fatty acid methyl esters.

Figure 3 presents the emissions of hydrocarbons (HC) for the engine running at the full load operation at rotational speeds of n=1,000, 2,000, 3,000 and 4,000 rpm and supplied with diesel oil, FAME and the mixtures B30 and B70.

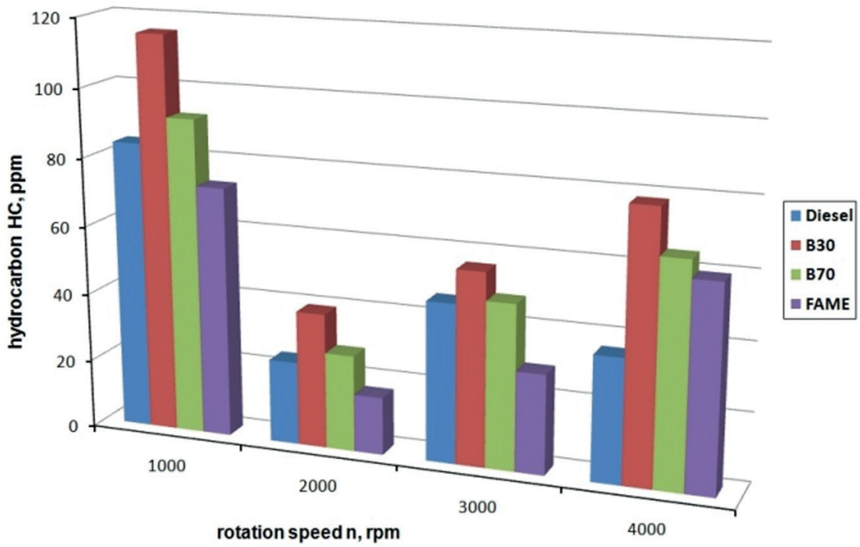

Fig. 3. Hydrocarbon emissions for the engine running at full load operation

The highest hydrocarbon emissions were obtained for the engine running at a rotational speed of 1,000 rpm. The rapid increase in emissions might be due to the poor air-fuel mixture during the combustion process. At this rotational speed, the combustion process proceeds slowest, which may also contribute to the increased hydrocarbon emissions. For the engine running at the full load operation and at rotational speeds of n=1,000, 2,000, 3,000 and 4,000 rpm and supplied with diesel oil, lower hydrocarbon emissions were obtained compared to the engine fed with the B30 and B70 mixtures.

Figure 4 shows the emission of carbon monoxide (CO) for the engine running at the full load operation at rotational speeds of n=1,000, 2,000, 3,000 and 4000 rpm, and supplied with diesel oil, FAME and the mixtures B30 and B70.

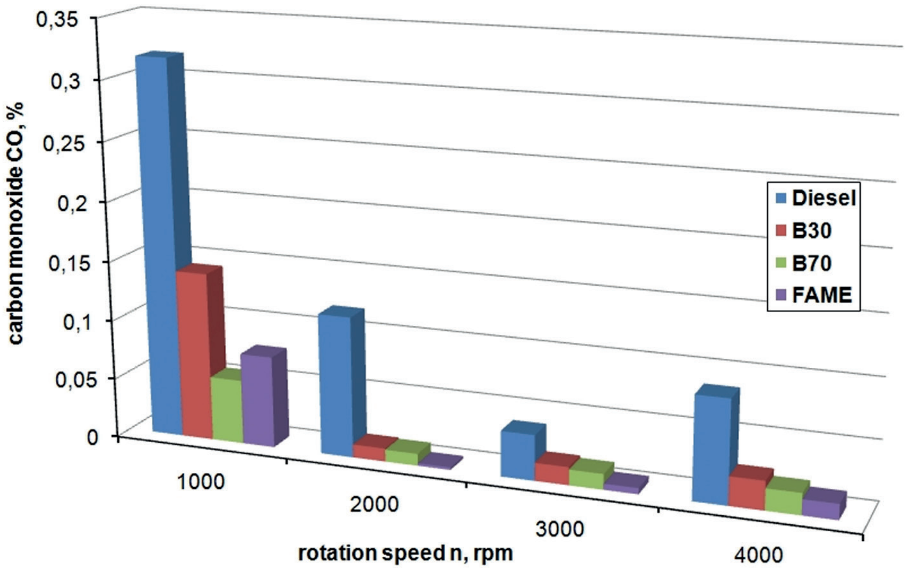

Fig. 4. Carbon monoxide emission for the engine running at full load operation

The highest carbon monoxide emission for the engine supplied with the investigated fuels was obtained for a rotational speed of 1000 rpm. The highest carbon monoxide emission was obtained for the diesel oil-fed engine. This is due to the elementary composition of the fuel, as the rape oil fatty acid methyl esters have a larger oxygen content than diesel oil. A greater oxygen quantity participating in the combustion process causes the combustion to be more effective, thereby reducing the carbon monoxide emission and increasing the emission of carbon dioxide.

Figure 5 illustrates the emission of carbon dioxide (CO2) for the engine running at the full load operation at rotational speeds of n=1,000, 2,000, 3,000 and 4,000 rpm, and supplied with diesel oil, FAME and the mixtures B30 and B70.

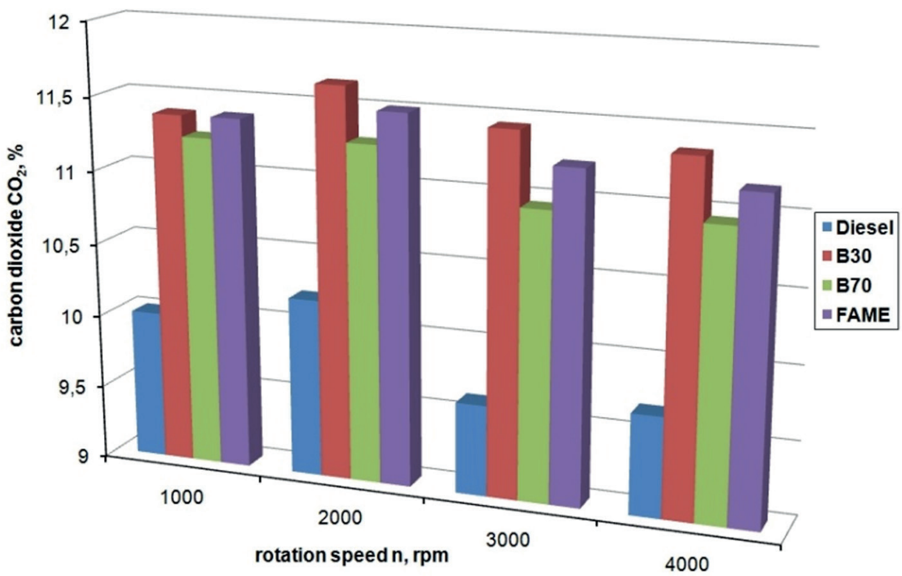

Fig. 5. Carbon dioxide emission for the engine running at full load operation

The highest carbon dioxide emission was obtained for the engine running under the full load operation and fed with the B30 and B70 mixtures and FAME. This is due to the fact that for these fuels, the combustion process proceeded most efficiently. In addition, fatty acid methyl esters have oxygen in their composition, which enables better mixing of the fuel vapour with the oxygen contained in the cylinder. Thus, the prepared air-fuel mixture burns faster and more intensively. The higher carbon dioxide emission resulted from the greater fuel consumption for the engine fed with the FAME fuel and its mixtures.

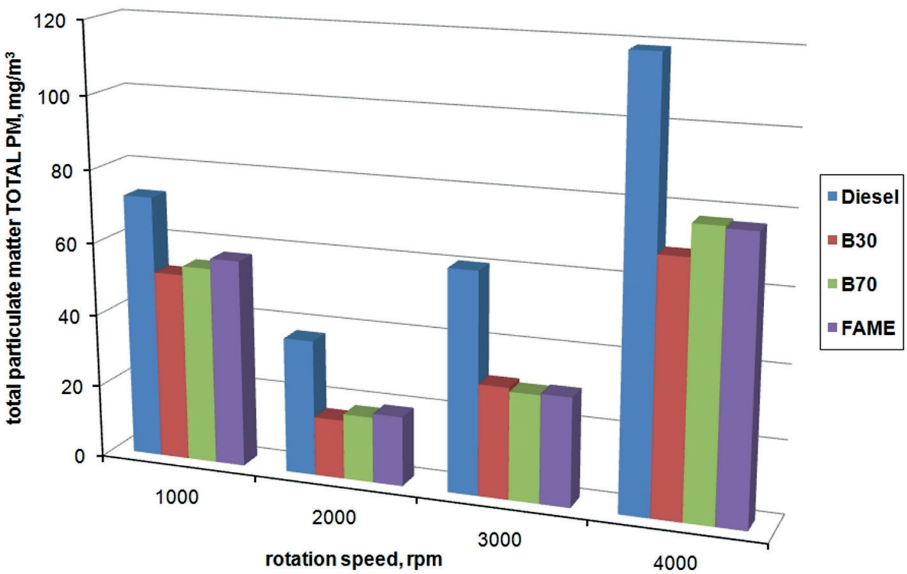

Fig. 6. Particulate emissions for the engine running at full load operation

The rate of particulate emission depends largely on the temperature and location in the cylinder–exhaust system–atmosphere system, where the capture of particulate solids takes place. The formation of soot in the flame is a complex process, whereby particulate solids form from fuel droplets within several microseconds. For an engine running under the full load operation and supplied with diesel oil, the soot formation rate is higher during the combustion process. This might result from the higher content of polycyclic aromatic hydrocarbons. The highest particulate emissions were obtained for the engine running under the full load operation at a rotational speed of n=4,000 rpm, while the lowest particulate emissions were noted at a rotational speed of n=2,000 rpm. The reduction in particulate emissions for the engine supplied with the mixtures, as against diesel oil, might be caused by the methyl ester oxygen content and the smaller excess air number.

4. Conclusions

It was found during the tests that the addition of esters to diesel oil considerably reduced the engine's effective power. This might be due to the poorer operational properties of the rape oil methyl esters, which are distinguished by higher kinematic viscosity and density and a lower cetane number and, first and foremost, a lower calorific value. Due to the lower calorific value, fuel which produces a smaller amount of energy in the combustion process compared to diesel oil is supplied to the engine. This, as a consequence, results in a lower effective power output and a greater fuel demand by the engine. With increasing rape oil fatty acid methyl ester contents of diesel oil, an increasing unit fuel consumption was obtained.

For the engine supplied with diesel oil with a FAME addition, higher nitrogen oxide emissions were observed, which was caused by higher temperatures prevailing in the cylinder during the combustion process. This is due to the fact that fatty acid methyl esters have oxygen molecules in their elementary composition. In such a case, the air-fuel mixture burns faster and more intensively, thus producing higher temperatures.

The highest hydrocarbon emissions were noted for the engine running under the full load operation and at n=1000 rpm, compared to the remaining rotational speeds. For the engine supplied with B20 and B40, the largest hydrogen emissions were obtained, as compared with the diesel oil-fed engine.

The addition of rape oil fatty acid methyl esters to diesel oil resulted in an increase in carbon monoxide emission. This is primarily due to the elementary composition of plant fuels, which have more oxygen molecules. Due to their larger quantity, a lower carbon monoxide emission was obtained for fuels with the addition of methyl esters. In turn, the emission of carbon dioxide increased. The oxygen contained in the esters causes the oxidation of CO to CO_2.

The addition of methyl esters to diesel oil resulted in reduced particulate emissions.

To sum up, it can be stated that for an engine enabling high-pressure fuel injection to the cylinder, the addition of ethyl esters to diesel oil reduces the engine's effective power output while increasing its fuel consumption. An advantage of using methyl esters as additives to diesel oils is the reduction of carbon monoxide, nitrogen oxides and particulate solids.

5. Nomenclature

B30 70% diesel oil and 30% fatty acid methyl esters
B70 30% diesel oil and 70% fatty acid methyl esters
CO carbon monoxide
CO_2 carbon dioxide
FAME fatty acid methyl esters
ge brake specific fuel consumption
HC hydrocarbons
n rotational speed
NO_x nitrogen oxides
PM particulate matter
SMD Sauter mean diameter

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