

Usability of food industry waste oils as fuel for diesel engines

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Received 23 November 2004; received in revised form 5 October 2006; accepted 8 October 2006

Available online 15 February 2007

Abstract

Two cogeneration units were each fitted with a prechamber (IDI) diesel engine in order to test the feasibility of using waste oils from the food industry as a fuel source, and additionally to test emissions generated by the combustion of these fuels. Esterified waste oils and animal fats as well as mustard oil were tested and compared to the more or less “common” fuels: diesel, rapeseed oil and rapeseed methyl ester.

The results show that, in principle, each of these fuels is suitable for use in a prechamber diesel engine. Engine performance can be maintained at a constant level. Without catalytic conversion, the nitrogen oxides emissions were comparable. A significant reduction in NO_x was achieved through the injection of urea. Combining a urea injection with the SCR catalytic converter reduced NO_x emissions between 53% and 67%. The carbon monoxide emissions from waste oils are not significantly different from those of “common” fuels and can be reduced the same way as of hydrocarbon emissions, through utilization of a catalytic converter. The rate of carbon monoxide reduction by catalytic conversion was 84–86%. A lower hydrocarbon concentration was associated with fuels of agricultural origin. With the catalytic converter a reduction of 29–42% achieved. Each prechamber diesel engine exhibited its own characteristic exhaust, which was independent of fuel type. The selective catalytic reduction of the exhaust emissions can be realized without restriction using fuels of agricultural origin.

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Keywords: Emission reduction; Waste oils; Food industry; Alternative fuels; Diesel engine

1. Problem description and definition of goals

In recent years, the application of vegetable oils as a source of fuel has been extensively researched. For prechamber (IDI) diesel engines straight vegetable oils can be used after minimal processing, while for direct injection (DI) diesel engines the oils must undergo esterification. The use of IDI diesel engines in the experiments was appropriate because on each engine tests with both, straight vegetable oils and esterified oils, had been carried out. IDI diesel engines are not widespread in vehicles, but standard in combined heat and power plants (CHP). DI diesel engines are not suitable

for running in CHP with vegetable oils or blends (Jones and Peterson, 2002). The use of biofuels in CHP becomes more and more common, also because these engines are often used in more rural areas and powered with self-produced fuels.

Unlike fossil fuels, the combustion of vegetable oil is regarded as CO₂ neutral and environmentally friendly. The limiting factor hindering their more widespread implementation is the amount of land available for the cultivation of these crops.

In many countries, cultivation of oil-producing crops is only economically feasible if the government subsidizes them, and where there is excess land for this purpose, which is not needed for the cultivation of comestibles. Triglycerides (fats and oils in the following) generated as waste by the food industry must either be disposed of or recycled in some way. From the viewpoint of sustainability, the use of this type of waste as fuel offers a plausible means by which it can be recycled.

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The goal of this research is to determine the nature of the emissions created through the combustion of waste oils from the food industry and to compare them with those from “common” fuels such as rapeseed oil, rapeseed oil methyl ester (RME) and diesel fuels. The experiments were conducted using two prechamber diesel engines, one of which was modified for combustion of vegetable oil. Furthermore, the efficacy of purifying waste oil exhaust emissions was to be proved.

2. Status of the current research

It is state of the art that stationary as well as automobiles diesel engines are capable of running on vegetable oil-based fuels, and recent modifications have also extended and optimized this applicability. Examples for these modifications were improvement of fuel injection time and volume, coating of the prechamber (at IDI diesel engines) and replacement of the fuel injector nozzles. Prechamber (IDI) diesel engines are capable of running with straight vegetable oils, while DI diesel engines need previously transesterification of the oils (Jurisch and Meyer-Pittroff, 1994; Birkner, 1995; Schumacher, 1996; Graboski and McCormick, 1998).

Vegetable oils possessing a higher viscosity can be utilized in non-modified IDI diesel engines, if the triglycerides have been converted to methyl esters through transesterification as well in non-modified DI diesel engines.

Currently in Europe almost exclusively RME is produced for use as a fuel. In USA soybean oil is the principal oil being utilized for biodiesel. In Japan the availability of used cooking oil and fat as a raw material reached its limits in the last years and so more and more Japanese municipalities now cultivate rapeseed (Schmidt). The main world biodiesel sources were in 2002: rapeseed oil (84%) and sunflower oil (13%), furthermore soybean oil (1%), palm oil (1%) and many others (1%) were used (Cyberlipid Center—Resource Site for Lipid Studies).

The motivation behind using vegetable oils as fuels:

- *Environmental concerns*: Unlike fossil fuels, vegetable oil fuels are renewable and are CO₂ neutral (von Weizsäcker et al., 1997; Sheehan et al., 1998).
- *Economic advantages*: Oil-producing plants not intended for use as food are eligible for subsidies within the European Union and are exempt from petroleum and CO₂ taxes.
- *Agreements on emissions reducing and fossil fuels replacement*: An action plan of the EU-Commission intend to replace fossil fuels by biogenous fuels from 2% in 2005 to 5.75% in 2010 (Bockey, 2002). In the Kyoto protocol, the EU member countries have committed to a reduction of their CO₂ emissions by 8% relative to 1990 levels by the year 2010 (Franke and Reinhardt, 1998).

The concept of using waste triglycerides from plant and animal sources as fuel emerged for obvious reasons (Iglhaut et al., 1998; Russ and Meyer-Pittroff, 2004). Utilizing this waste as fuel removes it from the food production cycle, because it will not be added to animal feed, as has been traditionally the case. Using these substances as fuel instead of additives to animal feed would eliminate any potential danger and therefore prevent food scandals such as in Belgium (van Larebeke et al., 2001) from occurring. Since the bovine spongiform encephalopathy (BSE) scandal addition of meat-and-bone meal or other animal remains to animal feed is forbidden in the European Community (EC) (Regulation, 2001). Though also recent regulations continuing this trend (Regulation, 2002a), it is still allowed to use some animal by-products in feed (Regulation, 2002b) and also illegal utilization is taken place. The more alternative ways of efficient and safe reusing animal waste will be available, the less misuse of these risk products will occur.

In a variety of studies, it was determined which emissions arise from the usage of rapeseed oil and RME as fuel (Jurisch and Meyer-Pittroff, 1994; Birkner, 1995; Schumacher, 1996; Graboski and McCormick, 1998; Hemmerlein et al., 1991; Widmann and Kern, 1999). The emissions were measured on production and modified diesel engines using various experimental parameters. Production engines are conventional engines that are not used for locomotion. This diesel fueled engines are mostly used in CHPs and in agriculture. The results obtained from these studies were summarized by Dobiasch, (2000) and are presented in Tables 1 and 2.

Particulate filters aid in the reduction of emissions from diesel engines, and catalytic and non-catalytic processes are employed for reducing the CO and NO_x content. The non-selective catalytic chemical reduction (i.e. three-way catalytic converter) is not feasible in diesel motors, because they operate with an excess of air.

In addition to a catalytic converter, selective catalytic reduction incorporates a reducing agent. Metal oxides such as V₂O₅, WO₃ and MoO₃ serve as catalysts. However, if

Table 1
Differences in the emissions of unmodified rapeseed oil in production engines and engines modified for rapeseed oil use, compared to diesel fuel

Emissions	Production engines	Motors modified for rapeseed oil fuel
CO	++	–
NO _x	o	o
Hydrocarbons	++	–
Soot particles	++	–
Aldehydes and ketones	++	+
Polycyclic aromatic hydrocarbons	Indifferent	–

+, Emissions increased.

–, Emissions decreased.

o, Emissions remained the same.

Table 2

Differences in the emissions of rapeseed oil methyl ester in production engines compared to diesel fuel

Emissions	Production engines
CO	–
NO _x	+
Hydrocarbons	–
Soot particles	–
Aldehydes and ketones	–
Polycyclic aromatic hydrocarbons	–

+, Emissions increased.

–, Emissions decreased.

o, Emissions remained the same.

only reducing agents such as ammonia or urea are used, this is referred to as selective catalytic reduction. Regulating the temperature to remain between 200 and 350 °C is necessary in order to achieve the high rate of conversion desired (Kind, 1998).

3. Materials and methods

3.1. Fuels used

Rapeseed oil, RME and diesel (DIN e.v., 2004) were chosen as the more or less “common” fuels, and the following three types of waste oils from the food industry were selected:

3.1.1. Used cooking oil collected from various sources

This type of oil is commonly collected and cleaned by recycling companies and afterwards made available for reuse. It is collected from industrial kitchens, restaurants and food producers, where it was primarily used for frying. After collection, the used oil is transferred to large holding tanks where it is blended with other waste oils; however the quality is very inconsistent. The impurities present in the used oil consist primarily of free fatty acids, polymers, chlorides and phospholipids, which cannot be adequately removed through the cleansing process. To use this oil as fuel a transesterification process must be performed which changes the molecular structure and decreases viscosity. The separation steps during this process leads to purification of the methylester fraction and the impurities are enriched in the glycerine fraction.

3.1.2. Mustard oil from mustard production

Mustard seeds contain 22–42% oil, which is primarily extracted by pressing. The oil consists of up to 60% erucic acid and between 110 and 115 µmol/g glucosinolates, both of which prevent mustard seed oil from further use in the food industry (Weiss, 1999).

3.1.3. Animal fat from rendering plants

In rendering plants, the ground animal parts are heat-treated for hygienic reasons, and afterwards the fat portion

is separated. For the same reasons as with the waste oils, only the esterified form of this fat can be used. Because of potential BSE contamination of animal material different processing steps compared to plant feedstock have to take place. In the last years processing methods for fuels from animal fats like sterilization, separation, purification, washing and distillation had been modified to reach risk reduction of 10^3 – 10^5 (Alm, 2004). Based on that developments the European Food Safety Authority concluded that the production of biodiesel, including the by-products potassium sulphate and glycerine, is safe for the treatment of fats of category 1 animal by-products (high risk) (Panel on Biological Hazards of the European Food Safety Authority, 2004).

3.2. Experiment design and measuring techniques

Two cogeneration units were selected as the diesel engines for this experiment, because their load profile can be regulated in such a way that it remains constant. Automobile diesel engines were not tested because stationary engines are more easily adapted for the varying fuel quality of waste oils. Hence, future applications of this technology focus chiefly on stationary diesel engines. Cogeneration unit 1 with a swirl chamber diesel engine was set up to run on diesel fuel, while cogeneration unit 2 with a prechamber diesel engine was specially modified to burn plant oils (see Table 3). The modifications of unit 2 included adjustment of fuel injection time and volume as well as replacement of the fuel injector nozzles.

For the data logging at the test stations a Almemo data logger (Ahlborn Mess- und Regelungstechnik) was used. Temperature was measured by Pt-100 and NiCr-Ni sensors, volume flow by a Turbotron VTP 15 MS-40 (VSE) and electrical real power using a MU-P4Wu/s transducer (Müller&Weigert). The manufacturers of the emission measuring devices as well as their technical data are given in Table 4. Data output was imported automatically into a Microsoft Excel file.

Fig. 1 shows the placement of the diesel engines and their integration into the system designed for measuring their exhaust emissions. If desired, a catalytic converter could be installed on cogeneration unit 2 in front of the heat exchanger, where urea could be injected for denitrification of the exhaust. The amount of fuel consumption as well as the amount of injected urea was measured gravimetrically. The catalytic converter contained an extruded honeycomb catalyst composed of titanium dioxide (TiO₂), vanadium oxide (V₂O₅) und tungsten oxide (WO₃).

The standard deviation of the test setup was ascertained in preliminary tests ($n = 9$) for each analyzed parameter. Because most fuels were not available in huge amounts, the tests in advance were conducted with waste oil methyl ester (WOME) and outcomes were utilized for general error estimation. For the fuel trials, the cogeneration units had a 4 h forerun with WOME before every test. After changing

Table 3
Specifications for both engines

	Cogeneration unit 1	Cogeneration unit 2
Manufacturer/Model	Icemaster GmbH/ Fischer Panda 10	Vereinigte Pflanzenölwerk-stätten/KW 5-3 AP
Engine	3 cylinder swirl chamber Kubota industries	3 cylinder prechamber Lombardini S.I.
Cylinder and piston	64 × 68 mm	72 × 75 mm
Volume	719 cm ³	916 cm ³
Injection pump	Bosch MD Type Mini Pump	Lombardini LDW 903
Injection pressure	13.73 MPa	13–14 MPa
Injection time	21° before TDC	22° before TDC
Compression ratio	23:1	22.8:1
Max. mechanical power	12.4 kW at 3000/min	13.7 kW at 3600/min
Generator	Asynchronous	Asynchronous
Max. electrical power	9.5 kW	8.4 kW
Nominal electrical output	6 kW	5 kW

Table 4
Technical information for the devices used in the emissions testing

Measuring device	Manufacturer	Gas	Range	Accuracy relative to final value	Detection limit	Zero drift relative to final value
Oxynos 100	Rosemount	O ₂	0–5% by vol. 0–100% by vol.	±1%	0.05% by vol.	±0.5%
MCS 100	Perkin Elmer Bodensee-werk	NO	0–200 mg/m ³ 0–10000 mg/m ³	±2% ±2%	1% of final value for all gases	±0.5% for all components
		CO	0–140 mg/m ³ 0–700 mg/m ³	±2% ±2%		
		NH ₃	0–30 mg/m ³	±2%		
		N ₂ O	0–50 mg/m ³	±2%		
		H ₂ O	0–20 vol.-%	±2%		
FID	Bayer Diagnostics	HC	0–10 ⁵ mg/m ³	n. g.	0.2 mg/m ³	n. g.
GC	Siemens	N ₂ O	Peak height 1:108	±1%	10 ppm	n. a.
CIMS 500	V&F	NO	0–1000 ppm	±5	10 ppm	n. a. for all components
		NO ₂	0–1000 ppm	±5	10 ppm	
		NH ₃	0–1000 ppm	±5	10 ppm	

n. g., no information given.

n. a., not applicable (based on measurement method).

fuel there was an initial break-in phase of at least 30 min for stabilizing of measurands.

3.3. Fuels and their properties

Diesel was selected as the standard fuel, and rapeseed oil and RME as the fuels of agricultural origin, because of their widespread availability. Mustard oil could be used in the non-ester form because of its purity. WOME was obtained from a supplier. The animal fat methyl ester (AFME) for the experiment was produced in the laboratory. Because of high free fatty acid content of the animal fat compared to other raw materials a modified method using ammonia for deacidification was applied (Dobiasch, 2000). The most important properties of each of these fuels are listed in Table 5.

The density and viscosity of unmodified vegetable oils are significantly higher than those of other types of fuel. Esterification reduces the viscosity and therefore eliminates

this problem. The impurities according to the reference method DIN 51419 (like sand, rust and organic compounds) in oil and the ash content of the emissions are directly related. The contamination level (impurities) of AMFE is more than ten times higher than recommended for continuously operating according to engines specifications. The implications of high contents of undissolved and dissolved impurities could result in different serious problems. For example impurities like sand, rust and other undissolvable matters can plug up filters or nozzles. Organic compounds, often containing nitrogen, can also block nozzles and cause carbon deposit in the combustion chamber and on outlets. Free fatty acids can impede the transesterification and form soaps. Not esterified free fatty acids and different kinds of salts (Ca²⁺, N⁺, K⁺) can cause corrosion in the engine and catalyze oxidation processes.

The fatty acid spectra of the vegetable oils in this experiment are typical for rapeseed oil and mustard oil (see

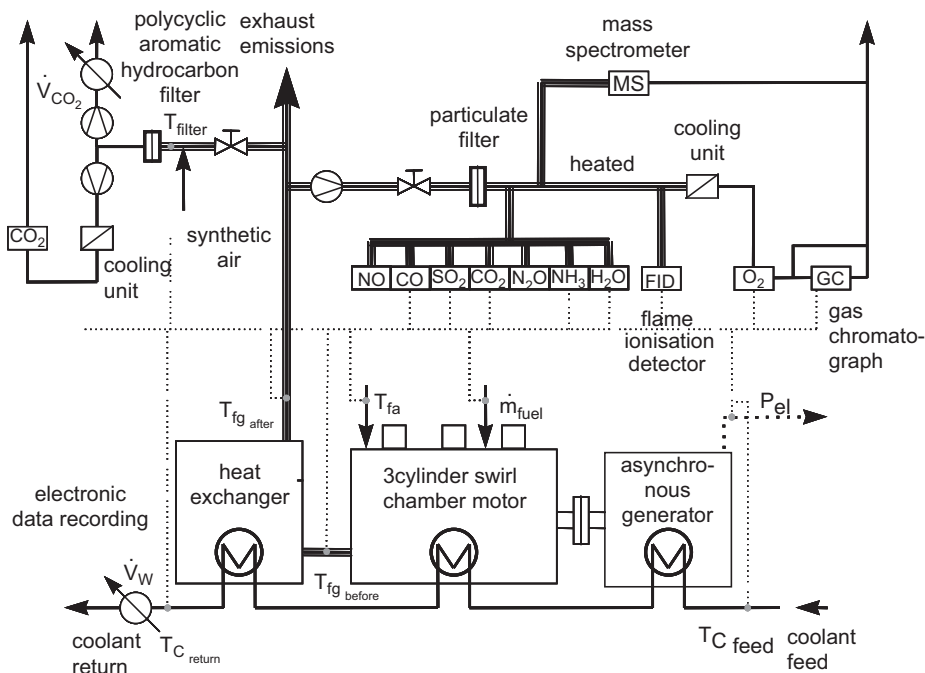


Fig. 1. Integration of the measuring devices used in the experiment into the test setup.

Table 5
Properties of the fuels

	Density (15 °C)	Net calorific value	Viscosity	Carbon residue	Impurities	Neutralization number	Ash content	Iodine value	Phos-phorus content
Reference method	DIN EN ISO 3675	DIN 51900	DIN EN ISO 3104	DIN EN ISO 10370	DIN 51419 ^a	DIN EN ISO 660	DIN EN ISO 6245	DIN 53241	ASTM D 3231
Measurement unit	kg/m ³	MJ/kg	mm ² /s	% by mass	mg/kg	mg KOH/g	% by mass	g/100 g	mg/kg
Diesel fuel	822	43.2	2.4	0.08	11.9	0.97	0.001	n. a.	n. a.
Rapeseed oil	918	37.6	36.7	0.70	32.4	1.66	0.007	106	11
RME	880	37.5	4.8	0.11	30.8	1.11	0.002	107	0
Mustard oil	911	37.8	46.1	0.34	36.4	1.11	0.007	86	2
WOME	883	37.2	5.4	0.07	30.4	0.97	0.001	100	0
AFME	876	37.0	4.3	0.03	305.0	0.23	0.039	97	0

n. a., not applicable (based on measurement method).

^aIn the meantime replaced by DIN EN 12662.

Fig. 2). The amounts of stearic acid and palmitic acid were noticeably high in the AFME.

4. Discussion of results

The amount of electrical power generated by the diesel engines served as the measure for engine performance. This was approximately the same for all the fuels in the experiment (Fig. 3).

The exhaust temperature provided a direct means for measuring the fuel performance, because the electrical power and therefore the mechanical power were held constant. A performance controller was set to keep about 5.5 kW at cogeneration unit 1 and about 4 kW at

cogeneration unit 2. To keep constant electrical power at constant revolution, fuel supply was regulated by the controller. Thus a change in temperature is an indication for a different performance of the fuel. The AFME did not burn as well in the diesel engine, as was evidenced by the increased temperature of the exhaust (Fig. 4). From previous experiments, it was determined that the optimal temperature for the catalytic NO_x conversion lies between 200 and 350 °C. Cogeneration unit 2 was within this range, with an operating temperature between 300 and 350 °C. Injection of a urea solution resulted in lower temperatures in contrast to measurements taken without urea (Lachenmaier, 2002).

As can be seen in Fig. 5, the levels of NO_x emissions from the AFME were markedly low. It could be

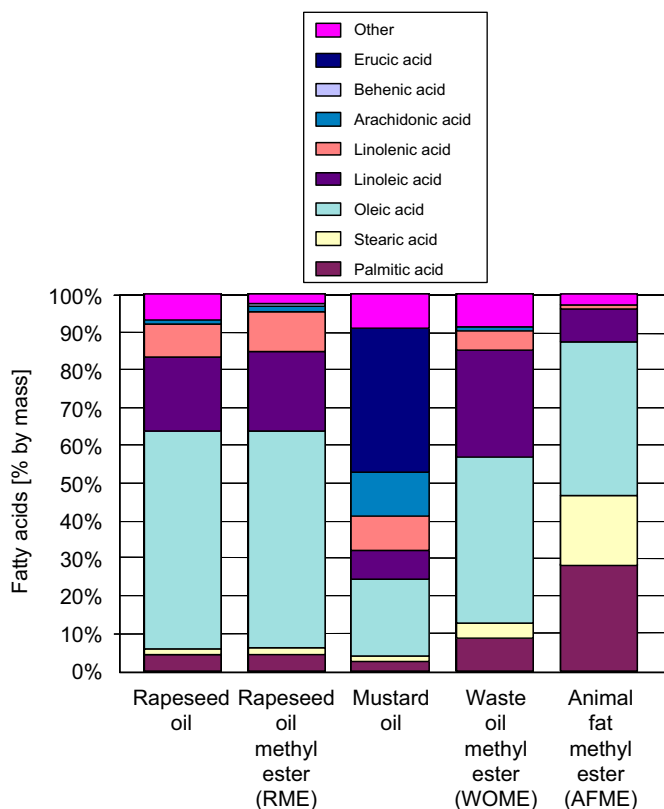


Fig. 2. The most important fatty acids present in the selected fuel types.

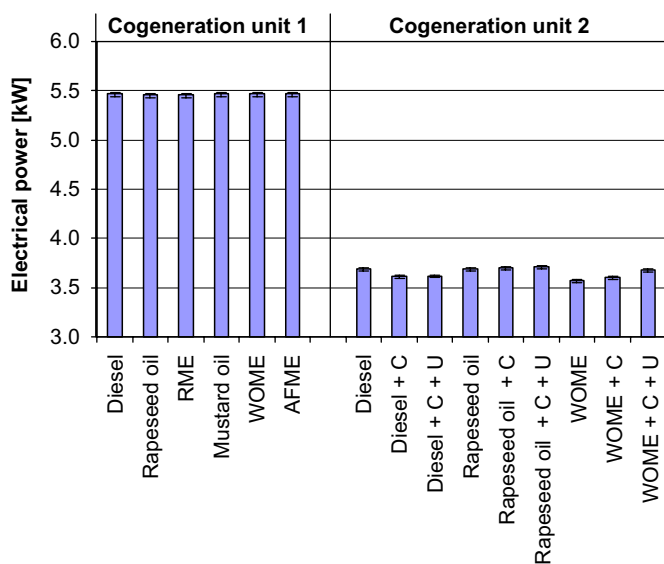


Fig. 3. Electrical power generated by both cogeneration units using different fuels (C: converter; U: urea).

hypothetical possible, that the higher exhaust emission temperature is a result of a different combustion process what influences the NO_x formation. Furthermore, the scores of impurities could theoretically contain catalytic compounds which are reducing NO_x emissions. The nitrogen oxides emissions from cogeneration unit 1 were higher than those from cogeneration unit 2, even when

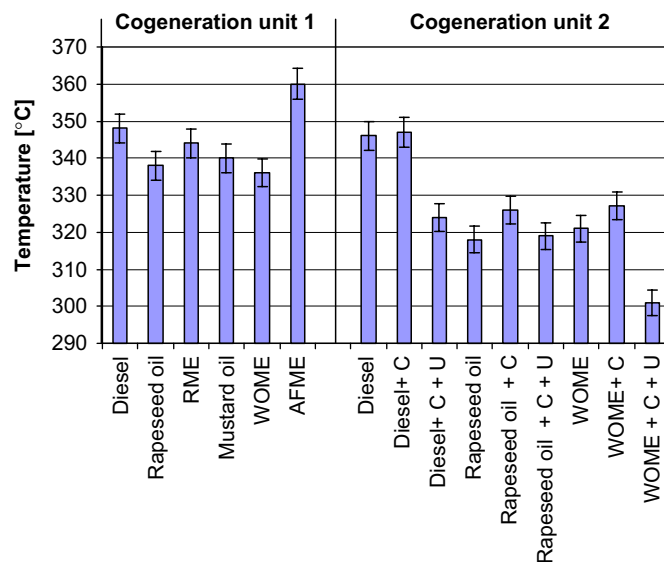


Fig. 4. Temperatures of the exhaust emissions measured before the heat exchanger (C: converter; U: urea).

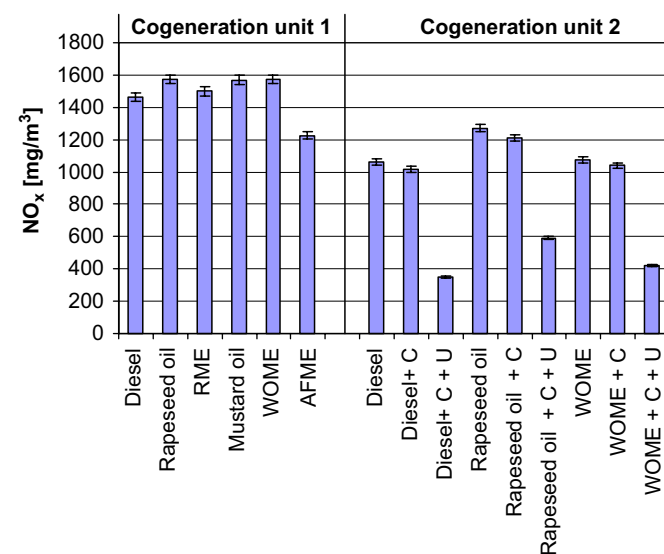


Fig. 5. Nitrogen oxides emissions based on residual oxygen content of 5% by volume in exhaust emissions (C: converter; U: urea).

burning the same type of fuel. This was due to the modifications made to the diesel engine for the combustion of vegetable oils. As expected, in the absence of a urea injection, the SCR catalytic converter had almost no effect. The rate of reduction (with catalytic converter and urea injection) in NO_x emissions using diesel fuel was 67%, which was somewhat better than that of the renewable fuels (54% and 61%).

For the catalytic conversions of NO_x to N_2 the availability of not complete oxidized compounds are important. Therefore, the engine of cogeneration unit 2 was calibrated in a way that at any rate enough CO for catalytic reduction process is present. On this account there will be always a minimum of CO in the exhaust emissions

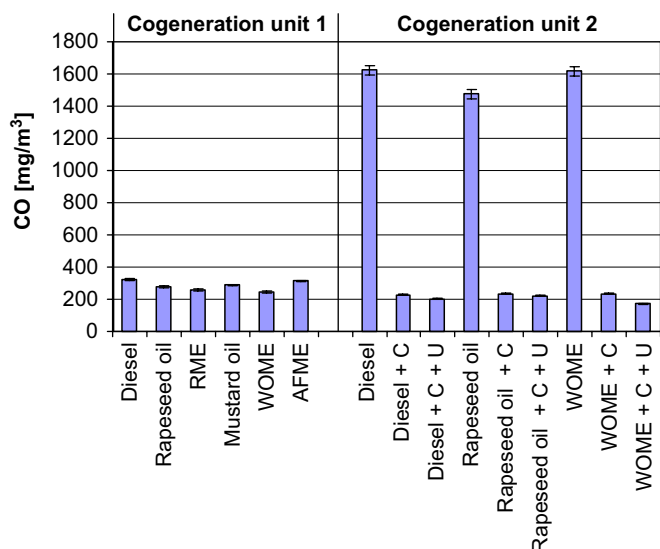


Fig. 6. Carbon monoxide emissions (CO) based on residual oxygen content of 5% by volume in the exhaust emissions (C: converter; U: urea).

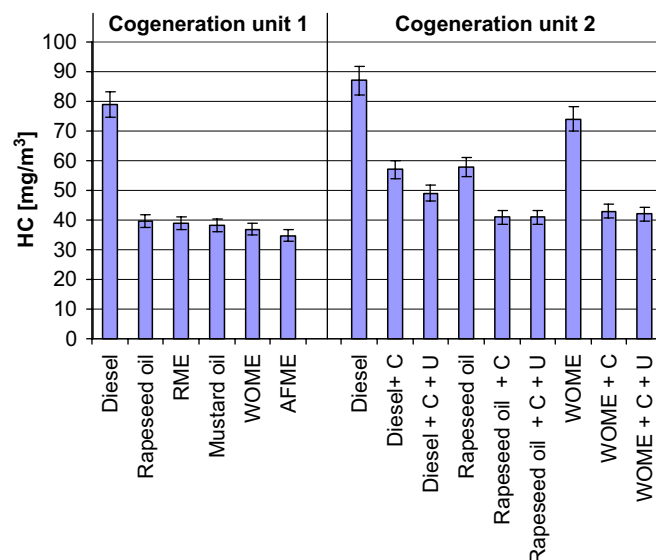


Fig. 7. Hydrocarbon emissions (HC) based on residual oxygen content of 5% by volume in exhaust emissions (C: converter; U: urea).

after the catalytic converter left. Without catalytic converter this setting appears in high CO levels (Fig. 6). However, this higher emission level allowed the amount of conversion taking place in the SCR catalytic converter to be measured. The rate of reduction was 84–86%, depending on the used fuel. Through the injection of urea, a further small improvement of the reduction rate was attained.

The hydrocarbon (HC) concentration functions well as a measure for the accuracy of injection, distribution and degree of combustion in a diesel engine. Both cogeneration units showed a typical increase in HC emissions (Fig. 7) of diesel fuel compared to fuels of agricultural origin (Schumacher, 1996; Graboski and McCormick, 1998; Dobiasch, 2000; Lachenmaier, 2002). In cogeneration unit 1, a more complete combustion and lower HC concentration was associated with all non-diesel fuels (Birkner, 1995). At cogeneration unit 2 the higher HC emissions of fuels combusted without installed catalytic converter shows also that the fuel injection was calibrated to reach a certain level of not complete combusted compounds for NO_x conversion. Here, it is even more apparent that the diesel engine was adapted for use with oils possessing a higher viscosity. The HC concentration was better in cogeneration unit 2 with rapeseed oil than with other fuels. The fuel-depending reduction rates of 29–42% by the catalytic converter were not significantly improved by the injection of urea.

5. Conclusion

The use of plant and waste oils as fuel is possible. Both engines (adapted to triglycerides or not) show a good performance regarding the exhaust gases. The catalytic conversion of NO_x and CO is possible with triglycerides as

with diesel. Regarding the emissions catalytic systems should be preferred. The injection of urea leads to a decrease of the emissions, but is not feasible in mobile engine systems (e.g. cars, HGV etc.).

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