Institute of Technology and Biosystems Engineering

Jürgen Krahl
Hendrik Stein
Ahmed Hassaneen
Axel Munack
Olaf Schröder

Fuel economy and environmental characteristics of biodiesel and low sulfur fuels in diesel engines

Published in: Landbauforschung Völkenrode 55(2005)2:99-106

Braunschweig
Federal Agricultural Research Centre (FAL)
2005

Fuel economy and environmental characteristics of biodiesel and low sulfur fuels in diesel engines

Jürgen Krahl[1], Axel Munack[2], Hendrik Stein[2], Olaf Schröder[2] and Ahmed Hassaneen[3]

Abstract

The effect of biodiesel (rapeseed oil methyl ester, RME) and low sulfur fuels on the fuel consumption and emission characteristics of a diesel engine was investigated. The engine tests were carried out based on the 13-mode ECE-49 procedure. Particulate Matter (PM) distribution was analyzed with the state-of-the-art technique of Scanning Mobility Particle Sizing (SMPS). Compared to the base line diesel fuel, biodiesel emitted 20 to 80 % less specific CO, HC, PM, and aromatic hydrocarbons. The electrical mobility diameter of the majority of PM emitted from biodiesel was found to be in the range of 10 to 100 nanometers. The low sulfur fuel emitted 50 % less specific PM compared to the conventional diesel fuel. The aldehydes emission of biodiesel is much lower compared to fossil fuels. The major deficit of the biodiesel fuel was its higher specific fuel consumption rate that was in the range of 12 % (by weight) higher than the other fuels. A relatively higher NO_x emission at high loads was encountered for biodiesel fuel.

Keywords: Diesel fuel, biodiesel, diesel engine exhaust, non-regulated emissions, fuel consumption

Zusammenfassung

Kraftstoffverbräuche und Umweltwirkungen von Biodiesel und schwefelarmen Kraftstoffen in Dieselmotoren

Der Einfluss von Biodiesel (Rapsölmethylester, RME) und anderen Dieselkraftstoffen auf Emissionen und Verbrauch wurde untersucht. Als Proband diente ein Mercedes-Benz Motor des Typ OM 904, der im 13-Stufen Test betrieben wurde. Neben dem Kraftstoffverbrauch und den gesetzlich limitierten Komponenten (CO, HC, NO_x und PM) wurden auch die Partikelanzahlverteilung sowie Aromaten und Aldehyde bestimmt. Im Ergebnis führt der Einsatz von Biodiesel zu einem gravimetrischen Mehrverbrauch in Höhe von ca. 12 %. Aufgrund des Dichteunterschiedes von Dieselkraftstoff und RME schlägt sich dieses in einem volumetrischen Mehrverbrauch von ca. 5 % nieder. Im Vergleich zu Dieselkraftstoff sind bei RME Vorteile bei CO-, HC-, PM-, Aldehyd- und Aromatenemissionen festzustellen. Schwefelfreie Kraftstoffe senken die Partikelemission auf das Niveau von Biodiesel ab. Die Partikelanzahlverteilungen zeigen für RME im Bereich von 10 bis 100 nm teilweise sehr hohe Werte. Hier besteht weiterer Forschungsbedarf.

Die auch in dieser Studie festgestellte höhere Stickoxidemission des Motors bei Biodieselbetrieb lag in der erwarteten Größenordnung.

Schlüsselworte: Dieselkraftstoff, Biodiesel, Dieselmotorabgase, nichtlimitierte Emission, Kraftstoffverbrauch

[1] University of Applied Sciences Coburg, Friedrich-Streib-Straße 2, 96450 Coburg/Germany
[2] Institute of Technology and Biosystems Engineering, Federal Agricultural Research Centre (FAL), Bundesallee 50, 38116 Braunschweig/Germany
[3] Department of Automotive Technology, Industrial Education College, Kobbah, Cairo/Egypt

1 Introduction

Environmental and health concerns due to the exposure to the exhaust gas and particulate matter of diesel engines are gaining a considerable attention worldwide. These concerns have increased as the conjecture that diesel particulate matter is hazardous to human health is probably confirmed (Mauderly, 1994). That is why diesel engines are nowadays designed to pass a set of stringent emission regulations. Engineers everywhere in the world are working hard to improve the fuel systems and combustion characteristics of the engines running on conventional diesel fuel (DF) (for the abbreviations, please see the list of abbreviations at the end of this paper). Besides these efforts and because of the energy crisis in the 70's of the last century, scientists have directed their attention to the potentials of alternative fuels to reduce the diesel particulate emissions. Advanced diesel fuel formulations are among the strategies being adopted to reduce diesel engine emissions. Reducing sulfur and aromatics contents in the diesel fuel was and still is a priority to minimize the harmful diesel pollutants (Krahl, 2003). The use of biodiesel fuels derived from vegetable oils or animal fats as a substitute for conventional diesel fuel is very promising. The interest in biodiesel is based on its renewable resource, its biodegradability, and its potential to reduce the particulate matter emission from diesel engines.

Diesel engine exhaust has been classified carcinogenic to experimental animals and as a probable carcinogenic agent to humans (Evaluation of Carcinogenic Risk to Humans: Diesel and Gasoline Exhaust and Some Nitroarenes, 1989). Several studies reported a relative risk of approximately 1.5 for lung cancer by diesel exhaust after a long-term exposure (Mauderly, 1994). The carcinogenic effect of diesel exhaust exposure is mainly ascribed to the inhalation of soot particles (Scheepers, 1992). The mass of the particulate matter is the regulated value in most of the regulations worldwide. However, in recent years it became evident that the particle size distribution may be more important than the mass itself. The reason behind this fact is that the small particles reach pulmonary alveoli and deposit, while larger particles are deposited in the upper airway and eliminated by its ciliated epithelium. Thus, small and ultra-fine particles under 100 nm of diameter are considered critical to human health.

The motivation for the present work was to compare different diesel fuels regarding their fuel economy and exhaust gas emission from a diesel engine. These fuels include the conventional diesel fuel (DF), Swedish low sulfur fuel (MK1), low sulfur formulated diesel fuel (DF05), and biodiesel made from rapeseed oil methyl ester (RME). The particulate matter emission is going to be characterized for its particle number and diameter distribution.

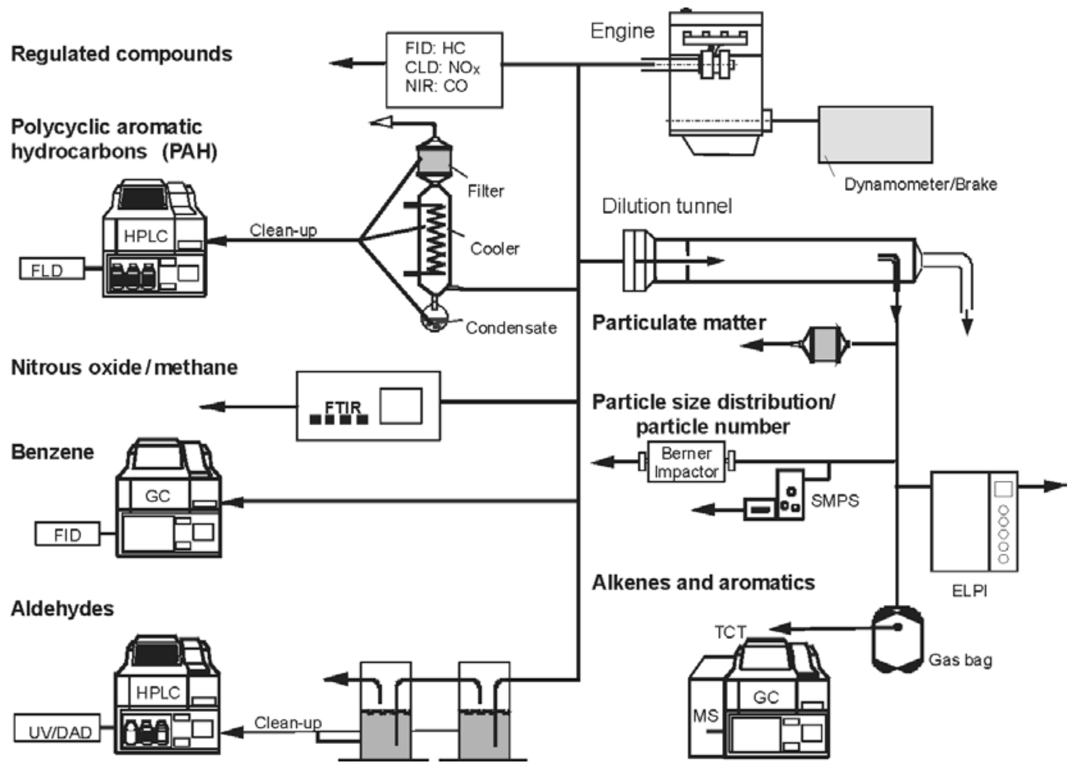

Figure 1:
Test set-up

2 Experimental

2.1 Engines Setup

A 4-cylinder, 4-strokes water cooled diesel engine, type OM 904 LA (Daimler/Chrysler) with turbocharger and intercooler was used in the study. Some data of the engine are shown in table 1. The engine is coupled to a fully controlled water-cooled brake dynamometer for loading purposes.

Table 1:
Engine specifications

Stroke/Bore	130 mm/102 mm
Number of cylinders	4
Displaced volume	4.25 L
Rated power	125 kW
Maximum speed	2300 rpm
Maximum torque	635 Nm @ 1380 rpm
Compression ratio	17.4

2.2 Instrumentation

A schematic overview of the complete test setup including all measuring equipments is shown in figure 1. Specific fuel consumption was measured using fuel flow control device and data were continuously recorded with the aid of a data acquisition system.

2.2 1 Regulated emission measurement

All regulated gaseous emissions were taken directly out of the undiluted exhaust gas stream. The particulate matter (PM) was sampled through a dilution tunnel. An emission rack is equipped with state-of-the-art instruments to continuously measure the concentration of the three major regulated emissions of carbon monoxide (CO), unburned hydrocarbons (HC) and nitrogen oxides (NO_x).

PM sampling is performed after passing through a part stream dilution tunnel. The total particulate mass during each test is measured by collecting it on PTFE coated glass fiber filters (T60A20). A balance with 20 µg standard deviation and 10 µg resolution is used for weighing the loaded and unloaded glass fiber filters.

2.2.2 Non-regulated organic compounds

The aromatic hydrocarbons were measured using gas chromatography (GC/MS type GC 17A and QP 5000). The GC is equipped with a thermal desorption cold trap (TCT) type Chrompack CP 2040. Benzene was determined with a flame ionization detector (FID) in the undiluted exhaust. Aldehydes and ketones were measured using high performance liquid chromatography (HPLC).

2.2.3 Particle size (number) distribution

The particle size distributions were measured using a Scanning Mobility Particle Sizer (SMPS). The SMPS (model 3934 TSI) system separates particles in a range from 10 to 300 nm. Inside the SMPS, exhaust gas particles are neutralized by a radioactive source. Because of this neutralization the particles get a defined charge distribution, such that their size distribution can be characterized by electrostatic field, under the assumption of a uniform density. The particle sizes obtained by this procedure are so-called electrical mobility diameters. The particles of different sizes are counted by the condensation particle counter (CPC) of the SMPS system. Since the CPC counts *numbers* of particles within particle size classes (not *mass* of particles within size classes), the obtained curves are referred to as particle number distributions in the following.

2.2.4 Test methods and procedures

The engine test mode applied was the ECE R49 test with 13 modes for engine speed and load as shown in figure 2. The engine is allowed to warm-up until the lubrication oil temperature reaches 50 °C. The test cycle is repeated three times with two hours rest between each test.

The glass fiber filters were conditioned in a climatic chamber that keeps temperature and humidity under control (20 °C and 50 % relative humidity) to limit the condensation and deposition of substances contained in the PM samples. Organic soluble matter was determined by

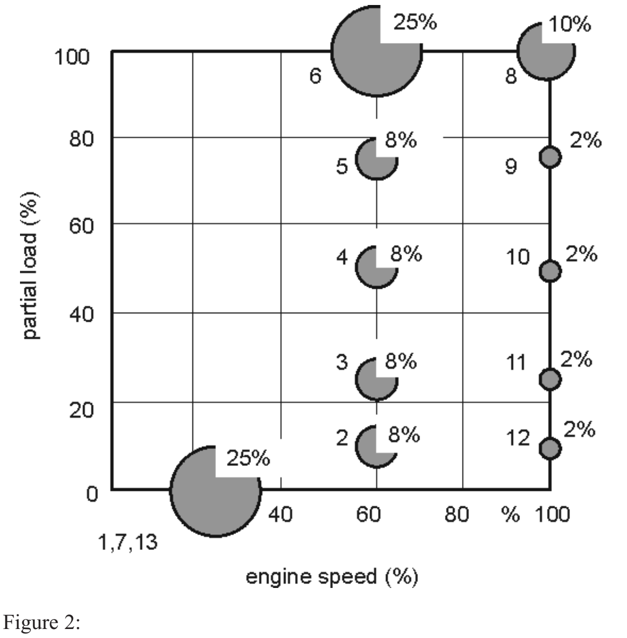

Figure 2:
ECE R49 13-mode test procedure; numbers designate the load points; percentages characterize the respective weights

heating the filters for 24 hours at 220 °C. Previous tests resulted in a good compatibility between this method and soxhlet extraction with dichloromethane. The exhaust gas stream needs to be diluted for the second time inside a secondary dilution tunnel before it enters into the SMPS system. The scanned particle distributions were recorded for one complete minute during the two minutes duration of each test mode.

2.2.5 Tested fuels

Four different fuels were evaluated in the present work. The first fuel is the Swedish low sulfur diesel fuel referred to as MK1. The second fuel is the German biodiesel (rapeseed oil methyl ester) referred to as RME. The third fuel is a low sulfur diesel fuel with high aromatic content and is referred to as DF05. The forth fuel is conventional diesel fuel referred to as DF. Some specifications of these fuels are shown in table 2.

Table 2:
Fuel properties

	MK1	RME	DF05	DF
Density (kg/m^3) at 15 °C	813.2	883	827.1	825.1
K. visc. (mm^2/s) at 40 °C	1.902	4.5	2.233	2.373
Flash point (°C)	-	< 150	73.0	62.5
Total sulfur (mg/kg)	> 5	> 10	> 10	41
Cetane number	-	< 55	65.1	53.6
Water content (mg/kg)	-	180	65	20

3 Results and discussion

The results are classified into several categories starting with the specific fuel consumption followed by the regulated and non-regulated emissions. The particle distribution is discussed in a separate section.

3.1 Specific fuel consumption

A comparison of the specific fuel consumption for the four fuels is shown in figure 3 and figure 4. Note that in these figures and in the following ones the load is given in absolute percentage of the maximum load, whereas in figure 2 the partial load is shown. Partial load is the percent-

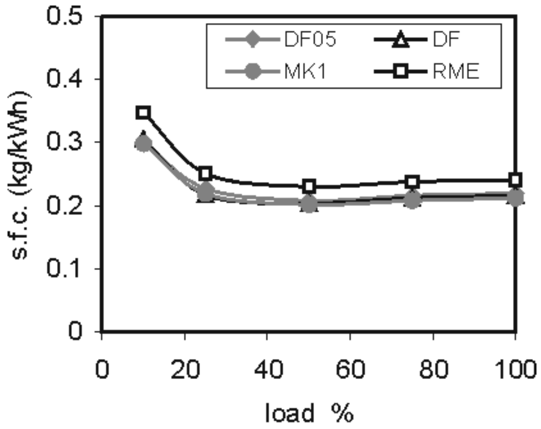

Figure 3:
Specific fuel consumption at 1400 rpm engine speed (modes 2 to 6 of the 13-mode test)

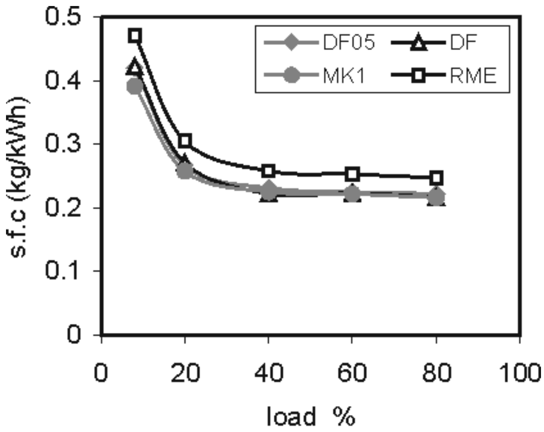

Figure 4:
Specific fuel consumption at 2300 rpm engine speed (modes 8 to 12 of the 13-mode test)

age of the maximum load at the actually considered engine speed. Thus a partial load of 100 % at 2400 rpm means a load of about 80 % for the engine used.

The fuel consumption of RME was 10 to 15 % higher (in weight) than for the other fuels. This disadvantage may be attributed to its lower energy content compared to the other fossil fuels. However, due to the higher density of RME, the increase becomes smaller when measured in L/kWh. The higher kinematic viscosity of biodiesel fuel could also affect its spray characteristics and consequently the whole combustion process and fuel consumption. The other fuels were found to have little differences in fuel consumption over the entire range of engine load.

3.2 The regulated emissions

The carbon monoxide (CO) emission was found to be below the regulated limit for most of the loads as shown in figure 5 and figure 6. The CO emission at low loads was slightly higher than the regulations, but the RME CO emission was the lowest among the other fuels and it was 30 to 40 % less than for DF.

The hydrocarbon emission (HC) showed almost the same trends as the carbon monoxide but with much clearer contrast as shown in figure 7 and figure 8. HC emission from biodiesel was far lower than that from the other fuels, especially at very low loads.

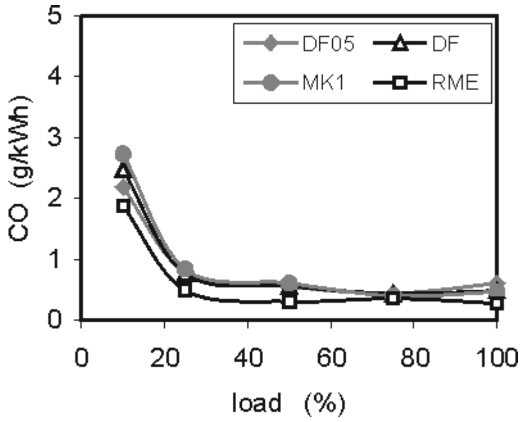

Figure 5:
Carbon monoxide (CO) emission at 1400 rpm engine speed

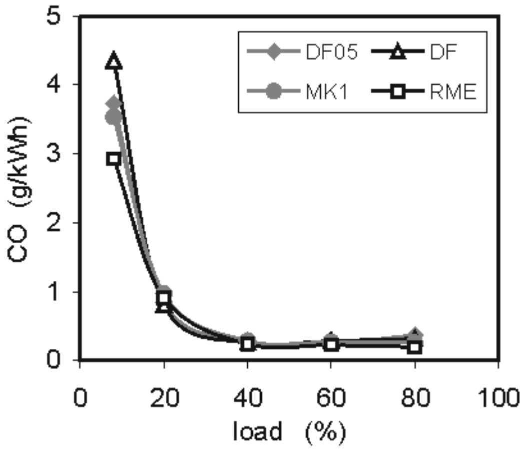

Figure 6:
Carbon monoxide (CO) emission at 2300 rpm engine speed

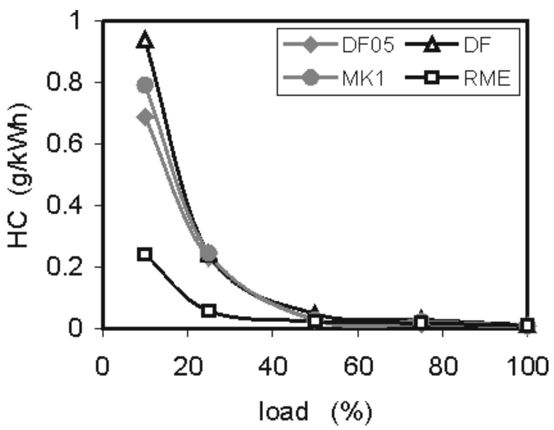

Figure 7:
Hydrocarbon (HC) emission at 1400 rpm engine speed

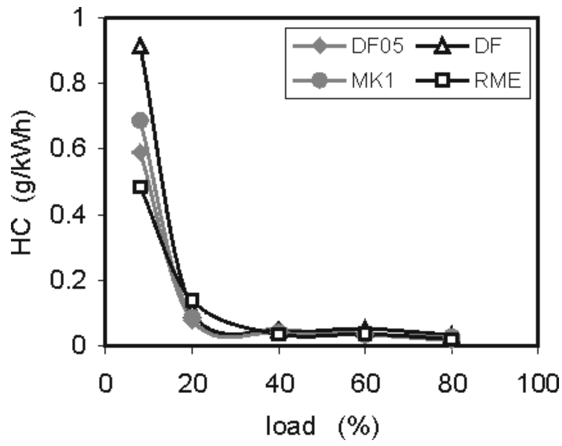

Figure 8:
Hydrocarbon (HC) emission at 2300 rpm engine speed

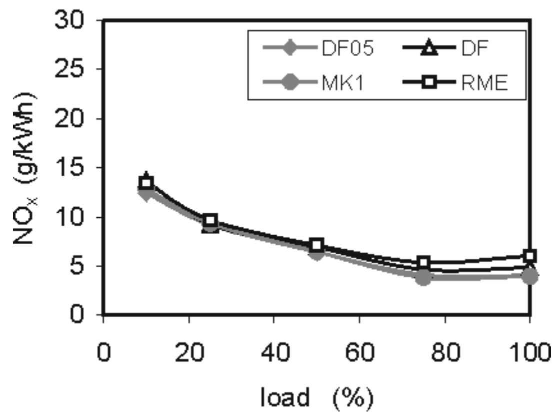

Figure 9:
Nitrogen oxides (NO_X) emission at 1400 rpm engine speed

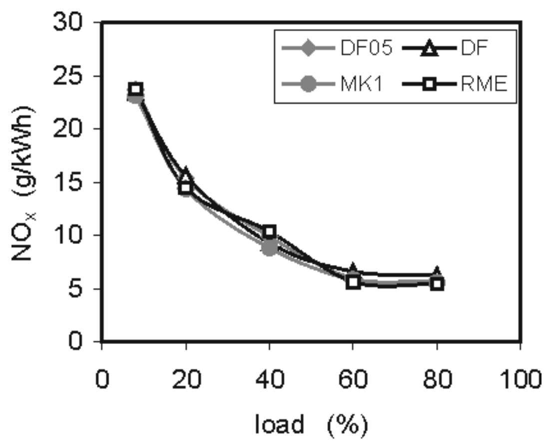

Figure 10:
Nitrogen oxides emission at 2300 rpm engine speed

The nitrogen oxides (NO_x) emission showed very little differences between the diesel-based fuels, cf. figures 9 and 10. However, biodiesel showed values that were a little higher than for the other fuels at the high loads and 60 % speed, as shown in figure 9.

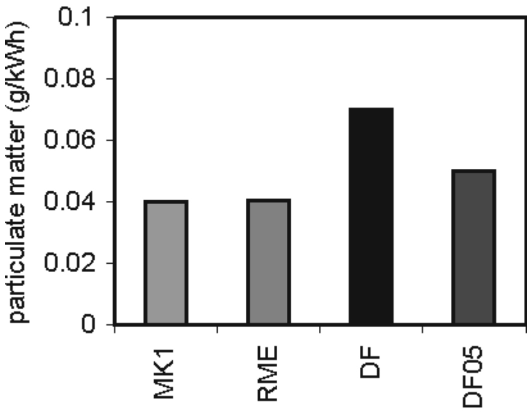

Figure 11:
Particulate matter (PM) emission; complete 13-mode test

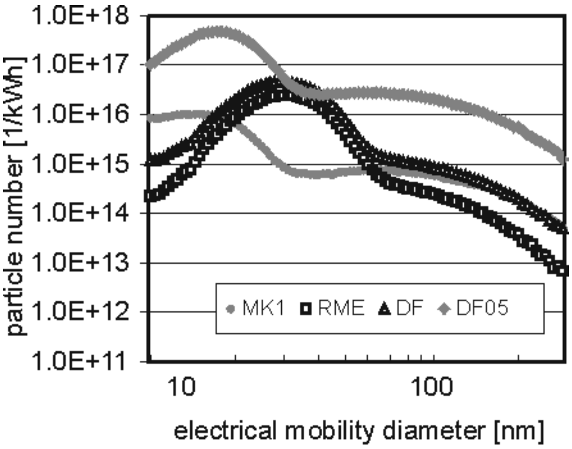

Figure 12:
Particle number distributions measured by SMPS at mode 2 of the 13-mode test

The overall NO_x for the whole ECE-R49 are as follows: RME leads to the highest emissions, whereas MK1 and DF05 show best results (Krahl, 2003). The reason for the elevated NO_x emission could be the difference in fuel injection pressure and injection timing compared to DF. The NO_x emission turns out to be the most critical problem with respect to the regulated emissions by the four fuels. In fact, for the majority of operating points the legal limit is not obeyed. The Euro II limit is 7 g/kWh.

The particulate matter (PM) emission (see figure 11) was very low compared to the regulations (Euro II: 0.15 g/kWh). The PM emission of biodiesel was almost 40 % less than for the conventional diesel fuel. The PM emission of MK1 is quite close to biodiesel. PM emission of DF05 fuel is little higher than biodiesel and MK1 still below the conventional diesel fuel (DF).

3.3 Particle distribution

The PM size was measured in the range between 10 and 300 nm as shown in figures 12 to 15. The results presented in figures 12, 13, and 14 show that the particle distribution of biodiesel ranges predominantly in diameters from 10 to 100 nm.

The engine speed doesn't seem to have a big effect on the particle number distribution. The engine load, however, seems to have a considerable effect on the distribution. The load effect can be understood from the analysis of the data in figures 12 to 14 that have been collected at constant speed and increasing loads from mode 2 to mode 8. The majority of the particle numbers of biodiesel were in the region from 10 to 30 nm. The maximum particle number of conventional diesel fuel, however, is in the region from 40 to 80 nm.

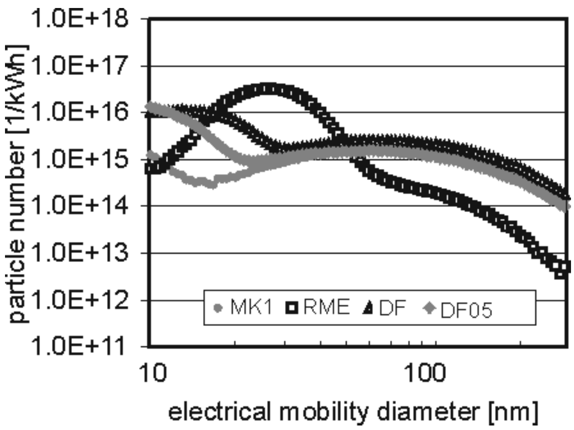

Figure 13:
Particle number distributions measured by SMPS at mode 5 of the 13-mode test

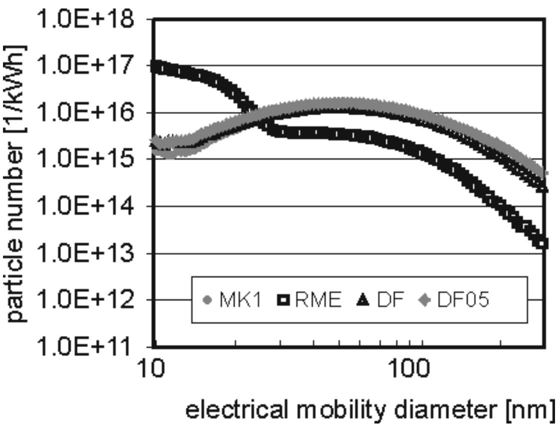

Figure 14:
Particle number distributions measured by SMPS at mode 8 of the 13-mode test

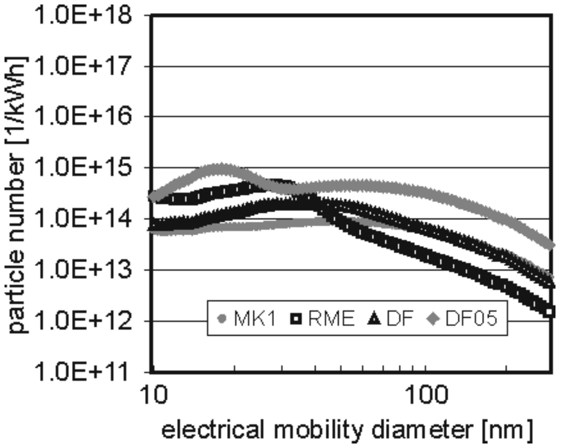

Figure 15:
Particle number distributions measured by SMPS; complete 13-mode test

The particle number of the 10 to 30 nm range of biodiesel is almost 100 times the particle number of the conventional diesel fuel in the same range. The average particle number distributions of the four fuels are shown in figure 15.

Although the PM emission of biodiesel is much lower than for fossil diesel fuel, its ultra-fine diameters raise an important question regarding its impact on lungs due to the fact that ultra-fine particles can go deeper into it. However, it is not clear whether these particles consist of soot or unburned fuel. So a possible health impact cannot be concluded as long as this question is not answered.

3.4 Non-regulated emissions

The aromatic compounds shown in figure 16 are mainly found at idle conditions and in the modes with light loads. The results show that biodiesel leads to a significant reduction of aromatic compounds. The results show the benefits of biodiesel in terms of the low HC emission at

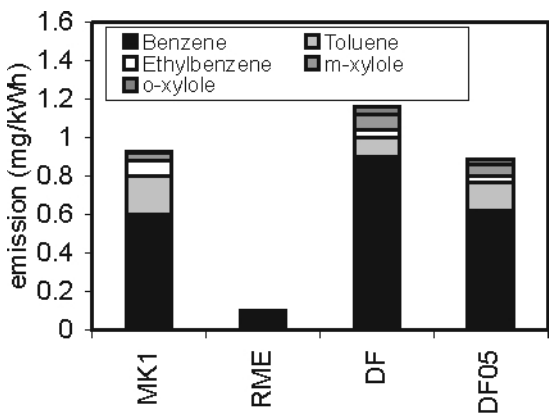

Figure 16:
Aromatic hydrocarbon emission; complete 13-mode test

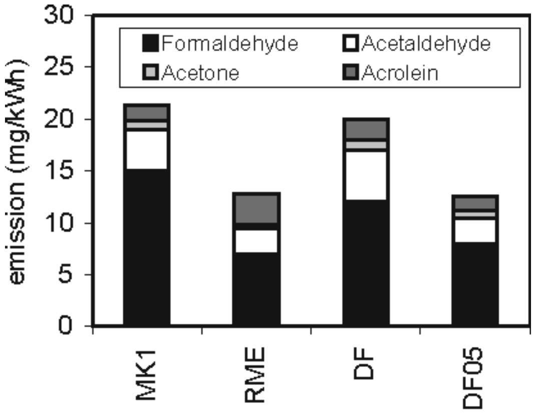

Figure 17:
Emission of aldehydes; complete 13-mode test

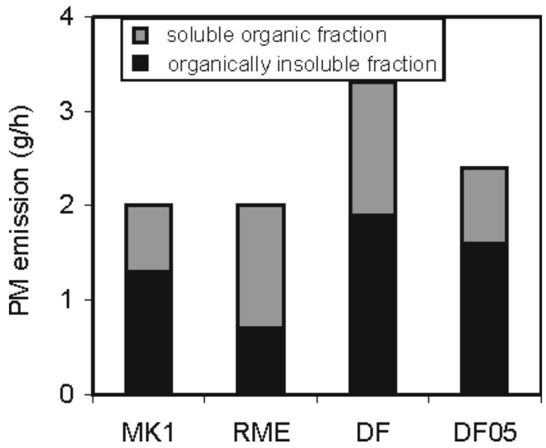

Figure 18:
Soluble organic and organically insoluble fractions of the particulate matter; complete 13-mode test

low loads as discussed in figure 7 above. Biodiesel seems to emit only benzene as aromatic compound.

The aldehydes emission from the four fuels is shown in figure 17. It can be seen that the aldehydes emission from biodiesel is comparable to that from the higher aromatic diesel (DF05) and both of them are 30 to 50 % less than conventional diesel fuel.

The soluble organic and the organically insoluble fractions of the particulate matter emission are shown in figure 18. The organically insoluble fraction (mainly soot and carbon) of biodiesel was almost 30 % of its total PM and it was about 30 % of that from conventional diesel fuel.

4 Conclusion

Four alternative fuels for diesel engines were tested and evaluated for fuel economy and exhaust gas emissions. Particulate matter distributions were also characterized. The following statements are the main conclusions of the investigation.

1. Biodiesel was the highest among the tested fuels as far as the fuel consumption is concerned with 10 to 15 % higher values by weight. These numbers decrease to 5 to 8 % when comparing fuel consumptions by volume.
2. Biodiesel was associated with 30 to 50 % less emissions of HC, CO, and PM compared with the other fossil fuels.
3. The maximum particle number was in the diameter range of 10 to 30 nm for biodiesel. For the conventional diesel fuel it was in the range of 30 to 100 nm.
4. Using biodiesel generally tended to increase NO_x emissions.
5. Non-regulated emissions data indicated that using biodiesel resulted in lower emissions of toxic aromatic hydrocarbons. Emissions of aldehydes were substantially reduced versus DF.
6. The solid fraction of biodiesel was almost 30 % of its total PM and it was about 30 % of that from the conventional diesel fuel.

Acknowledgement

The authors gratefully acknowledge funding of this research work by the German Working Group for Biodiesel Quality Management, Berlin, Germany. The financial support from the European Commission through the TEMPUS-IMG program for Dr. Hassaneen's visit to the FAL is highly appreciated.

Abbreviations

CO	carbon monoxide
DF	fossil (reference) diesel fuel
DF05	specially formulated low sulfur diesel fuel with higher aromatic content
HC	hydrocarbons
MK1	Swedish diesel fuel MK1
NO_x	nitrogen oxides
PM	particulate matter
RME	rapeseed oil methyl ester
rpm	revolutions per minute
s.f.c.	specific fuel consumption
SMPS	scanning mobility particle sizer

References

Mauderly JL (1994) Toxicological and epidemiological evidence for health risks from inhaled diesel engine emissions. Environ Health Perspect 102(4):165-171

Krahl J, Munack A, Schröder O, Stein H, Bünger J (2003) Influence of biodiesel and different designed diesel fuels on the exhaust gas emissions and health effects. SAE-Paper 2003-01-3199

International Agency for Research on Cancer (1989) Evaluation of carcinogenic risks to humans : diesel and gasoline exhausts and some nitroarenes. IARC Monographs 46:41-185

Scheepers PTJ, Bos RP (1992) Combustion of diesel fuel from a toxicological perspective : II. Toxicity. Int Arch Occup Environ Health 64:163-177