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RESEARCH REPORT

# Local and Innovative Biodiesel

# Final Report
# FJ-BLT Wieselburg


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# Content

# ABSTRACT

The “LOCAL AND INNOVATIVE BIODIESEL”-project’s objective in general is to contribute to the Biofuels market share of 5,75 % by 2010 as indicated by the Biofuels Directive. Main aims of the INNOVATIVE part of the project are removing the barrier of feedstock shortage and feedstock costs through broadening the feedstock basis by demonstrating the suitability of a variety of oils and fats of vegetable and animal origin. Besides others, cost reduction of biodiesel production should be achieved. In the frame of the INNOVATIVE part of the project FJ-BLT has selected a number of oils and fats, produced and analyzed initial volumes of innovative biodiesel, carried out short term engines tests including emission measurements on a test bench with the lab scale biodiesel volumes, purchased feedstock of larger volumes for pilot production, produced innovative biodiesel in batches of 700 liter and carried out long term endurance test with these selected samples of innovative biodiesel. The respective report includes the results of feedstock selection and market analysis, lab scale and pilot scale production, lab analysis and engine tests. These results are summarized, conclusions are drawn.

# INTRODUCTION

The Biofuels Directive[1] set as "reference values" targets of a 2% market share for biofuels in 2005 and 5.75% in 2010. For the EU 25 the target would require 18.6 Mtoe of biofuels by 2010. If the energy policy objectives of the Union are to be met, much more bioenergy will have to be brought into the market than at present. Developing countries face similar and even greater challenges with respect to transport energy: rising oil prices are badly affecting their balance of payments; reliance on imported fossil fuels implies vulnerability and they too are faced with the challenge of reducing greenhouse gas emissions.

Nearly all the energy used in the EU transport sectors comes from oil. Securing energy supplies is therefore not only a question of reducing import dependency from crude oil producing countries but calls for a wide range of policy initiatives, including diversification of sources. The Commission has worked out an EU Strategy for Biofuels shown in the following picture.

The recent Biomass Action Plan has already described various actions that will be taken to encourage the use of all kinds of biomass for renewable energy production. This Communication now sets out **An EU Strategy for Biofuels** with three aims:

- to further promote biofuels in the EU and developing countries, ensure that their production and use is globally positive for the environment and that they contribute to the objectives of the Lisbon Strategy taking into account competitiveness considerations;
- to prepare for the large-scale use of biofuels by improving their cost-competitiveness through the optimised cultivation of dedicated feedstocks, research into "second generation" biofuels, and support for market penetration by scaling up demonstration projects and removing non-technical barriers;
- to explore the opportunities for developing countries – including those affected by the reform of the EU sugar regime – for the production of biofuel feedstocks and biofuels, and to set out the role the EU could play in supporting the development of sustainable biofuel production.

http://europa.eu.int/comm/agriculture/biomass/biofuel/com2006_34_en.pdf

The feedstock supply is crucial to the success of the biofuels strategy. Following the proposed strategy some of the provisions of the Common Agricultural Policy will be reviewed. The expected increase in the world trade of biofuels and biofuels feedstock could also contribute to stability of supply in the EU and other parts of the world. To derive the greatest benefits, the Commission is committed to encouraging the first-generation biofuels market.

Developing countries face similar and even greater challenges with respect to transport energy: rising oil prices are badly affecting their balance of payments; reliance on imported fossil fuels implies vulnerability and they too are faced with the challenge of reducing greenhouse gas emissions. Biomass productivity is highest in tropical environment. For biodiesel, the EU is currently the principle producer and there is now significant trade. Developing countries such as Malaysia, Indonesia and the Philippines, that currently produce biodiesel for their domestic market, could well develop export potential. Additionally plant oil producing countries could export oils and fats as feedstock for biodiesel production in Europe too. In general, the production of biodiesel and/ or biodiesel feedstock could

1 Directive 2003/30/EC of 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport (OJ L 123, 17.5.2003).

provide an opportunity to diversify agricultural activity, reduce dependence of oil and contribute to economic growth.

Among others the Commission will propose an amendment to the biodiesel standard EN 14 214 to facilitate the use of a wider range of vegetable oils for biodiesel production. The present EN 14214 was developed on the basis of rape-seed based biodiesel which was and is the predominant source of biodiesel in Europe. However, this resulted in certain restrictions that are not directly related to the fuel quality and make it difficult for other sources such as sunflower biodiesel and animal tallow biodiesel to meet the fuel quality specifications defined by the standard. According to a tender of DG TREN (No. TREN/D2-44/2005) the European biodiesel standard needs to be updated in relation to the iodine number which excludes pure biofuels from practically all seeds, as well as animal tallow and used cooking oils, except rape seed. This standard significantly limits the overall biodiesel potential; work should be done to widen the scope of the resource base for biodiesel production in the EU.

The iodine number is a measure of unsaturation within a mixture of fatty material. Whereas the American norm does not contain regulations on this parameter, iodine number is limited to ≤ 120 in Europe. Moreover, *EN 14214* also regulates the maximum content of linolenic acid methyl ester and polyunsaturated fatty acid methyl esters (i.e. compounds with four or more double bonds) to 12% and 1% respectively. These limits are not undisputed among biodiesel experts world-wide. Engine manufacturers have long argued that fuels with a higher iodine number tend to polymerize and form deposits on injector nozzles, piston rings and piston ring grooves, when they are heated. Moreover, unsaturated esters introduced into the engine oil are suspected of forming high-molecular compounds, which negatively affect the lubricating quality and can thus result in serious engine damage. However, the results of various engine tests indicate that polymerization reactions appear to a significant extent only in fatty acid esters containing three or more double bonds.

The behavior of fuels under low ambient temperatures is an important quality criterion in regions of temperate and arctic climates. Partial solidification in cold weather may cause blockages of fuel lines and filters, leading to fuel starvation and problems during engine start-up. Melting points of neat FAME depend on chain length and degree of unsaturation. Long-chain saturated fatty acid methyl esters display particularly unfavorable cold-temperature behavior whereas fatty acids with two and more double bonds show excellent cold flow properties. This means that high iodine number will result in favorable winter performance.

The “LOCAL AND INNOVATIVE BIODIESEL”-project’s objective is to contribute to the biofuels market share as indicated by the Biofuels Directive in general. Main aims of the INNOVATIV part of the project are:

1. Removing the barrier of feedstock shortage and feedstock cost through broadening the feedstock basis by demonstrating the suitability of a variety of oils and fats of vegetable and animal origin from INNOVATIVE BIODIESEL production.
2. Demonstrating the utilization of INNOVATIVE BIODIESEL at markets where biodiesel´s environmental benefits are needed most.

Besides others, guidelines for producing of “multi-feedstock” biodiesel should be worked out, cost reduction of biodiesel production should be achieved.

In the frame of the INNOVATIVE part of the project FJ BLT has carried out the following work:

- Selection of to be investigated oils and fats
- Identification of possible blend recipes

- Laboratory scale production of initial volumes of most interesting recipes
- Analysis of the laboratory scale samples
- Short term engines tests including emission measurements with a single cylinder diesel engine on a test bench with the lab scale biodiesel volumes
- Feedstock purchase of larger volumes for pilot production
- Production of INNOVATIVE BIODIESEL in batches of 700 liter
- Long term endurance test with selected samples.

The respective report includes the results of feedstock selection and market analysis, lab scale and pilot scale production and engine tests. Results are summarized and conclusions are drawn.

# SUMMARY AND CONCLUSIONS

Nearly all the energy used in the EU transport sectors comes from oil. Securing energy supplies therefore calls for a wide range of policy initiatives, including diversification of sources. Developing countries have similar challenges with respect to transport energy. The development of biofuel production is expected to offer new opportunities. The importance of the transport fuels sector shows the EU Strategy for Biofuels which was published by the Commission early in 2006. The feedstock supply is crucial to the success of the strategy. The expected increase in the world trade of biofuels and biofuels feedstock may contribute to a stable of supply of the biofuels sector worldwide.

The “LOCAL AND INNOVATIVE BIODIESEL”-project’s objective was to contribute to the Biofuels market share of 5,75 % by 2010 as indicated by the Biofuels Directive. Main aims of the INNOVATIVE part of the project are removing the barrier of feedstock shortage and feedstock costs through broadening the feedstock basis by demonstrating the suitability of a variety of oils and fats of vegetable and animal origin. In the frame of the INNOVATIVE part FJ-BLT has selected a number of oils and fats, produced and analyzed initial volumes of innovative biodiesel in the lab, carried out emission measurements on a single cylinder engine with the lab scale biodiesel volumes, produced innovative biodiesel in batches of 700 liter and carried out long term endurance test with selected samples.

Starting with a list of 24 different raw materials that were considered to be suitable for the production of biodiesel, 25 samples could actually be purchased and tested in the lab. They were furthermore used for emission tests. Five out of these 25 were additionally objected to engine endurance tests.

The conclusions from the market analysis performed are as follows:

- Rapeseed oil and soybean oil are the most common feedstock for FAME at the moment.
- Palm oil and Jatropha Curcas Oil are of increasing importance.
- Other tropical oil plants can be assumed to be suitable from an availability and price point of view. But their fatty acid profiles indicate that they will have poor cold flow properties, thus suitability for FAME production could be limited to the use as a blending component.
- New varieties are entering the market and may produce FAME with improved properties. Naturally, their availability right now is very low.
- Used frying oils are a cheap alternative source, but limited in their availability.
- Same is true for animal fats, which additionally are subject of import/export restrictions.

The lab scale volumes have been analyzed according the EN 14214:2003. These innovative biodiesel volumes cover a very broad range e. g. fatty acid profile and iodine Value from 12 to 189. Some of them are not fulfilling the limits of the mentioned standard. The investigations concerning the boiling line have shown that FAME with a high portion of very short fatty acid chains have a similar characteristic as fossil diesel. But this short fatty acid chains are also responsible for a relatively high oxygen content of the biofuel resulting in a decrease of the lower heating value.

With the 25 lab scale volumes emission tests have been carried out. Emissions of a single cylinder engine were measured with diesel fuel and 23 fatty acid methyl esters with iodine values between 12 and 189. A clear dependence could be found between iodine value and nitrogen oxide emission. Weak dependency was found between carbon monoxide while hydrocarbons are independent from the iodine value.

Endurance tests were carried out with seven different test fuels to find influences of the fuel on the long term performance. A single cylinder engine was operated 256 hours at varying load and speed with Diesel fuel, rapeseed oil methyl ester (RME), animal fat methyl ester, coconut oil methyl ester, and soy oil methyl ester, a blend of 30% jet fuel and 70% RME and Jatropha oil methyl ester.

Engine performance (power, consumption) was determined at the beginning and at the end of each test. A significant loss of power caused by decreased fuel injection volume and efficiency after 256 was observed with RME, animal fat and coconut oil ME.

Engine oil viscosity decreased with all fuels; with RME and animal fat ME viscosity dropped most while the other fuels have shown a slight increase towards the end of the test. Engine oil dilution with fuel was less than 1% in all cases. No significant differences were found in wear, contamination or additive content. Engine oil dispersancy was decreasing mainly with RME but also with animal fat, soy oil and Jatropha oil ME.

The engine parts were inspected carefully by the engine manufacturer. No remarkable differences were found in coke deposits on piston, piston rings grooves and gap clearance of piston rings. Neither significant difference no unusual wear marks were visible at cylinder liners. Most differences were found at the injectors: carbon built-ups at the sprayholes were higher with all biodiesel fuels than with fossil diesel, extreme cratering was found with coconut oil methyl ester and with the jet fuel-RME blend. The determination of the nozzle flow rate has shown a decrease with all fuels, highest change was found with RME and animal fat methyl ester. The spray formation was influenced by external coke deposits; an influence of carbon deposits inside the holes is supposed, but not verified yet.

Especially with RME and coconut oil methyl ester long term endurance overall results where surprisingly worse, RME results differ significantly to previous work in our institute and elsewhere. As engine inspection results were obtained at the end of the project we were not able to cross-check these unpleasant and suspect results in time. The difference may be caused by fuel quality, load cycle or the injection equipment itself; all these results will be reviewed carefully as soon as possible.

All in all differences between the investigated “innovative biodiesel” were considerable low, an “ideal” fatty acid profile could not be found. Low temperature flow properties are most important in countries with cold winters. For those fatty acids double bonds are unavoidable. The $NO_X$ emissions are significantly influenced by the proportion of double bonds, saturated fatty acid ester result in low $NO_X$ emissions; for the evaluation the $NO_X$-HC trade-off must be considered: favourable $NO_X$ emission are accompanied by increased hydrocarbon emissions. Fuel quality has been proved again as crucial factor for a sustainable market development. Especially for B100 the quality on the market will decide, an ambitious quality monitoring system is indispensable.

The project results show considerable opportunities for broadening the feedstock basis. Animal fats, new varieties of oil plants for moderate climates as well as oils and fats from developing countries can be used for biodiesel production. Thus clearly can lead to feedstock cost reduction. Future work should concentrate on fuel quality aspects as well as the influence of the degree of unsaturated fatty acid esters on the long term performance under real life conditions.

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## Local and Innovative Biodiesel

# Feedstock Selection and Market Analysis

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# Content

# 1 OBJECTIVES

The EU-funded project Local and Innovative Biodiesel aimed at broadening the feedstock basis for Biodiesel production (Innovative Activities) and implementing the collection of used cooking oil and its use for Biodiesel production (Local Activities). In order to broaden the feedstock basis, suitable oils needed to be identified. The objective of the feedstock selection and the market analysis was to identify feedstock that would be suitable for Biodiesel production in respect to its fatty acid content, and check the availability of such feedstock.

# 2 INTRODUCTION

Currently, the main feedstock for Biodiesel production in the EU is rapeseed oil. Other feedstock in use is used cooking oil and rendered fats, but their contribution is limited due to their limited availability. If the targets of the EU Biofuels Directive of 5.75% market share of biofuels in 2010 shall be met, the EU will be short in feedstock to support the necessary Biodiesel production. Thus, new feedstock needs to be considered and tested for its suitability for the production of Biodiesel and use of this Biodiesel in modern diesel engines.

# 3 FEEDSTOCK SELECTION

The use of Biodiesel as a transport fuel is regulated by the European Standard for fatty acid methyl ester (FAME), EN 14214. This standard includes 26 parameters; some of these are regulated in order to control the production process and ensure good conversion of the fatty acids into FAME. Other parameters depend on the feedstock used, e.g. the iodine value depends on the fatty acid profile of the utilized oil. As EN 14214 is very restrictive in its limits, some oil crops that would be suitable in regard of their fatty acid content are excluded from FAME production because they exceed these limits. Crucial parameters in this context are the iodine value, stability and the CFPP for wintertime.

Considerations of the possibility to produce FAME from a blend of different raw materials led to the conclusion that suitable feedstock was not obliged to meet EN 14214. Furthermore, FAME sold in European markets could be produced from imported raw materials, or even the FAME itself could be imported. Thus, the search for suitable feedstock was not limited to European climate, but extended to a worldwide search.

The feedstock that would be considered suitable on first sight was:

- Oil bearing plants (oil crops)
    - Top ten oil seeds (= those produced in the largest amounts worldwide)
    - Other oil crops, including non-food oil crops
    - New varieties
- Rendered fats
- Used oils

In Table 1 the first selection of feedstock is listed.

*Table 1: First Selection of Suitable Feedstock*

| **Oil Crops** | | | **Animal Fats and Used Oils** |
|---|---|---|---|
| **Top Ten Oil Seeds** | **Other Oil Crops** | **New Varieties** | |
| Soy bean | Camelina | HO[1] Sunflower | Tallow |
| Cotton seed | Hemp | HO[1] Rapeseed | Lard |
| Ground nut | Olive | LL[2] Rapeseed | Poultry fats |
| Sunflower | Jatropha | HEA[3] Rapeseed | Rendered fats |
| Rapeseed | Corn | | Used frying oil |
| Sesame | | | |
| Oil palm | | | |
| Coconut | | | |
| Linseed | | | |
| Castor | | | |

[1]high oleic
[2]low linoleic
[3]high erucic acid

These first considerations were succeeded by a market analysis.

# 4 MARKET ANALYSIS

The market analysis should assess the potential availability of the selected raw materials. In this context the project team was supported by the Vienna University of Economics and Business Administration (WU Wien); its department of technology and sustainable product management (ITNP) conducted two diploma theses under the guidance of E. Waginger, research assistant, and G. Vogel, head of department.

The first diploma thesis, conducted by Barbara Sigmund, assessed the market trends over the past 25 years of international trade of the Top Ten Oil Seeds. On the following page there is a summary of her work.

The second diploma thesis, conducted by Alexander Apl, assessed the potential of rendered fats in Austria and the EU. There is a summary of his work on the page next but one.

**Market Analysis of the Top Ten Oil Seeds / Summary of B. Sigmund´s Diploma Thesis [1]**

The Top Ten Oil Seeds are the ten oil seeds that are produced in the largest amounts worldwide. These include at least 5 potential raw materials for Biodiesel production: soy, sunflower, rapeseed, oil palm and coconut. But how much of these is produced currently, where is this done, how and why do the prices change, and what are the prospects for future development?

Generally, the worldwide production of oil seeds has increased continuously over the past 25 years, and is prospected to increase even further. Table 2 lists the figures for worldwide production and for the largest producer of each of these 5 oil seeds in 2000/01.

*Table 2: Production of important oil seeds*

| Oil Seeds [t] | World Production in 2000/01 | Largest Producer | Production of Largest Producer in 2000/01 |
|---|---|---|---|
| Soy | 175 477 000 t | USA | 75 055 000 t |
| Rapeseed | 37 463 000 t | China | 11 381 000 t |
| Sunflower | 23 038 000 t | Ex USSR | 7 882 000 t |
| Oil Palm | 7 768 000 t | Malaysia | 4 000 000 t |
| Coconut | 5 000 000 t | The Philippines | 2 150 000 t |

From these seeds oil and meal can be produced. Table 3 lists the average production of the most important oils and how much of these is currently exported.

*Table 3: Average production of important oils*

| Vegetable Oil [Mio. t] | Soy oil | Palm oil & palm kernel oil | Rapeseed oil & sunflower oil | Others |
|---|---|---|---|---|
| Average production in the years 2001 to 2005 | 29,56 | 28,36 | 25,17 | 20,13 |
| Exported amounts | 8,88 | 20,05 | 4,68 | 4,33 |
| % of all worldwide exports | 20 | 48 | 15 | 10 |

The figures above indicate that most of the soy oil, rapeseed oil and sunflower oil production is consumed in the producing countries. Only the palm oil and palm kernel oil is mainly exported and accounts for nearly half of all worldwide exports. Unfortunately, the oil palm cultivation in Malysia and Indonesia, who are the largest producers in this respect, is far away from sustainable production and often causes harm to indigenous people and the environment.

The EU-15 are the worlds largest importer of oil seeds, oils and oil meals. Which oil crops are cultivated within the EU mainly depends on subsidies. The prices of oil seeds within the EU are influenced by EU politics, the price of wheat and the price of soy on the global markets. Quite a number of trade pacts regulate the amounts traded of oil seeds, oils and oil meals, and influence their prices.

If the targets set by the European Directive (5.75% market share of biofuels in 2010) are to be achieved, domestically grown oil crops will not be sufficient to support the necessary Biodiesel production. International trade of biofuels and/or the biomass for their production will therefore be inevitable. The global markets will offer sufficient quantities of oil seeds and oils; but their sustainable production needs to be assured if the environmental benefits of biofuels are to be captured.

**Market Analysis for Rendered Fats / Summary of A. Apl´s Diploma Thesis [2]**

Up to the year 2000, rendered fats were used as animal feed, and the rendering industry gained profits with it. But due to the TSE crisis in 2000/2001, rendered fats are now classified into 3 different risk categories, and category I and II could no longer be fed to animals. Nevertheless, rendered fats continued (and still continue) to accumulate, and the rendering industry had to find new uses for this material.

Most rendering plants started burning it for their steam production, the rest was sold to the cement industry, where it was burnt as well. Large rendering plants, that were able to process risk material separate from no-risk material, could still use the rendered fats from the no-risk material for various purposes, including production of food for pets, production of fertilizer and selling it to the chemical industry. The German rendering company Saria started processing rendered fats into Biodiesel, which – although it would not fulfill the European standard EN 14214 in all parameters – fuelled Saria´s own truck fleet. Thus, rendered fats seem to be a suitable feedstock for Biodiesel production. (The BIODIEPRO project even approved that risk material would no longer be harmful when processed into Biodiesel and burnt in diesel engines.) But how much of this material is available?

As export of rendered fats from category 1 and 2 material is limited by restrictive regulations, markets are country-specific. In Austria there are 4 rendering plants, and two of these process the risk material together with the no-risk material; thus all rendered fats produced are categorized as I or II and can hardly be exported. The other two rendering plants belong together, and they process the risk material in one of their facilities, and the no-risk material in the other. The rendered fats produced from no-risk material (approximately 10.000 t in 2004) can be traded easily and achieve suitable prices. The rest of approximately 15.000 t in 2004 for entire Austria is burnt for steam production either in the rendering facility itself or in the cement industry. Table 4 lists the amounts and the categories of rendered fats in Austria for the year 2004.

*Table 4: Amounts of rendered fats produced in Austria in 2004*

| Name of rendering facility | Location of rendering facility | Amount of rendered fat produced in 2004 [t] | Category |
|---|---|---|---|
| SARIA Bio Industries GmbH | Tulln | 5.000 | I |
| Steir. Tierköperverwertung GmbH | Gabersdorf | 10.000 | III |
| Bgl. Tierkörperverwertung GmbH | Unterfrauenhaid | 3.000 | I |
| Tierkörperverwertungsanstalt Regau GmbH | Regau | 7.000 | I |
| | **Total** | **25.000** | |

As there is no regulated market for rendered fats Category I and II, prices are agreed on individually, and thus vary very much (about 40 to 150 €/t for risk material). Prices for no-risk material in Austria in 2005 (according to A. Apl´s own investigation) were at about 230 to 270 €/t. This is only half the price of rapeseed oil (according to UFOP about 550 to 650 €/t in Germany). All the material could be processed into Biodiesel in existing multi-feedstock Biodiesel production facilities in Austria. If this were done, the Biodiesel from animal fats could substitute 0.44% of the annual Austrian diesel consumption (of year 2003). As the life cycle analysis for Biodiesel from rendered fats is better than for RME, the use of rendered fats as additional feedstock for Biodiesel production is an economic and ecologic alternative.

All other selected raw materials were analyzed for their availability and price by the project team as follows:

- As olive oil and corn oil are used as quality oils in human nutrition, farmers will achieve much higher prices when selling them to the food industry as when selling them to Biodiesel producers. Therefore their availability at adequate prices will be very low.
- Camelina, hemp and jatropha should be available at moderate prices, quantities could be increased by increasing demand.
- The new varieties are of course currently available in small amounts only; however, if they proof suitability to this or any other use, their cultivation could be increased.
- The availability of tallow, lard and poultry fats is included in the diploma thesis on rendered fats.
- There is sufficient literature data on the availability of used frying oil in Austria. The potential in other EU countries is assessed in the local activities of this project. However, the contribution to the total necessary Biodiesel production is small and limited by the use of virgin oil for cooking. But, if collected regionally, it is a low cost option and can contribute to the economic feasibility of Biodiesel production plants.

# 5 SAMPLE PURCHASE

Olive oil and corn oil were deleted from the list of selected feedstock due to their high price, same as were cotton seed, ground nut and sesame. Castor was deleted from the list because its viscosity is too high for use in diesel engines.

The others on the list were purchased with help from ABI. However, not all oil crops on the list were available; others, like jatropha, were very difficult to obtain; and some oils samples broke during shipment. In return, some additional oil samples could be purchased, that were not on the list initially:

- 4 new soy bean varietiesacrocomia nutmilk thistle

Table 5 lists all received oil or FAME samples, with indication of supplier.

The received oil samples (10 to 20 l samples) were processed into FAME in the BLT lab. All FAME samples were then analyzed in the lab. Please find more information in the section “FAME Production and Lab Analysis”.

*Table 5: All oil samples received for lab testing*

| FAME | Labornr: | Company | Country/ZIPCode/City |
|---|---|---|---|
| **Rapeseed oil** | **04-255** | BLT, blend of various rapeseed oils | AT 3250 Wieselburg |
| **Lard** | **04-398** | Moser GmbH | AT 3250 Wieselburg |
| **Camelina oil** | **04-280** | BLT, own production | AT 3250 Wieselburg |
| **Palm fruit oil** | **04-148** | Deutsch-Parag. Industrie- u. Handelskammer | Paraquay |
| **Sunflower oil Raffinat** | **04-257** | Vereinigte Fettwarenindustrie GmbH | AT 4600 Wels |
| **HEA Rapeseed oil** | **04-350** | Frontier Agriculture Ltd | UK WC1B4JA London |
| **HO Sunflower oil** | **04-405** | Pioneer Saaten GmbH | AT 7111 Parndorf |
| **Animal fat-ME** | **05-107** | SARIA Bioindustries GmbH | D 17139 Malchin |
| **Rapeseed-soybean oil app. 50:50** | **05-098** | Vereinigte Fettwarenindustrie GmbH | AT 4600 Wels |
| **Palm fat** | **05-100** | Vereinigte Fettwarenindustrie GmbH | AT 4600 Wels |
| **Linseed oil** | **04-226** | Waldland Vermarktungs GesmbH | AT 3533 Friedersbach |
| **Milk thistle oil** | **04-227** | Waldland Vermarktungs GesmbH | AT 3533 Friedersbach |
| **Coconut fat** | **05-099** | Vereinigte Fettwarenindustrie GmbH | AT 4600 Wels |
| **Soybean oil** | **05-309** | Vereinigte Fettwarenindustrie GmbH | AT 4600 Wels |
| **Rapeseed oil (Raffinat Express 03)** | **05-324** | Deutsche Saatveredlung AG | D 33154 Salzkotten/Thüle |
| **Rapeseed oil (Raffinat HO_2)** | **05-325** | Deutsche Saatveredlung AG | D 33154 Salzkotten/Thüle |
| **Used frying oil (thin)** | **04-278** | Fa. Baier | AT 3300 Amstetten |
| **Used frying oil (thick)** | **04-279** | Fa. Baier | AT 3300 Amstetten |
| **Rapeseed oil** | **05-012** | BLT, RÖ aus 1998 | AT 3250 Wieselburg |
| **Canola oil** | **05-415** | DOW Agrosciences LLC | Canada, Calgary, Alberta T2E7P1 |
| **Soybean oil regular** | **05-556** | American Soybean Association | D 21149 Hamburg |
| **Soybean oil LowLin** | **05-557** | American Soybean Association | D 21149 Hamburg |
| **Soybean oil MidOleic** | **05-558** | American Soybean Association | D 21149 Hamburg |
| **Soybean oil HighOleic** | **05-559** | American Soybean Association | D 21149 Hamburg |
| **Jatropha oil-ME** | **05-728** | CSMCRI | India, Bhavnagar, Gujarat |
| **RME&Jet Fuel (70:30 %m/m)** | **05-571/05-481** | Aiport Gneixendorf | AT 3500 Gneixendorf |
| **Pongamia oil (container leaked)** | **05-490** | Nandan Biomatrix Ltd | India 500016 Hyderabad |
| **Neem oil (container leaked and empty)** | **05-491** | Nandan Biomatrix Ltd | India 500016 Hyderabad |
| **Aleurites moluccana (drying oil, 3 l)** | **05-489** | Nandan Biomatrix Ltd | India 500016 Hyderabad |
| **Jatropha oil** | **05-482** | Nandan Biomatrix Ltd | India 500016 Hyderabad |

# 6 TEST FUEL SELECTION

Besides measurements of EN 14214 parameters for all FAME samples, some were selected as test fuels for engine endurance tests. The selection was based on the following criteria:

- Availability of the oil
- Price of the oil
- Fatty acid profile
- Cold flow properties

Due to time restrictions not more than 7 endurance tests with different test fuels could be run.
Of these 7, two needed to be reference fuels: standard fossil diesel and reference rapeseed oil methyl ester (RME). The remaining 5 were selected according to the above criteria as shown in table 6:

*Table 6: Selection of test fuels*

| | |
|---|---|
| high availability | soybean oil |
| | jatropha oil |
| low price | animal fat |
| unique fatty acid profile | coconut oil |
| good cold flow properties | blend of RME and jet fuel |

Soybean oil is the main feedstock for Biodiesel production in the USA, and it ranges among the ten most traded oil crops. Jatropha oil is not yet available in large quantities, but will gain importance in the future, as there are governmental programs for the cultivation of jatropha in India and Egypt.

Animal fat was chosen as a low price option, and because its FAME was expected to cause more difficulties in the engine than FAME of used frying oil.

Tropical palm fruit contain oil with a high content of short fatty acid chains. (For fatty acid profiles please check the section “FAME Production and Lab Analysis”.) Of the three tested oils (oil palm, acrocomia nut and coconut), the coconut oil was easiest to purchase, and thus was selected for the endurance test.

The composition of the RME/jet fuel blend was chosen according to CFPP measurements of various blends, as listed in table 7; the chosen ratio of 70:30 fulfills the EN 14214 requirement for wintertime Biodiesel (CFPP < -20°C).

*Table 7: CFPP of blends of RME and jet fuel*

| RME-content [%] | Jet fuel-content [%] | CFPP [°C] |
|---:|---:|---:|
| | | |
| 100 | 0 | -14 |
| 95 | 5 | -15 |
| 90 | 10 | -16 |
| 85 | 15 | -17 |
| **70** | **30** | **-22** |
| 40 | 60 | -27 |
| 0 | 100 | <-38 |

The chosen oils were either purchased in about 500l quantities (soybean oil, coconut oil) and transesterified in the BLT Biodiesel pilot plant, or purchased as FAME (animal fat ME, jatropha ME, RME). The reference fossil diesel fuel was purchased via OMV, and the jet fuel at the airport Gneixendorf.


*Figure 1: Test fuels selected for engine endurance tests*

In table 8 the selected test fuels are listed with their lab numbers and abbreviations used for their identification.

*Table 8: Test fuels overview*

| No. | Test fuels | Abbreviation | Lab number |
|---|---|---|---|
| VK1 | Diesel fuel | Diesel | 05-185 |
| VK2 | Rapeseed oil methyl ester | RME | 05-187 |
| VK3 | Animal fat methyl ester | TFME | 05-107 |
| VK4 | Coconut oil methyl ester | KOME | 05-308 |
| VK5 | Soy oil methyl ester | SOME | 05-314 |
| VK6 | Blend of:<br>30% jet fuel<br>70 % rapeseed oil methyl ester | KERM | 05-666 |
| VK7 | Jatropha oil methyl ester | JAME | 05-728 |

# 7 SUMMARY/CONCLUSIONS

Starting with a list of 24 different raw materials that were considered to be suitable for the production of Biodiesel, 25 samples could actually be purchased and tested in the lab. They were furthermore used for emission tests. 5 out of these 25 were additionally objected to engine endurance tests. Please find results of lab and engine tests in the sections “FAME Production and Lab Analysis” and “Engine Tests”.

The conclusions from the market analysis performed are as follows:

- Rapeseed oil and soybean oil are the most common feedstock for FAME production at the moment.
- Palm oil and jatropha oil are of increasing interest.
- Other tropical oil plants can be assumed to be suitable from an availability and price point of view. But their fatty acid profiles indicate that they will have poor cold flow properties, thus suitability for FAME production could be limited to the use as a blending component.
- New varieties are entering the market and may produce FAME with improved properties. Naturally, their availability right now is very low.
- Used frying oils are a cheap alternative source, but limited in their availability.
- Same is true for animal fats, which additionally are subject of import/export restrictions due to TSE.

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## Local and innovative Biodiesel

# FAME Production and Lab Analysis

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# CONTENT




*Samples of raw materials and FAME*

# 1 OBJECTIVES

The choice of raw materials is based on several discussions within the project partners and on extensive literature research. On the one hand the most important vegetable oils and fats for Europe should be tested on the other hand some exotic raw materials should be investigated within the project too.

As the reference Fatty Acid Methyl Ester (FAME) rapeseed oil methyl ester (RME) can be considered. This is the most important raw material in the European Union countries used for the FAME production. The leading countries are Germany and France but a lot of other countries are forcing the FAME-production for reaching the goals of the EU biofuels directive 2003/30. [1]

# 2 MATERIALS AND METHODS

In table 1 the raw materials which have been transesterified in the BLT´s laboratory are listed. The most common vegetable oils are rape oil, sunflower oil and soy bean oil in the temperate climate and for the tropical an suptropical regions palm oil and coconut fat.

*Table 1: Considered raw materials*

| Num. | Latin name of the oil crop | English name | Country |
|---|---|---|---|
| 1 | Brassica napus | Rape seed | Austria |
| 2 | Brassica napus | High erucic acid rape seed oil | United Kingdom |
| 3 | ---- | Lard | Austria |
| 4 | Camelina sativa | False flax, gold of pleasure | Austria |
| 5 | Acrocomia totai nut | Palm fruit | Paraquay |
| 6 | Helianthus annuus | Sunflower | Austria |
| 7 | Helianthus annuus | High Oleic sunflower | Austria |
| 8 | ---- | Animal fat ME | Germany |
| 9 | Elaeis guineensis | Oil palm | ??; packed in Austria |
| 10 | Linum usitatissimum | Linseed | Austria |
| 11 | Silybum marianum | Holy thistle | Austria |
| 12 | Cocos nucifera | Coconut fat | ??; packed in Austria |
| 13 | Glycine max | Soy bean (regular) | Austria, USA |
| 14 | Glycine max | Soy bean (Low Lin) | USA |
| 15 | Glycine max | Soy bean (Mid Oleic) | USA |
| 16 | Glycine max | Soy bean (High Oleic) | USA |
| 17 | ---- | Used frying oil “bottom fraction” | Austria |
| 18 | ---- | Used frying oil “top fraction” | Austria |
| 19 | Jatropha curcas | Physic nut | India |

Furthermore there was a very intensive exchange and discussion with research institutes and plant breeding companies all over the world. Several oil samples have been delivered, especially vegetable with a changed fatty acid profile and their changed physical properties are of interest for this project. The physic nut is an oil crop which is considered as FAME raw material in India and Egypt. It stands hot and dry conditions and the gained vegetable oil can not be used for nutrition. Last but not least there are three FAME samples prepared from secondary raw materials: animal fat and used frying oil.

The collected raw materials have been transesterified in the BLT´s lab. The production process has been developed by the own staff. It is based on a surplus of methanol and with potassium hydroxide as catalyst. After the two stage transesterification at approx. 60°C the surplus of methanol is distilled of. At the end the FAME is washed and dried under vacuum.

In figure 1 the lab transesterification plant is shown. The vessel is made of glass and has a brutto volume of 10 litres, can be heated with electricity and is equipped with a mechanical stirrer.

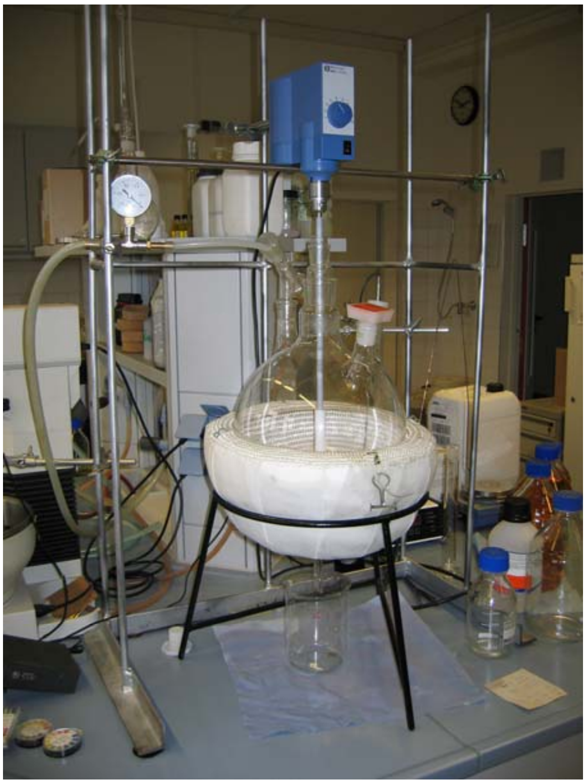

*Figure 1: BLT´s lab transesterification plant*

In the BLT´s Lab and at IMU most of the parameters of the European Biodiesel Standard have been analysed. Some of these parameters are just an indication for the quality of the transesterification process. These values are just reported but not intensely discussed in this report. The used analysis methods are listed in the FAME standard EN 14214: 2003.[2]

# 3 RESULTS

The fatty acid distribution has been determined with the gas chromatograph HP 6890 with a Flame ionisation detector. In table 2 the fatty acid profiles of the analysed FAME are listed. The investigated FAME cover a range of the Iodine Value from 12 till 189. The calculation of the Iodine Value has been done according to the AOCS method Cd 1c-85 [3] respectively Annex B of the EN 14214. The fatty acid profile has a big influence on the cold temperature behaviour of the biofuels which is described by the cold filter plugging point (CFPP).

*Table 2: Fatty Acid Profile, Iodine Value (IV) and Cold filter plugging point (CFPP) and Specific Density of the analysed FAME*

| FAME | Labornr: | C 8:0 | C 10:0 | C 12:0 | C 14:0 | C 16:0 | C 18:0 | C 20:0 | C 22:0 | C 24:0 | C 18:1 | C 22:1 | C 18:2 | C 18:3 | Total [%] | Iodine Value [g $I_2$/100g] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Coconutfat-ME | 05-308 | 7,0% | 5,7% | 42,4% | 18,1% | 11,3% | 4,2% | 0,0% | 0,0% | 0,0% | 8,7% | 0,0% | 2,5% | 0,0% | 100,0% | 12 |
| Palm fruit oil-ME | 04-358 | 5,4% | 4,5% | 38,2% | 8,8% | 8,2% | 3,3% | 0,0% | 0,0% | 0,0% | 27,9% | 0,0% | 3,6% | 0,0% | 100,0% | 30 |
| Palm oil-ME | 05-141 | 0,0% | 0,0% | 0,0% | 1,3% | 44,7% | 5,4% | 0,5% | 0,0% | 0,0% | 37,2% | 0,0% | 10,8% | 0,0% | 100,0% | 51 |
| Lard-ME | 04-319 | 0,0% | 0,0% | 0,4% | 2,3% | 29,6% | 20,0% | 0,0% | 0,0% | 0,0% | 33,2% | 0,0% | 13,1% | 1,5% | 100,0% | 55 |
| Animal fat-ME | 05-107 | 0,0% | 0,0% | 0,0% | 2,3% | 29,8% | 17,1% | 0,0% | 0,0% | 0,0% | 37,7% | 0,0% | 11,5% | 1,7% | 100,0% | 57 |
| HO Sunfloweroil-ME | 05-102 | 0,0% | 0,0% | 0,0% | 0,0% | 5,2% | 4,2% | 0,0% | 2,0% | 0,0% | 78,7% | 0,0% | 10,0% | 0,0% | 100,0% | 85 |
| Soybeanoil-ME (HighOleic soy) | 05-710 | 0,0% | 0,0% | 0,0% | 0,0% | 5,4% | 4,1% | 0,0% | 0,0% | 0,0% | 81,3% | 0,0% | 3,8% | 5,3% | 100,0% | 90 |
| Jatrophoil-ME | 05-728 | 0,0% | 0,0% | 0,0% | 0,0% | 17,7% | 7,9% | 0,0% | 0,0% | 0,0% | 37,8% | 0,0% | 36,6% | 0,0% | 100,0% | 96 |
| Used frying oil-ME thick | 05-344 | 0,0% | 0,0% | 0,0% | 0,0% | 16,5% | 5,9% | 0,9% | 1,2% | 0,0% | 40,9% | 0,0% | 26,8% | 7,9% | 100,0% | 102 |
| Canolaoil-ME | 05-693 | 0,0% | 0,0% | 0,0% | 0,0% | 5,6% | 2,4% | 1,0% | 0,8% | 0,0% | 63,6% | 0,0% | 23,4% | 3,2% | 100,0% | 104 |
| Used frying oil-ME thin | 05-339 | 0,0% | 0,0% | 0,0% | 0,0% | 14,3% | 5,0% | 1,0% | 1,2% | 0,0% | 41,6% | 0,8% | 27,4% | 8,8% | 100,0% | 107 |
| Soybeanoil-ME (MidOleic soy) | 05-709 | 0,0% | 0,0% | 0,0% | 0,0% | 11,1% | 5,0% | 0,6% | 0,9% | 0,0% | 43,7% | 0,0% | 35,5% | 3,1% | 100,0% | 107 |
| Rapeoil-ME (Raff HO_2) | 05-333 | 0,0% | 0,0% | 0,0% | 0,0% | 6,0% | 2,4% | 0,9% | 0,0% | 0,0% | 59,3% | 0,0% | 28,6% | 2,7% | 100,0% | 108 |
| Milk thistle-ME | 05-178 | 0,0% | 0,0% | 0,0% | 0,0% | 10,0% | 6,2% | 4,1% | 3,9% | 1,2% | 22,7% | 0,0% | 50,7% | 1,2% | 100,0% | 110 |
| Rapeoil-ME (Raffinat Express_03) | 05-330 | 0,0% | 0,0% | 0,0% | 0,0% | 6,9% | 2,5% | 1,0% | 0,8% | 0,0% | 58,0% | 0,0% | 20,9% | 9,8% | 100,0% | 112 |
| HEARapeoil-ME | 05-093 | 0,0% | 0,0% | 0,0% | 0,0% | 4,3% | 1,2% | 0,9% | 1,0% | 0,0% | 14,0% | 47,2% | 15,5% | 15,8% | 100,0% | 114 |
| Rapeoil-ME | 04-260 | 0,0% | 0,0% | 0,0% | 0,0% | 6,3% | 2,3% | 0,9% | 0,0% | 0,0% | 57,9% | 0,0% | 22,2% | 10,4% | 100,0% | 115 |
| Rapeoil-ME | 05-348 | 0,0% | 0,0% | 0,0% | 0,0% | 5,7% | 2,3% | 0,9% | 0,7% | 0,0% | 57,1% | 0,0% | 22,7% | 10,5% | 100,0% | 116 |
| Soybeanoil-ME (LowLin soy) | 05-701 | 0,0% | 0,0% | 0,0% | 0,0% | 12,1% | 6,1% | 0,5% | 0,7% | 0,0% | 24,2% | 0,0% | 54,9% | 1,5% | 100,0% | 120 |
| Sunfloweroil-ME (Raffinat) | 05-078 | 0,0% | 0,0% | 0,0% | 0,0% | 8,0% | 4,7% | 0,0% | 1,2% | 0,0% | 28,9% | 0,0% | 56,5% | 0,7% | 100,0% | 125 |
| Soybeanoil-ME | 05-314 | 0,0% | 0,0% | 0,0% | 0,0% | 13,0% | 4,9% | 0,5% | 0,8% | 0,0% | 23,9% | 0,0% | 49,6% | 7,3% | 100,0% | 125 |
| Rape-Soybeanoil-ME (ca. 50:50) | 05-108 | 0,0% | 0,0% | 0,0% | 0,0% | 12,3% | 5,6% | 0,0% | 0,7% | 0,0% | 22,1% | 0,0% | 52,1% | 7,3% | 100,0% | 128 |
| Soybeanoil-ME (Regular soy) | 05-700 | 0,0% | 0,0% | 0,0% | 0,0% | 12,5% | 5,2% | 0,0% | 0,0% | 0,0% | 22,3% | 0,0% | 50,2% | 9,8% | 100,0% | 132 |
| Camelinaöl-ME | 04-321 | 0,0% | 0,0% | 0,0% | 0,0% | 6,7% | 3,0% | 2,3% | 0,7% | 0,0% | 14,3% | 6,5% | 18,2% | 48,4% | 100,0% | 175 |
| Linseedoil-ME | 05-166 | 0,0% | 0,0% | 0,0% | 0,0% | 6,1% | 4,6% | 0,0% | 0,0% | 0,0% | 17,5% | 0,0% | 15,9% | 55,9% | 100,0% | 189 |
| Mean value | | 0,5% | 0,4% | 3,2% | 1,3% | 12,4% | 5,4% | 0,6% | 0,7% | 0,0% | 38,2% | 2,2% | 26,5% | 8,5% | | 103 |
| Minimum | | 0,0% | 0,0% | 0,0% | 0,0% | 4,3% | 1,2% | 0,0% | 0,0% | 0,0% | 8,7% | 0,0% | 2,5% | 0,0% | | 12 |
| Maximum | | 7,0% | 5,7% | 42,4% | 18,1% | 44,7% | 20,0% | 4,1% | 3,9% | 1,2% | 81,3% | 47,2% | 56,5% | 55,9% | | 189 |

The most two or three important FAME of every biofuel have been highlighted. There are two samples which have the lauric acid ME (C 12:0) as main FAME. Animal fats and the palm oil ME have one of their main peaks with the palmitic acid ME (C 16:0) which seems to increase the CFPP very much as well as the fatty acid profile of the milk thistle (see table 5).

## 3.1 Distillation curve

The distillation curve of the fossil diesel is seen as ideal for Diesel engines. The distillation curve is one of the mentioned parameters in the European standard EN 590:2004 Automotive fuels – Diesel – Requirements and test methods [4]. This parameter (RME) has been investigated for rapeoil methyl ester in former projects and differs very much from that of the fossil diesel. [5] The distillation of diesel starts at approx. 100°C and goes up to 360°C steadily; the distillation for RME starts not before 300°C.

The distillation curves of 25 different fuel samples have been analysed. The distillations have been carried according to EN ISO 3405: 2000 Petroleum products – Distillation characteristics at atmospheric pressure [6].

In figure 3 the distillation curves of diesel and FAMEs are shown. Two of the analysed FAME have a similar distillation behaviour as diesel. These are the coconut fat ME and the palm fruit oil ME, two FAME with a high amount of short fatty acid chains especially the lauric acid. The arithmetic mean of 22 different FAMEs is the red coloured line – starting at approx. 180°C and increasing rapidly over 320°C.

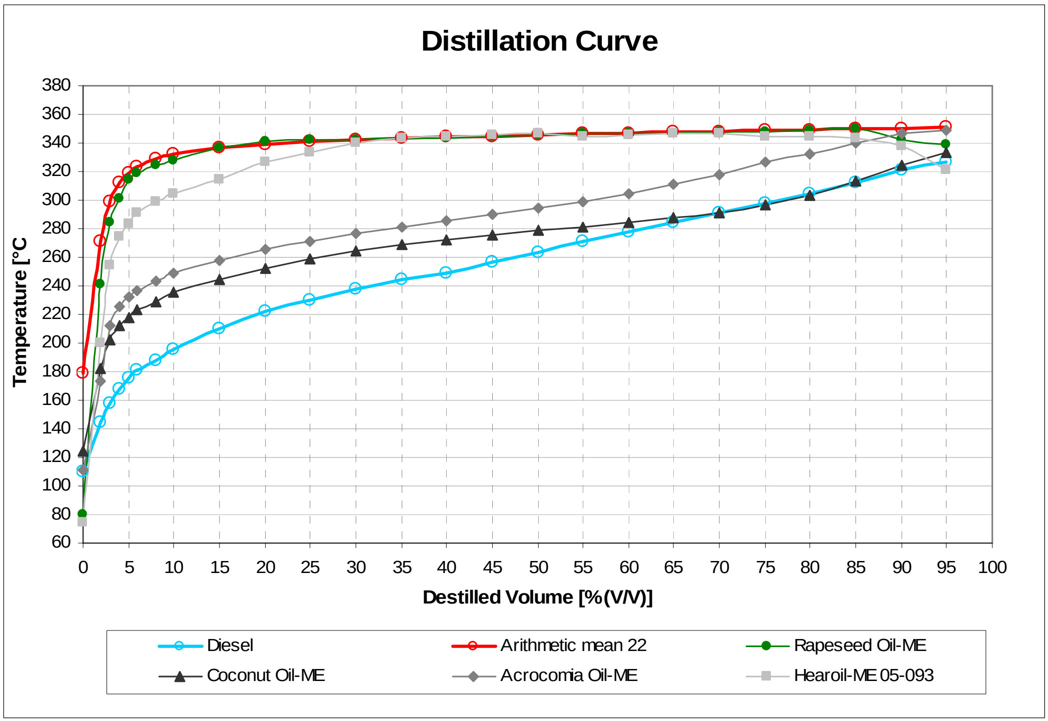


*Figure 3: Distillation curves of Diesel and FAME*

As the coconut fat ME has the most similar behaviour as diesel special optimisation trials have been carried out. As one example the mixture of coconut fat ME (50 %) with HO-sunfloweroil ME (50 %) is shown in Figure 4. The weak point is that the net calorific value is lowered through the high amount of short fatty acid chains.

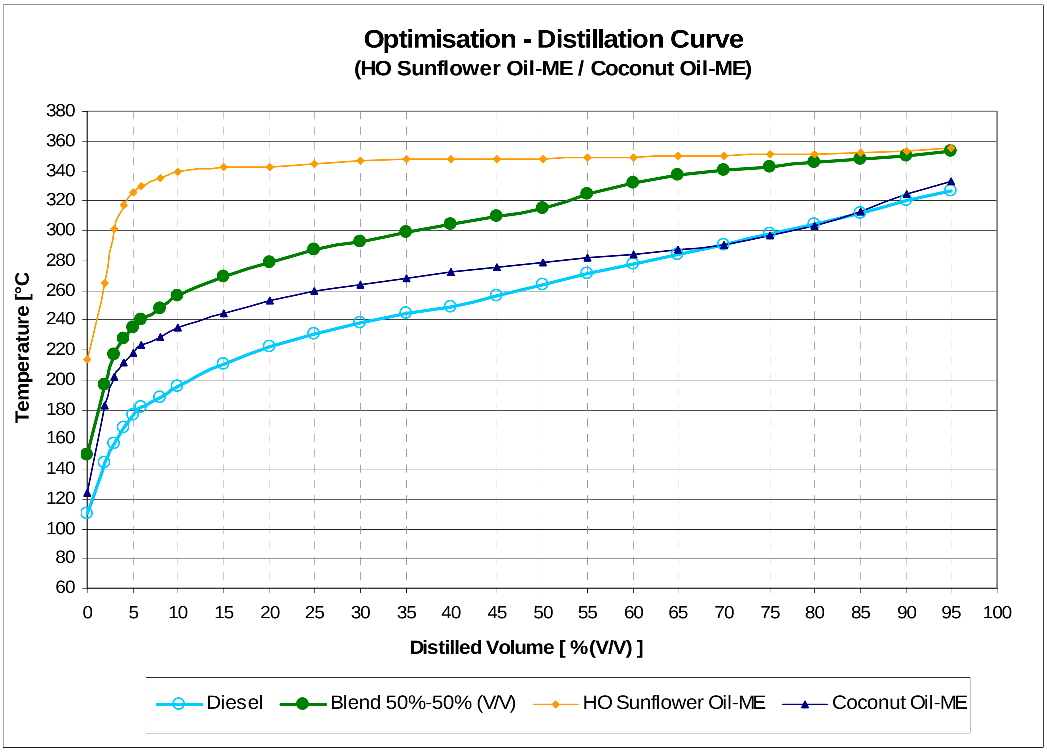


*Figure 4: Distillation curve optimisation (HO Sunfloweroil-ME/ Coconut fat-ME)*

The specific considerations and results in detail are published as diploma thesis of Bachler Kerstin [7]. In table 3 the boiling points of the pure FAME at 1013 mbar are listed. The main source for these data was the Beilstein databank. Some others have been calculated.

*Table 3: Boiling points of the pure FAME at 1013 mbar*

| Fatty acid methyl esters | | Boiling Point: [°C] |
|---|---|---|
| **C 8:0** | **Octanoic acid methyl ester** | 192 |
| **C 10:0** | **Decanoic acid methyl ester** | 229 |
| **C 12:0** | **Dodecanoic acid methyl ester** | 256 |
| **C 14:0** | **Tetradecanoic acid methyl ester** | 301 |
| **C 16:0** | **Hexadecanoic acid methyl ester** | 332 |
| **C 18:0** | **Octadecanoic acid methyl ester** | 359 |
| **C 20:0** | **Eicosanoic acid methyl ester** | 369 |
| **C 22:0** | **Docosanoic acid methyl ester** | 393 |
| **C 24:0** | **Tetracosanoic acid methyl ester** | 420 |
| **C 18:1** | **Octadec-9-enoic acid methyl ester** | 346 |
| **C 22:1** | **Docos-13c-enoic acid methyl ester** | 393 |
| **C 18:2** | **Octadeca-9,12-dienoic acid methyl ester** | 346 |
| **C 18:3** | **Octadeca-9,12,15-trienoic acid methyl ester** | 347 |

*Table 4: Results of different parameters (BLT)*

**Analysen BLT:**

| FAME | | Density at 15°C [kg/m³] | Flashpoint [°C] | Neutralisation-number [mg KOH/g] | Watercontent $H_2O$ [mg/kg] | Viscosity (40°) V40 [mm²/s] | Oxidationstability [h] | Total contamination [mg/kg] | Free Glycerol [%] |
|---|---|---|---|---|---|---|---|---|---|
| | | EN ISO 12185 | ÖNORM C 1122 | prEN 14104 | EN ISO 12937 | EN ISO 3104 | prEN 14112 | EN 12662 | |
| | | EN ISO 3675 | prEN ISO 3679 | prEN 14104 | EN ISO 12937 | EN ISO 3104 | prEN 14112 | DIN 51419 | |
| | | EN ISO 12185 | | | | | | | |
| **Limits** | | min. 860 max. 900 | min. 120 | max.0,5 | max.500 | min.3,5 max.5,0 | min. 6 | max. 24 | max 0,02 |
| | **Labornr:** | | | | | | | | |
| **Rapeoil-ME** | **04-260** | 884,7 | 194 | 0,83 | 800 | 4,80 | | 8,6 | <0,01 |
| **Lard-ME** | **04-319** | 875,9 | 182 | 1,05 | 660 | 4,54 | | 15,2 | <0,01 |
| **Camelinaoil-ME** | **04-321** | 888,8 | 183 | 1,88 | 450 | 4,38 | | 6,4 | <0,01 |
| **Palm fruitoil-ME** | **04-358** | 877,6 | 113 | 0,42 | 530 | 3,18 | | | <0,01 |
| **Sunfloweroil-ME Raffinat** | **05-078** | 885,3 | 184 | 1,63 | 85 | 4,24 | | 28,6 | <0,01 |
| **HEARapeoil-ME** | **05-093** | 880,2 | 192 | 1,94 | 250 | 5,73 | | 26,7 | <0,01 |
| **HO Sunfloweroil-ME** | **05-102** | 878,7 | 184 | 1,66 | 70 | 4,74 | | 14,3 | <0,01 |
| **Animal fat-ME** | **05-107** | 875,7 | 169 | 0,23 | 120 | 4,50 | 12,5 | 10,3 | <0,01 |
| **Rape-Soybeanoil-ME ca. 5** | **05-108** | 885,5 | 185 | 1,39 | 140 | 4,14 | | 46,1 | <0,01 |
| **Palmfat-ME** | **05-141** | 875,7 | 174 | 1,22 | 80 | 4,53 | | 61,9 | <0,01 |
| **Linseedoil-ME** | **05-166** | 894,0 | 179 | 1,60 | 130 | 3,73 | | 6,9 | <0,01 |
| **Milk thistle oil-ME** | **05-178** | 884,0 | 178 | 1,15 | 180 | 4,88 | 3,03? | 99,6 | <0,01 |
| **Coconutfat-ME** | **05-308** | 874,9 | 103 | 0,48 | 500 | 2,75 | 2,9 | 47,8 | 0,01 |
| **Soybeanoil-ME** | **05-314** | 885,9 | 185 | 3,85 | 500 | 4,28 | 0,6 | 44,7 | <0,01 |
| **Rapeoil-ME (Raffinat Express 0** | **05-330** | 884,6 | 177 | 1,08 | 370 | 4,57 | 4,5 | 20,8 | <0,01 |
| **Rapeoil-ME (Raffinat Express** | **05-333** | 882,9 | 180 | 1,13 | 110 | 4,58 | 5,6 | 19,5 | <0,01 |
| **Used frying oil-ME (thin)** | **05-339** | 886,8 | 170 | 1,09 | 110 | 4,85 | 0,6 | 6,4 | <0,01 |
| **Used frying oil-ME (thick)** | **05-344** | 885,6 | 172 | 0,50 | 110 | 4,85 | 1,1 | 12,7 | <0,01 |
| **Rapeoil-ME** | **05-348** | 884,3 | 177 | 1,97 | 150 | 4,55 | 1,2 | 18,5 | <0,01 |
| **CanolaOil-ME** | **05-693** | 880,3 | 185 | 0,95 | 170 | 4,66 | 7,2 | 6,1 | <0,01 |
| **Soybeanoil-ME regular** | **05-700** | 884,7 | 181 | 0,73 | 140 | 4,09 | 2,2 | 3,5 | <0,01 |
| **Soybeanoil-ME LowLin** | **05-701** | 884,0 | 180 | 0,67 | 420 | 4,14 | 5,1 | 4,4 | 0,01 |
| **Soybeanoil-ME MidOleic** | **05-709** | 892,7 | 173 | 0,61 | 160 | 4,35 | 7,4 | 9,3 | <0,01 |
| **Soybeanoil-ME HighOleic** | **05-710** | 880,2 | 185 | 0,61 | 210 | 4,63 | 35,5 | 0,7 | <0,01 |
| **JatrophaOil-ME** | **05-728** | 878,7 | 182 | 0,27 | 730 | 4,31 | 3,0 | 13,8 | 0,01 |
| **Mean Value** | | 882,9 | 175 | 1,2 | 287 | 4,40 | 6,4 | 22,2 | 0,01 |
| **Minimum** | | 874,9 | 103 | 0,2 | 70 | 2,75 | 0,0 | 0,7 | 0,00 |
| **Maximum** | | 894,0 | 194 | 3,9 | 800 | 5,73 | 35,5 | 99,6 | 0,01 |

*Table 5: Results of different parameters (IMU)*

**Analysen IMU:**

| FAME | | CCR | Monoglyceride | Diglyceride | Triglyceride | K & Na | Ca & Mg | P-Content | CFPP |
|---|---|---|---|---|---|---|---|---|---|
| | | [% m/m] | [% m/m] | [% m/m] | [% m/m] | [mg/kg] | [mg/kg] | [mg/kg] | [°C] |
| | | EN 10370 | EN 14105 | EN 14105 | EN 14105 | EN 14109 | EN14538 | ASTM D 3231 | EN 116 |
| | | max. 0,3 | max. 0,8 | max. 0,2 | max. 0,2 | max. 5 | max. 5 | max. 10 | < 0 |
| | **Labornr:** | | | | | | | | |
| **Rapeoil-ME** | **04-260** | 0,22 | 0,812 | 0,775 | 1,387 | < 5 | < 5 | < 0,2 | -10 |
| **Lard-ME** | **04-319** | < 0,01 | 0,372 | < 0,096 | < 0,096 | < 5 | < 5 | 0,6 | 8 |
| **Camelinaoil-ME** | **04-321** | 0,06 | 0,309 | < 0,096 | < 0,096 | < 5 | < 5 | 2,4 | -5 |
| **Palm fruitoil-ME** | **04-358** | 0,09 | 0,262 | 0,598 | 0,169 | < 5 | < 5 | 15,0 | -12 |
| **Sunfloweroil-ME Raffinat** | **05-078** | 0,07 | 0,434 | < 0,095 | < 0,095 | < 5 | < 5 | < 0,2 | -3 |
| **HEARapeoil-ME** | **05-093** | 0,07 | 0,469 | < 0,092 | < 0,092 | 6,5 | < 5 | 3,3 | -13 |
| **HO Sunfloweroil-ME** | **05-102** | 0,04 | 0,417 | < 0,097 | < 0,097 | < 5 | < 5 | < 0,2 | 2 |
| **Animal fat-ME** | **05-107** | 0,03 | < 0,097 | < 0,097 | < 0,097 | < 5 | < 5 | < 0,2 | 7 |
| **Rape-Soybeanoil-ME ca. 50:50** | **05-108** | 0,09 | 0,393 | < 0,09 | < 0,09 | < 5 | < 5 | 0,4 | -5 |
| **Palmfat-ME** | **05-141** | 0,06 | 0,409 | 0,103 | < 0,099 | < 5 | < 5 | 0,2 | 11 |
| **Linseedoil-ME** | **05-166** | 0,18 | 0,461 | < 0,098 | < 0,098 | < 5 | < 5 | < 0,2 | -9 |
| **Milk thistle oil-ME** | **05-178** | 0,28 | 0,401 | < 0,091 | < 0,091 | 29,9 | < 5 | 43,0 | 10 |
| **Coconutfat-ME** | **05-308** | 0,02 | 0,168 | < 0,092 | < 0,092 | < 5 | < 5 | 2,9 | -9 |
| **Soybeanoil-ME** | **05-314** | 0,12 | 0,552 | < 0,093 | < 0,093 | < 5 | < 5 | 0,5 | -5 |
| **Rapeoil-ME (Raffinat Express 03)** | **05-330** | 0,11 | 0,396 | < 0,095 | < 0,095 | < 5 | < 5 | < 0,2 | -13 |
| **Rapeoil-ME (Raffinat Express 03)** | **05-333** | 0,08 | 0,432 | < 0,089 | < 0,089 | < 5 | < 5 | 0,4 | -13 |
| **Used frying oil-ME (thin)** | **05-339** | 0,31 | 0,393 | < 0,093 | < 0,093 | < 5 | < 5 | 1,3 | -3 |
| **Used frying oil-ME (thick)** | **05-344** | 0,26 | 0,457 | < 0,096 | < 0,096 | <5 | < 5 | 1,1 | -2 |
| **Rapeoil-ME** | **05-348** | 0,19 | 0,414 | < 0,094 | < 0,094 | <5 | 12,1 | 1,5 | -12 |
| **CanolaOil-ME** | **05-693** | 0,28 | 0,344 | < 0,095 | < 0,095 | <5 | <5 | 1,0 | -16 |
| **Soybeanoil-ME regular** | **05-700** | 0,29 | 0,373 | < 0,095 | < 0,095 | 16,7 | 21,7 | 2,2 | -7 |
| **Soybeanoil-ME LowLin** | **05-701** | 0,24 | 0,408 | < 0,096 | < 0,096 | 14,7 | <5 | 0,4 | -5 |
| **Soybeanoil-ME MidOleic** | **05-709** | 0,16 | 0,407 | < 0,093 | < 0,093 | 9,2 | <5 | 0,8 | -7 |
| **Soybeanoil-ME HighOleic** | **05-710** | 0,08 | 0,482 | < 0,096 | < 0,096 | <5 | <5 | 0,3 | -10 |
| **JatrophaOil-ME** | **05-728** | 0,15 | 0,183 | < 0,098 | < 0,098 | <5 | <5 | 0,5 | -3 |
| **RME&Kerosin (70:30 %m/m)** | **05-666** | 0,09 | < 0,097 | < 0,097 | < 0,097 | <5 | <5 | <0,2 | -23 |
| **Mean value** | | 0,14 | | | | | | | -6 |
| **Minimum** | | 0,00 | 0,00 | 0,00 | 0,00 | 0 | 0 | 0,0 | -23 |
| **Maximum** | | 0,31 | 0,81 | 0,78 | 1,39 | 30 | 22 | 43,0 | 11 |

# 4 SUMMARY AND CONCLUSIONS

From 25 different raw materials FAME have been produced on lab scale. These biofuels have been analysed according the EN 14214:2003. The FAME cover a very broad range e. g. Fatty acid profile and Iodine Value from 12 to 189. Some of them are not fulfilling the limits of the mentioned standard.

The investigations concerning the distillation curve have shown that FAME with a high portion of very short fatty acid chains have a similar characteristic as fossil diesel. But this short fatty acid chains are also responsible for a relatively high Oxygen content of the biofuel resulting in a decrease of the lower heating value.

Few selected raw materials have been transesterfied in the pilot production plant for getting enough biofuel for long duration tests with a single cylinder engine on the test bench. With the FAME where only small amounts have been available only emission tests at two specific loads have been carried out.

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## Local and innovative Biodiesel

# Engine Tests

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# CONTENT

# 1 OBJECTIVES

Endurance tests with an engine on the test bench are an important step in showing the suitability of Biodiesel test fuels. Thus, main objectives of the investigations were to find effects of the fuel composition on the engine performance during a long term test. Different fuel parameters might have an influence on carbon residue, injection system, engine oil and emission of the test engine. Correlations should be found between analytical data and engine test results.

# 2 MATERIALS AND METHODS

## 2.1 Test engine

The test engine is one of the SUPRA series of the HATZ company. It is an air cooled single cylinder 4-stroke direct injection diesel engine with a crankshaft and cylinder head of light alloy and a multi hole nozzle. The engine is used for minor problems with drive in mobile applications. This small engine was selected because of the low fuel consumption of less than 2 l/h and the robust long engine life. The engine is shown in Figure 1.

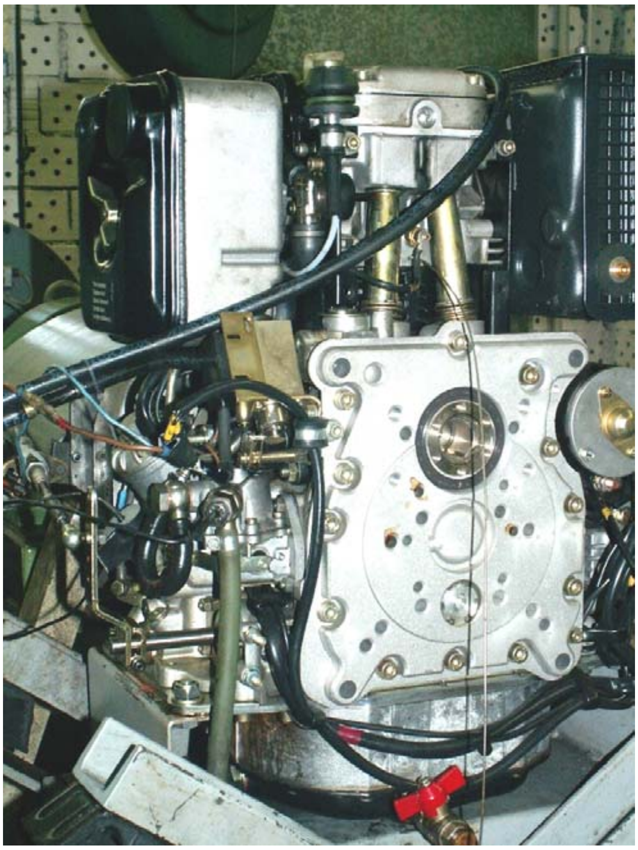

*Figure 1: Test engine*

The power output of the engine is 5.6 kW at 3000 rev/min operated by fossil diesel fuel. Because of the lower calorific value of Biodiesel the power is reduced approx. by 12 %. Main data of the engine are shown in Table 1. It was the aim to operate the engine during 250 hours without adding engine oil. Thus, a bigger oil sump of 3.5 litres was applied.

*Table 1: Data of the test engine (Source: HATZ)*

| | | |
|---|---|---|
| Type | | HATZ 1D41 Z, 4-stroke |
| Number | | 094 20 04 061793 |
| Injection | | direct |
| Cylinder | | 1 |
| Bore x Stroke | mm | 90 x 65 |
| Capacity | mm | 413 |
| Average piston speed at 3000 rev/min | m/s | 6.5 |
| Compression ratio | | 21:1 |
| Engine oil consumption at rated power | | max. 1% of fuel consumption. |
| Engine oil volume (bigger oil sump) | l | ~ 3.5 |
| Difference max/min | l | ~ 2.5 |
| Drain oil interval | h | 250 |
| Lower engine speed | rev/min | ~ 900 |
| Rated engine speed | rev/min | 3000 |
| Power at rated speed | kW | 5.6 |
| Specific fuel consumption at rated speed | g/kWh | 270 |

## 2.2 Engine oil

For all tests the engine oil 'OMV eco truck extra SAE 10W-40' was used. OMV eco truck extra SAE 10W-40 is a synthetic based low friction oil for mixed fleet operation and for extended oil drain intervals applied to commercial vehicles. The engine oil combines the advantages of high performance passenger car motor oil with those from super-high-performance diesel motor oil for extended oil drain intervals. It is motor oil for high performance diesel and gasoline engines including turbo-charged engines. It is ideal for mixed fleet operation and for all season operating. Engine oil properties are shown in Table 2.

*Table 2: Engine oil properties (Source: OMV)*

| Property | Unit | OMV eco truck extra SAE 10W-40 |
|---|---|---|
| Density/15°C | $Kg/m^3$ | 872 |
| Flash point COC | °C | 223 |
| Viscosity class | SAE | 10W-40 |
| Viscosity/40°C | $mm^2/s$ | 93 |
| Viscosity/100°C | $mm^2/s$ | 14.0 |
| Viscosity index | --- | 155 |
| CCS/-25°C | mPa.s | 6350 |
| Pour point | °C | <–36 |

## 2.3 Engine test bench

The test bench, an eddy current brake type 1 WB 115, is used for high speed engines up to 15 kW rated power. The water cooled brake has a low moment of inertia and is connected with the test engine by an elastic torque shaft. Speed and torque is controlled by the control unit (see Figure 2 and Table 3).

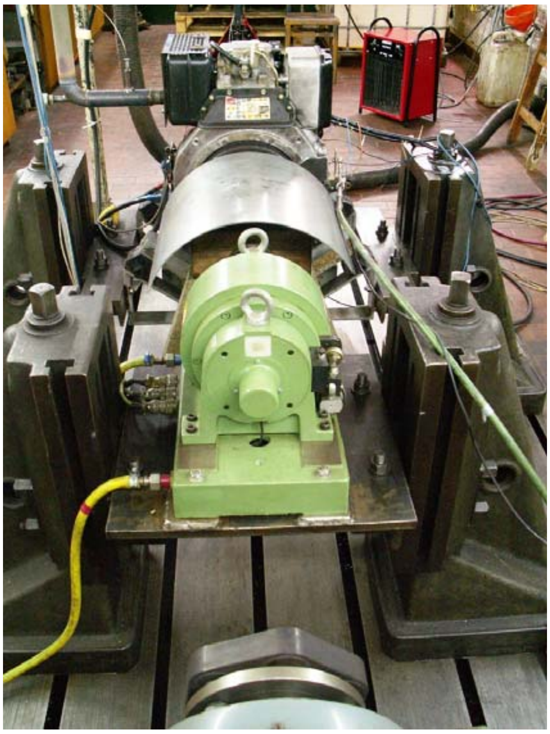

*Figure 2: Engine on the test bench*

*Figure 3: Test bench control unit*

*Table 3: Eddy current brake*

| Type | | Vibro-meter 1 WB 115 |
|---|---|---|
| Rated torque /at speed | Nm | 50 Nm / 2865 rev/min |
| Rated power / at speed | kW | 15 kW / 2865 rev/min |
| Precision of the measuring system | % | ≤ 0.5 % of the rated torque |

The test bench control unit (Figure 3) includes a data logging system which can be used to register all necessary parameters during the whole endurance test.

The following parameters were registered automatically every minute:
- speed
- torque
- air intake temperature
- engine oil temperature
- exhaust gas temperature
- cylinder head temperature
- fuel filter temperature
- ambient temperature

The fuel consumption was measured daily by weighing the fuel tank.

## 2.4 Temperature control

To improve the comparability between the different endurance tests during the year a control unit for ambient temperature was installed. A heating system (7.5 / 15 kW) was used to keep the room temperature at a rather high level of 32 – 33 °C. Thus, temperature deviations caused by the season as well as by varying load points of the engine could be compensated.


*Figure 4: Heating system for temperature control*

## 2.5 Endurance tests

### 2.5.1 Test fuels

Due to time restrictions a maximum of 7 endurance tests could be carried out. Fossil diesel fuel and rape seed oil methyl ester were chosen as reference fuels. The selection of the remaining test fuels was based on the following criteria:

- Availability of the oil
- Price of the oil
- Fatty acid profile
- Cold flow properties.

Details are included in section "Feedstock Selection and Market Analysis". Finally, animal fat methyl ester, coconut methyl ester, soy oil methyl ester, a blend of rape seed oil methyl ester and jet fuel and jatropha oil methyl ester were chosen. An overview is shown in the following Table 4.

*Table 4: Test fuels overview*

| No. | Test fuels | Abbreviation | Lab number |
|---|---|---|---|
| VK1 | Diesel fuel | Diesel | 05-185 |
| VK2 | Rapeseed oil methyl ester | RME | 05-187 |
| VK3 | Animal fat methyl ester | TFME | 05-107 |
| VK4 | Coconut oil methyl ester | KOME | 05-308 |
| VK5 | Soya oil methyl ester | SOME | 05-314 |
| VK6 | Blend of:<br>30% jet fuel A-1<br>70 % rapeseed oil methyl ester | KERM | 05-666 |
| VK7 | Jatropha oil methyl ester | JAME | 05-728 |

For the first test a CEC-reference diesel fuel was used according to Directive 2002/80/EC. KERM is a blend of 70% RME and 30% of a jet fuel. Jet A-1 is an aviation fuel according AFQRJOS, issue 20 (March 2005) with a freezing point of < -47°C. Further description of the fuels sources see "Feed Stock Selection and Market Analyses". The fatty acid profile is shown in Table 5. Analyses data are included in Table 6.


*Figure 5: Test fuels for the endurance tests*

*Table 5: Fatty acid profile of the test fuels (Source: FJ-BLT Wieselburg) [%mass]*

| | RME | TFME | KOME | SOME | KERM [1)] | JAME |
|---|---|---|---|---|---|---|
| | rapeseed oil methyl ester | animal fat methyl ester | coconut oil methyl ester | soy oil methyl ester | 30% jet fuel + 70 % RME | jatropha oil methyl ester |
| Lab no. | 05-571 | 05-107 | 05-308 | 05-314 | 06-666 | 05-728 |
| C 8:0 | - | - | 7.0 | - | - | - |
| C 10:0 | - | - | 5.7 | - | - | - |
| C 12:0 | - | - | 42.4 | - | - | - |
| C 14:0 | - | 2.3 | 18.1 | - | - | - |
| C 16:0 | 6.2 | 29.8 | 11.3 | 13.0 | 6.2 | 17.7 |
| C 18:0 | 2.2 | 17.1 | 4.2 | 4.9 | 2.2 | 7.9 |
| C 20:0 | 0.9 | - | - | 0.5 | 0.9 | - |
| C 22:0 | - | - | - | 0.8 | - | - |
| C 24:0 | - | - | - | - | - | - |
| C 18:1 | 55.5 | 37.7 | 8.7 | 23.9 | 55.5 | 37.8 |
| C 22:1 | - | - | - | - | - | - |
| C 18:2 | 22.6 | 11.5 | 2.5 | 49.6 | 22.6 | 36.6 |
| C 18:3 | 12.6 | 1.7 | - | 7.3 | 12.6 | - |
| Total | 100 | 100 | 100 | 100 | 100 | 100 |

1) Fatty acid profile is identical with RME.

*Figure 6: Fatty acid profile of the test fuels (Source: FJ-BLT Wieselburg)*

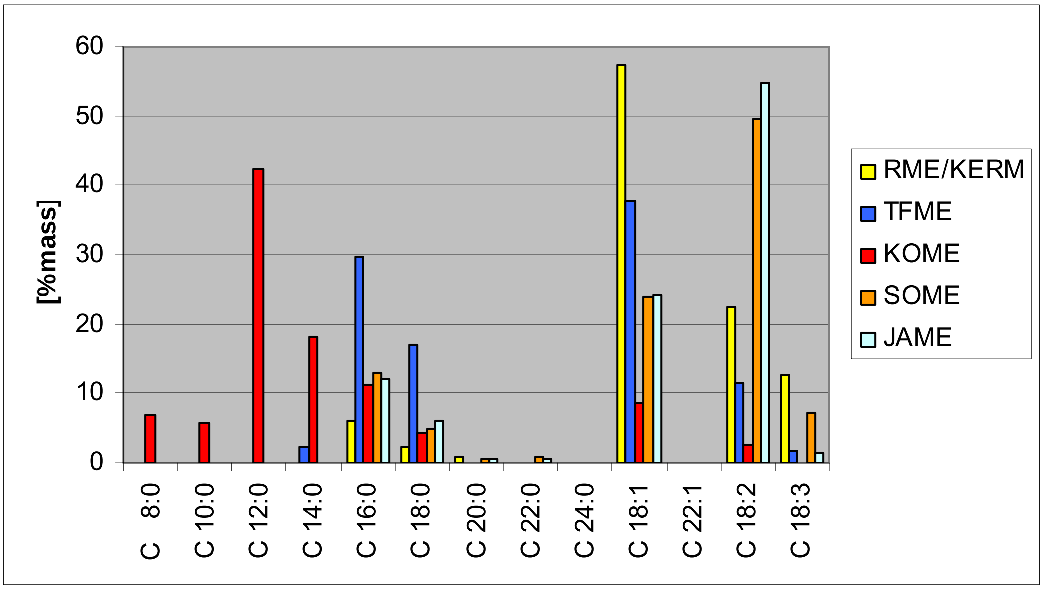


*Table 6: Test fuel analysis*

| Parameter | Unit | Method | Diesel | RME | TFME | KOME | SOME | KERM | JAME |
|---|---|---|---|---|---|---|---|---|---|
| Lab-N0. | | | 05-185 | 04-260 | 05-107 | 05-308 | 05-314 | 05-666 | 05-728 |
| Density at 15°C | g/cm3 | EN ISO 12185 | 0.8356 | 0.8865 | 0.8757 | 0.8749 | 0.8859 | 0.8578 | 0.8787 |
| Viscosity at 40°C | mm2 /s | EN ISO 3104 | 3.1 | 4.8 | 4.5 | 2.75 | 4.28 | | 4.31 |
| CFPP | °C | EN 116 | -19 | -10 | 7 | -9 | -5 | -23 | -3 |
| Flash point | °C | ON C 1122 | 82 | 194 | 169 | 103 | 185 | 60 | 182 |
| Sulfur content | mg/kg | EN ISO 20846 | 9 | - | - | - | - | 43.5 | 2.5 |
| Carbon residue (10% dist.resid.) | % mass | EN ISO 10370 | 0.04 | 0.22 | 0.03 | 0.02 | 0.12 | 0.09 | 0.15 |
| Cetane Number | - | EN ISO 5165 | 57 | 59.4 | 62.7 | 58.8 | 57 | 59.3 | 59.9 |
| Sulfated ash | % | ISO 3987 | | | | | | 0.001 | 0.001 |
| Water content | mg/kg | EN ISO 12937 | 60 | 800 | 120 | 500 | 500 | 390 | 730 |
| Total contamination | mg/kg | EN 12662 | 4.5 | 8.58 | 10.33 | 47.78 | 44.68 | 4.5 | 13.8 |
| Oxidat. stability, 110°C | h | EN 14112 | - | 2.6 | 12.5 | 2.9 | 0.6 | 2.7 | 3.0 |
| Acid value | mgKOH/g | EN 14104 | 0.04 | 0.10 | 0.23 | 0.48 | 3.85 | 0.07 | 0.27 |
| Iodine value | g iodine/ 100g | EN 14111 | - | 116 | 57 | 12 | 125 | 81 *) | 96 |
| Monoglyc.cont. | % (m/m) | EN 14105 | - | 0.812 | < 0.1 | 0.168 | 0.552 | < 0.1 | 0.183 |
| Diglyceride cont. | % (m/m) | EN 14105 | - | 0.775 | < 0.1 | < 0.1 | < 0.1 | < 0.1 | < 0.1 |
| Triglyceride cont. | % (m/m) | EN 14105 | - | 1.387 | < 0.1 | < 0.1 | < 0.1 | < 0.1 | < 0.1 |
| Free glycerol | % (m/m) | EN 14105 | - | < 0.01 | < 0.01 | < 0.01 | < 0.01 | | < 0.01 |
| Group I metals (Na + K) | mg/kg | EN 14108 EN 14109 | - | < 5 | < 5 | < 5 | < 5 | < 5 | < 5 |
| Group II metals (Ca + Mg) | mg/kg | prEN 14538 | - | <5 | <5 | < 5 | < 5 | < 5 | < 5 |
| Phosphorus content | mg/kg | EN 14107 | - | <0.2 | <0.2 | 2.9 | 0.5 | < 0.2 | 0.5 |
| Calorific value | MJ/kg | | 43.07 | 37.27 | 37.07 | 35.56 | 37.09 | 39.12 | 37.14 |

*) ...........calculated

Sources: Diesel: OMV, FJ-BLT
Biodiesel: FJ-BLT, IMU

### 2.5.2 Test steps

In Table 7 the steps of the test program performed with each fuel are described. A full motor service is done at the beginning. The piston, cylinder, nozzle and the engine oil are changed. A new oil- and fuel filter are fitted. A pre-run of the engine with diesel fuel follows during 48 hours. After the pre-run the full load characteristic is determined with diesel fuel and with the test fuel (step 4). The actual long term run with the test fuel begins after changing the engine oil, the oil filter and the fuel filter. During the long term run 6 oil samples are taken for analyses. At the end of the long term run (256 hours) a full load characteristic is repeated with the test fuel.

*Table 7: The steps of a long term run*

| Step | Work to do |
|---|---|
| 1 | Motor service: new piston, cylinder, nozzle |
| 2 | Filling in of engine oil |
| 3 | Pre- run with diesel fuel for 48 hours:<br>1 h at 2000 rev/min, 10% load<br>47 h at 2950 rev/min, 90% load |
| 4 | Full load characteristic with diesel fuel and test fuel |
| 5 | Change of the engine oil, oil filter and fuel filter |
| 6 | Long term run with test fuel:<br>16 days, 16 hours per day = 256 hours |
| 7 | Oil samples at 0, 48, 96, 144, 192 and 256 operating hours |
| 8 | Full load characteristic with the test fuel |

### 2.5.3 Load cycles

To mimic realistic operation conditions varying speed and load was applied during an operation day. The load cycle was chosen according to ISO 8178-4:1996.

*Table 8 : Load cycle G1 und G2 corresponding EN ISO 8178-4*[1]

| | Step | Speed [rev/min] | Load [%] | Run time [min] | Start at |
|---|---|---|---|---|---|
| G2 | 1 | 3000 | 100 | 45 | 06:00 |
| | 2 | 3000 | 75 | 90 | 06:45 |
| | 3 | 3000 | 50 | 135 | 08:15 |
| | 4 | 3000 | 25 | 150 | 10:30 |
| | 5 | 3000 | 10 | 30 | 13:00 |
| | 6 | 1000 | 0 | 30 | 13:30 |
| G1 | 7 | 2500 | 100 | 45 | 14:00 |
| | 8 | 2500 | 75 | 90 | 14:45 |
| | 9 | 2500 | 50 | 135 | 16:15 |
| | 10 | 2500 | 25 | 150 | 18:30 |
| | 11 | 2500 | 10 | 60 | 21:00 |

[1] ÖNORM EN ISO 8178-4:1996: Hubkolben-Verbrennungsmotoren - Abgasmessung. Teil 4: Prüfzyklen für verschiedene Motorverwendungen (1. Dezember 1996).

For this type of test engines the cycles 'G1' and 'G2' can be used. For the long-term tests a load cycle of 16 hours a day was chosen, 8 hours for each cycle. The time for each test point was calculated on the basis of the rating factors of ISO 8178. In Table 8 and Figure 7 the test cycle of one day is shown.

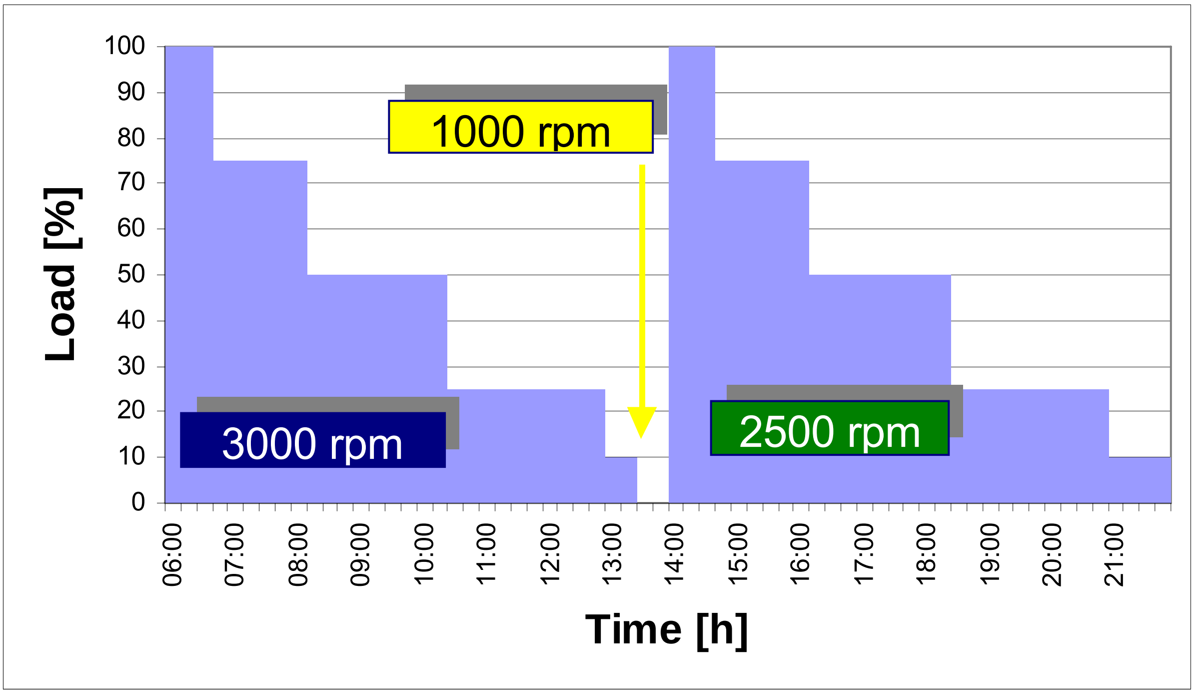


*Figure 7: Load cycle of the test engine on a test day*

### 2.5.4 Engine components inspection

After each endurance test a full engine service was done: the engine was dismantled and piston, cylinder and nozzle were changed. The spare parts were inspected immediately and images were taken. The final inspection of the engine was done by the engine manufacturer. The following inspections and measurements were carried out:

- Piston: Inspection, coke deposits at crown, inside first and second ring groove, gudgeon pin
- Piston rings: gap clearance, related sealing surface
- Cylinder: Inspection for overheat marks, polished spots, honing grooves. Roughness value
- Injector: nozzle opening pressure, spray behaviour, nozzle flow rate, assessment of spray pattern with high speed camera.

## 2.6 Emission measurements

### 2.6.1 Test fuels

Concerning the emission measurements not only the 7 test fuels of the endurance tests were used but also further samples which were produced and analysed in the laboratory during the project. For a total number of 24 fuels a minimum amount of 2 litres was available to be included in the emission testing programme. Table 9 shows an overview of the fuels including density, calorific value and iodine value. The fuels are described in detail including all analysis data in part „FAME Production and Lab Analysis“ of the report.

*Table 9: Overview of the test fuels for emission measurements*

| No. | Fuel | Lab. no. | Density | Calorific value | Iodine value |
|---|---|---|---|---|---|
| | | | kg/l | MJ/kg | g iodine / 100g |
| 1 | VK2 – RME – Rapeseed oil methyl ester | 05-187 | 0.8865 | 37.27 | 116 |
| 2 | VK3 – TFME – Animal fat methyl ester | 05-107 | 0.8757 | 37.07 | 57 |
| 3 | VK1 – Diesel | 05-185 | 0.8356 | 43.07 | 0 |
| 4 | VK4 – KOME – Coconut oil ethyl ester | 05-308 | 0.8749 | 35.56 | 12 |
| 5 | VK5 – SOME – Soy oil methyl ester | 05-314 | 0.8859 | 37.09 | 125 |
| 6 | VK6 – KERM – Blend of 30% jet fuel and 70 % rape seed oil methyl ester | 05-666 | 0.8574 | 39.12 | 81 |
| 7 | VK7 – JAME – Jatropha oil methyl ester | 05-728 | 0.8787 | 37.14 | 96 |
| 8 | Lard methyl ester | 04-319 | 0.8759 | 37.10 | 55 |
| 9 | Camelina oil methyl ester | 04-321 | 0.8888 | 37.34 | 175 |
| 10 | Sunflower oil methyl ester (refined) | 05-078 | 0.8853 | 37.14 | 125 |
| 11 | Rapeseed - soy oil methyl ester (ca. 50:50) | 05-108 | 0.8855 | 37.16 | 128 |
| 12 | Linseed oil ethyl ester | 05-166 | 0.8940 | 37.07 | 189 |
| 13 | Milk thistle oil methyl ester | 05-178 | 0.8840 | 37.05 | 110 |
| 14 | Rapeseed oil methyl ester (refined express 03) | 05-330 | 0.8846 | 37.00 | 112 |
| 15 | Rapeseed oil methyl ester (refined HO_2) | 05-333 | 0.8829 | 37.01 | 108 |
| 16 | Used frying oil methyl ester (low viscosity) | 05-339 | 0.8868 | 36.99 | 107 |
| 17 | Used frying oil methyl ester (high viscosity) | 05-344 | 0.8856 | 36.99 | 102 |
| 18 | Rapeseed oil methyl ester | 05-348 | 0.8843 | 36.97 | 116 |
| 19 | Canola oil methyl ester | 05-693 | 0.8803 | 37.04 | 104 |
| 20 | Soy oil methyl ester (regular) | 05-700 | 0.8847 | 36.86 | 132 |
| 21 | Soy oil methyl ester (low Lin) | 05-701 | 0.8840 | 36.93 | 120 |
| 22 | Soy oil methyl ester (mild oleic) | 05-709 | 0.8927 | 36.99 | 107 |
| 23 | Soy oil methyl ester (high oleic) | 05-710 | 0.8802 | 37.09 | 90 |
| 24 | Palm oil methyl ester | 05-141 | 0.8757 | 37.02 | 51 |

*Figure 8: Test fuels for emission measurements*

### 2.6.2 Emission test bench

Emission measurements were done by using a Horiba MEXA 7170D test bench. Carbon monoxide, hydro carbon and nitrogen emission can be detected. The test bench consists of:

- analyzer rack with control unit, power supply and analyzer module
- heated sample unit

The analyzer module is equipped with the following analyzer units:

- AIA-721/722 NDIR: a non dispersive infrared retrospective analyzer for detecting carbon monoxide (CO) and carbon dioxide (CO2) emission
- CLA-756: a heated vacuum chemilumineszenz analyzer for detecting nitrogen emission (NOx and NO) and
- FIA-726D: a heated flame ionisation analyzer for detecting total hydro carbon emission (T.HC)


*Figure 9: Emission test bench Horiba MEXA 7170 D*

### 2.6.3 Test cycle

The emission measurements were based on the test cycle according to ISO 8178–C1[2]. The test cycle comprises 8 steps, 4 at rated speed, 3 at the speed of maximum torque and idle. Speed and load is shown in Table 10. Because of feasibility reasons only 2 of the 8 steps were selected: step 2 at 3000 rev/min and 75% load and step 7 at 2500 rev/min and 50% load.

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[2] ÖNORM EN ISO 8178-4:1996: Hubkolben-Verbrennungsmotoren - Abgasmessung. Teil 4: Prüfzyklen für verschiedene Motorverwendungen (1. Dezember 1996).

*Table 10: Test cycle according ISO 8178 - C1*

| Step | speed | load |
|---|---|---|
| | [rev/min] | [%] |
| 1 | 3000 | 100% |
| 2 | 3000 | 75% |
| 3 | 3000 | 50% |
| 4 | 3000 | 10% |
| 5 | 2500 | 100% |
| 6 | 2500 | 75% |
| 7 | 2500 | 50% |
| 8 | 900 | 0% |

### 2.6.4 Procedure

It was of high importance to avoid any influence of the measurement conditions besides the fuels compositions. First the engine was operated at load point of step 2 with all test fuels, one after the other, and exhaust emissions were registered. Then the testing programme was repeated at the load point of step 7.

At first, rapeseed oil methyl ester was used to determine maximum torque at rated speed. The first load point was adjusted (3000 rev/min and 75% load). After reaching stable conditions, the emission measurement procedure was started. Then, the test fuel was changed. Due to differences in the calorific value small adjustments hat to be done concerning speed and load. The fuel consumption was controlled at a constant level. 24 several test fuels were determined in total. After completing the measurements at the first load point, the second load point at 2500 rev/min and 50% load was adjusted and the measurements were repeated.

### 2.6.5 Evaluation

As only 2 of the 8 test points were measured it was necessary to use scaling factors for calculating the 6 missing measurement values. The scaling factors of Table 11 are mean values of several emission measurements according ISO 8178. The measurements were carried out with the test engine using test fuels of the endurance tests. The results were calculated in g/kWh using an evaluation programme.

*Table 11: Scaling factors for emission measurements*

| Step | Fuel consumption | CO2 | CO | HC | NO | |
|---|---|---|---|---|---|---|
| | % | % | % | % | % | related to |
| 1 | 124% | 127% | 140% | 116% | 117% | step 2 |
| 2 | 100% | 100% | 100% | 100% | 100% | -- |
| 3 | 80% | 78% | 114% | 102% | 77% | step 2 |
| 4 | 49% | 47% | 197% | 153% | 42% | step 2 |
| 5 | 161% | 167% | 128% | 107% | 149% | step 7 |
| 6 | 128% | 130% | 92% | 103% | 129% | step 7 |
| 7 | 100% | 100% | 100% | 100% | 100% | -- |
| 8 | 21% | 68% | 115% | 160% | 165% | step 4 |

# 3 RESULTS

## 3.1 Data measurements during endurance tests

During each endurance test several parameters (speed, torque, exhaust gas-, engine oil-, air intake, fuel-, cylinder head- and ambient temperature) were registered automatically with 1 measurement per minute. Based on the data it is possible to assess influences from test conditions. During the endurance tests mean values were evaluated per day. The overall average of the whole test (256 hours) has to be considered when results are compared.

### 3.1.1 Average temperatures

In the following Table 12 the mean values of the 256-hours-test of all temperatures are shown. The ambient temperature was controlled at approx. 32 – 33 °C to ensure constant conditions. The engine oil temperature could be kept at 104 (+/- 1) °C.

*Table 12: Average temperatures during endurance tests*

| Test fuel | methyl ester made of | exhaust | engine oil | intake | fuel | ambient | cylinder head |
|---|---|---|---|---|---|---|---|
| | | [°C] | [°C] | [°C] | [°C] | [°C] | [°C] |
| Diesel | | 254 | 103.0 | 35.4 | 22.0 | 31.1 | 119 |
| RME | rapeseed oil | 227 | 104.6 | 37.8 | 20.4 | 33.6 | 128 |
| TFME | animal fat | 236 | 103.8 | 37.1 | 20.8 | 32.3 | 124 |
| KOME | coconut oil | 221 | 104.3 | 37.6 | 21.2 | 32.2 | 126 |
| SOME | soy oil | 245 | 104.7 | 37.7 | 21.6 | 32.5 | 130 |
| KERM | jet fuel + RME | 245 | 104.9 | 36.0 | 20.8 | 31.6 | 131 |
| JAME | jatropha oil | 243 | 104.8 | 36.5 | 19.8 | 31.1 | 133 |

### 3.1.2 Average power output and fuel consumption

The average speed, torque and power output is shown in Table 13. The power output is varying between 1.88 kW for KOME and 2.37 kW for diesel. It is mainly reasoned by the calorific value at the one hand (35.5 MJ/kg for KOME and 43.1 MJ/kg for diesel). On the other hand the engine was dismantled after each test. Piston, cylinder and nozzle were changed which also has influenced the engine performance. Fuel consumption is shown in Table 14. It was measured by daily weighing of the fuel tank.

*Table 13: Average speed, torque and power*

| Test fuel | average speed | average torque | average power | calorific value |
|---|---|---|---|---|
| | [rev/min] | [Nm] | [kW] | [MJ/kg] |
| Diesel | 2833 | 7.9 | 2.37 | 43.07 |
| RME | 2792 | 6.9 | 1.96 | 37.27 |
| TFME | 2808 | 7.0 | 2.07 | 37.07 |
| KOME | 2811 | 6.3 | 1.88 | 35.56 |
| SOME | 2819 | 7.1 | 2.13 | 37.09 |
| KERM | 2815 | 7.3 | 2.16 | 39.12 |
| JAME | 2814 | 7.5 | 2.23 | 37.14 |

*Table 14: Fuel consumption*

| Test fuel | density | total fuel consumpt. | fuel con-sump./hour | specific fuel consumption | total energy consumption | power input | efficiency (average) |
|---|---|---|---|---|---|---|---|
| | [kg/l] | [kg] | [l/h] | g/kWh | [kWh] | [kW] | [%] |
| Diesel | 0.8356 | 210.0 | 0.98 | 346 | 2512 | 9.81 | 24.2% |
| RME | 0.8865 | 224.5 | 0.99 | 447 | 2324 | 9.08 | 21.6% |
| TFME | 0.8757 | 230.0 | 1.03 | 434 | 2368 | 9.25 | 22.4% |
| KOME | 0.8749 | 231.5 | 1.03 | 482 | 2287 | 8.93 | 21.0% |
| SOME | 0.8859 | 236.5 | 1.04 | 434 | 2437 | 9.52 | 22.4% |
| KERM | 0.8578 | 225.3 | 1.03 | 407 | 2448 | 9.56 | 22.6% |
| JAME | 0.8787 | 237.5 | 1.06 | 416 | 2450 | 9.57 | 23.3% |

### 3.1.3 Trend of power output during the 256-hours-test

Figure 10 shows the trend of the power output during the long term tests (mean value of a test day). A drop of the power during the 256 hours can be observed with the fuels RME (rapeseed oil methyl ester), TFME (animal fat methyl ester) and KOME (coconut oil methyl ester). It was confirmed by measuring the full load characteristic (see 3.2) and the nozzle flow rate (see 3.4) at the end of the tests.

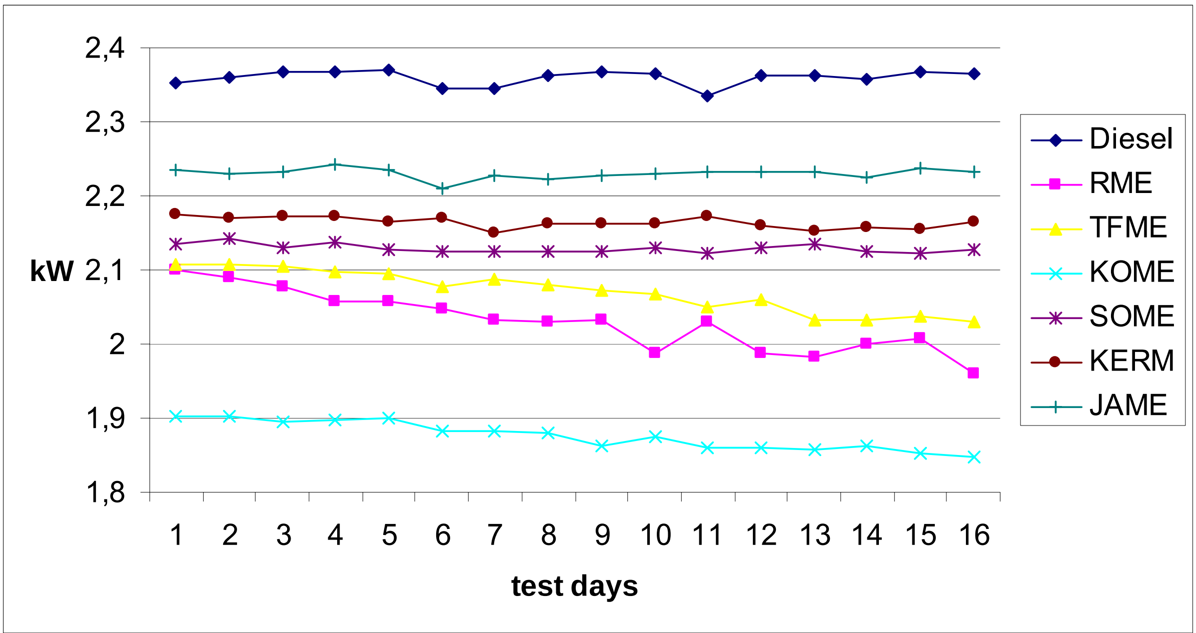



*Figure 10: Trend of engine power of the long term run with test fuels*

### 3.1.4 Engine oil balance

Between 2 and 2.4 kg of engine were filled in the engine at the beginning of each long term test. The oil consumption varied between 1.4 g/kg fuel (with RME and KERM) and 2.3 g/kg fuel (with diesel). See Table 15 and Figure 11.

*Table 15: Engine oil balance*

| Test fuel | methyl ester made of | oil volume at beginning | total oil consumption | oil consumption per kg fuel | oil consumption per hour |
|---|---|---|---|---|---|
| | | [g] | [g] | [g/kg] | [g/h] |
| Diesel | | 2437 | 478 | 2.28 | 1.87 |
| RME | rapeseed oil | 1974 | 326 | 1.45 | 1.27 |
| TFME | animal fat | 2279 | 519 | 2.26 | 2.03 |
| KOME | coconut oil | 2196 | 439 | 1.90 | 1.72 |
| SOME | soy oil | 1913 | 445 | 1.88 | 1.74 |
| KERM | jet fuel + RME | 2185 | 325 | 1.44 | 1.27 |
| JAME | jatropha oil | 2026 | 489 | 2.06 | 1.91 |

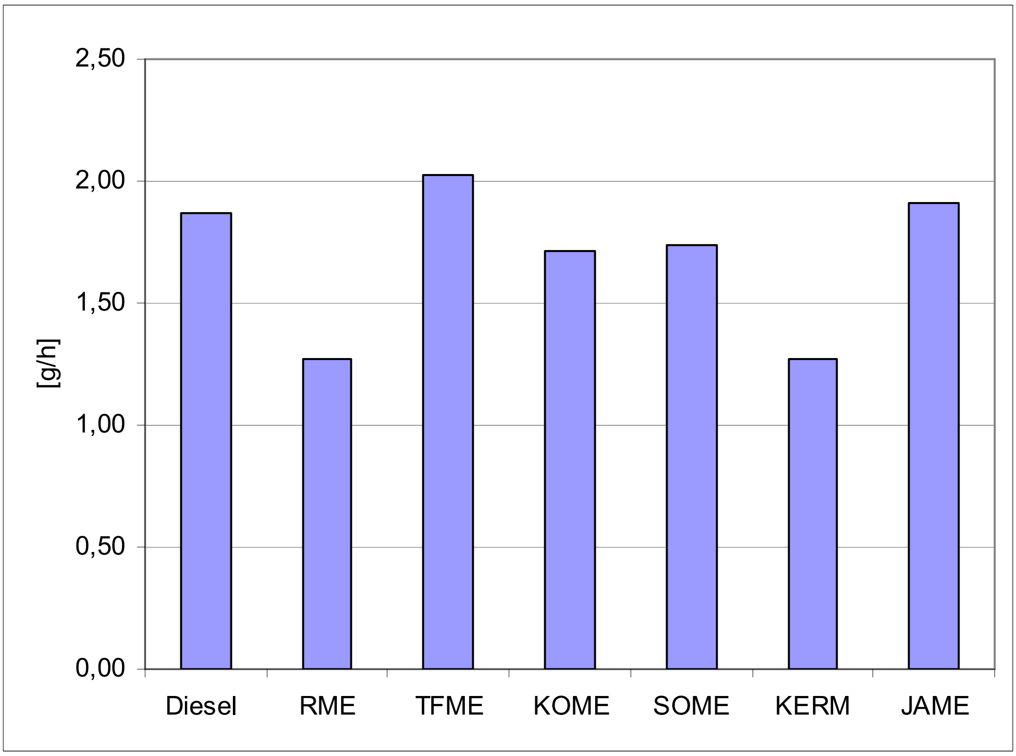



*Figure 11: Engine oil consumption*

## 3.2 Full load characteristic

At the beginning of each endurance test (but after 48 hours pre-run with the new engine parts) a full load characteristic was determined with diesel fuel and with the test fuel. Immediately after the 256-hours-endurance test the full load characteristic was repeated with the test fuel. In Table 16 the results of one measuring point (max. torque at rated speed) are compared. A typical full load characteristic determined with soy oil methyl ester is shown in Figure 12 and Figure 13.

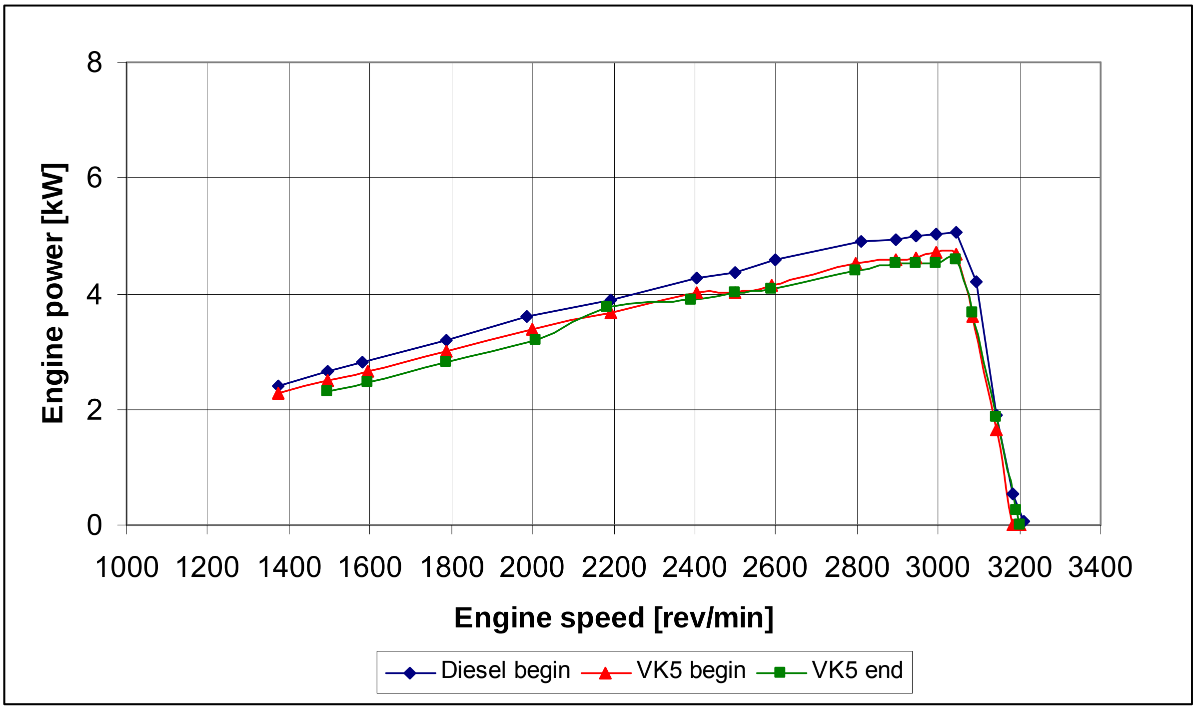



*Figure 12: Full load characteristic (engine power) with soy oil methyl ester (SOJE)*

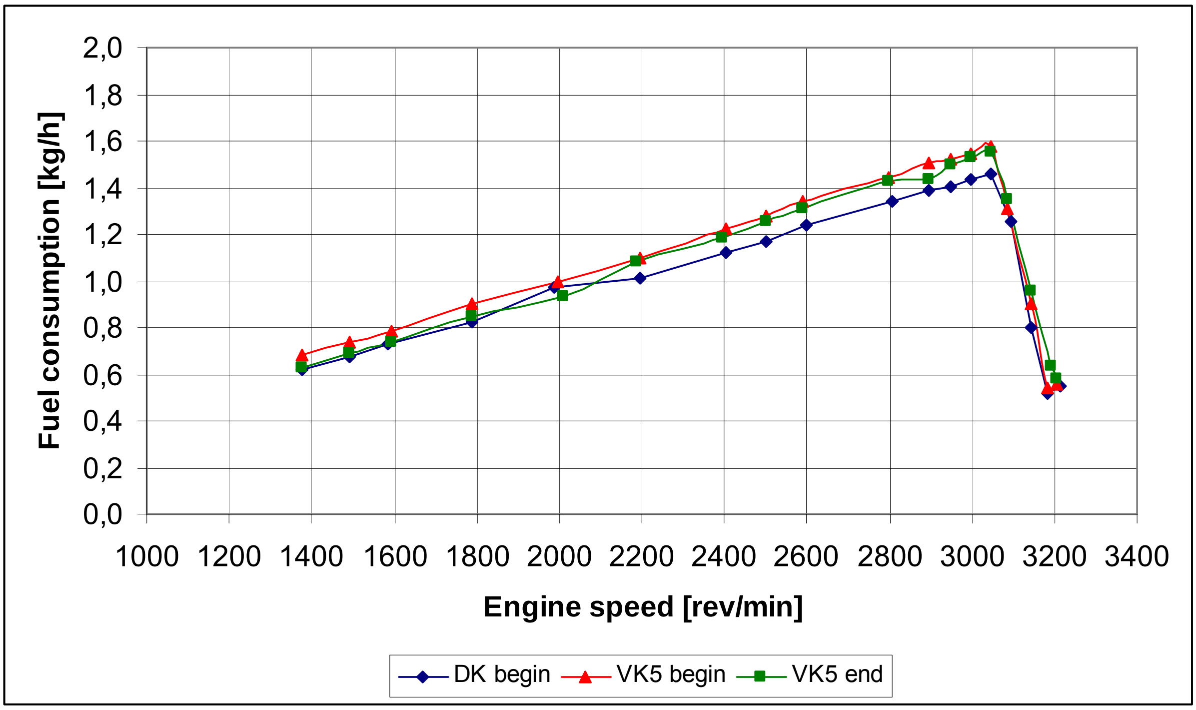



*Figure 13: Full load characteristic (fuel consumption) with soy oil methyl ester*

*Table 16: Full load measurements at rated speed*

| Test Fuel | Speed | Torque | Power | Fuel cons | Fuel cons | Fuel cons | Specific fuel cons. | Efficien-cy | Calorific value |
|---|---|---|---|---|---|---|---|---|---|
| | [rev/min] | [Nm] | [kW] | [cm$^3$/min] | [mm³/ stroke] | [kg/h] | [g/kWh] | [%] | [MJ/kg] |
| **Diesel begin** | 2950 | 16.8 | 5.19 | 27.8 | 18.6 | 1.39 | 267 | 31.3 | 43.07 |
| **Diesel end** | 2956 | 17.0 | 5.26 | 26.6 | 17.9 | 1.33 | 252 | 33.1 | 43.07 |
| End / begin | 100% | 101% | 101% | 96% | 96% | 96% | 94% | 106% | 100% |
| **Diesel begin** | 2946 | 16.1 | 5.00 | 28 | 19.0 | 1.44 | 280 | 29.0 | 43.07 |
| **RME begin** | 2976 | 15.3 | 4.78 | 28.4 | 19.1 | 1.51 | 316 | 30.6 | 37.27 |
| **RME end** | 2946 | 11.0 | 3.41 | 22.8 | 15.4 | 1.21 | 355 | 27.2 | 37.27 |
| RME / diesel | 101% | 95% | 96% | 101% | 100% | 105% | 113% | 105% | 87% |
| End / begin | 99% | 72% | 71% | 80% | 81% | 80% | 112% | 89% | |
| **Diesel begin** | 2996 | 16.1 | 5.06 | 28.7 | 19.3 | 1.45 | 285 | 29.2 | 43.07 |
| **TFME begin** | 2996 | 15.3 | 4.81 | 29.2 | 19.7 | 1.55 | 323 | 30.1 | 37.07 |
| **TFME end** | 2996 | 12.3 | 3.87 | 26.0 | 17.5 | 1.38 | 358 | 27.1 | 37.07 |
| TFME / diesel | 100% | 95% | 95% | 102% | 102% | 107% | 113% | 103% | 86% |
| End / begin | 100% | 80% | 80% | 89% | 89% | 89% | 111% | 90% | |
| **Diesel begin** | 2996 | 15.4 | 4.84 | 28.6 | 19.0 | 1.43 | 295 | 28.3 | 43.07 |
| **KOME begin** | 2986 | 14.3 | 4.46 | 28.8 | 19.3 | 1.53 | 343 | 29.5 | 35.56 |
| **KOME end** | 2946 | 12.0 | 3.69 | 26.4 | 17.8 | 1.38 | 373 | 27.2 | 35.56 |
| KOME / diesel | 100% | 92% | 92% | 101% | 101% | 107% | 116% | 104% | 83% |
| End / begin | 99% | 84% | 83% | 92% | 92% | 90% | 109% | 92% | |
| **Diesel begin** | 2996 | 16.0 | 5.03 | 28.7 | 19.1 | 1.43 | 285 | 29.4 | 43.07 |
| **SOME begin** | 2996 | 15.0 | 4.70 | 29.2 | 19.3 | 1.54 | 329 | 29.5 | 37.09 |
| **SOME end** | 2996 | 14.4 | 4.52 | 28.9 | 19.5 | 1.55 | 344 | 28.2 | 37.09 |
| SOME / diesel | 100% | 93% | 93% | 102% | 101% | 108% | 116% | 101% | 86% |
| End / begin | 100% | 96% | 96% | 99% | 101% | 101% | 105% | 96% | |
| **Diesel begin** | 2996 | 15.7 | 4.94 | 29.0 | 19.3 | 1.45 | 294 | 28.5 | 43.07 |
| **KERM begin** | 2996 | 15.6 | 4.89 | 29.4 | 19.4 | 1.54 | 315 | 29.2 | 39.12 |
| **KERM end** | 2986 | 14.5 | 4.54 | 28.0 | 18.7 | 1.46 | 322 | 28.5 | 39.12 |
| KERM / diesel | 100% | 99% | 99% | 101% | 101% | 106% | 107% | 103% | 91% |
| End / begin | 100% | 93% | 93% | 95% | 96% | 95% | 102% | 98% | |
| **Diesel begin** | 2996 | 16.3 | 5.11 | 29.0 | 19.3 | 1.45 | 284 | 29.4 | 43.07 |
| **JAME begin** | 2996 | 15.6 | 4.90 | 29.4 | 19.4 | 1.54 | 314 | 30.8 | 37.14 |
| **JAME end** | 2996 | 15.5 | 4.87 | 29.7 | 19.8 | 1.56 | 320 | 30.3 | 37.14 |
| JAME / diesel | 100% | 96% | 96% | 101% | 100% | 106% | 111% | 105% | 86% |
| End / begin | 100% | 99% | 99% | 101% | 102% | 101% | 102% | 98% | |

The measurement with diesel fuel at the beginning was necessary to ensure comparable conditions. It can be seen that the power output even with diesel is varying between 4.8 and 5.2 kW. Comparing the results between beginning and end of the test a drop in power output can be observed especially with rapeseed oil methyl ester (RME), animal fat methyl ester (TFME) and coconut oil methyl ester (KOME). The drop can be explained by a decreasing fuel consumption which was caused by a decreasing nozzle flow rate. The nozzle flow rate was determined after the tests by the engine manufacturer. Results are included in 3.4. Figure 14 shows a correlation between change of power output and change of fuel consumption and in fig. 16 the change of fuel consumption is related to the change of nozzle flow rate during the endurance test.

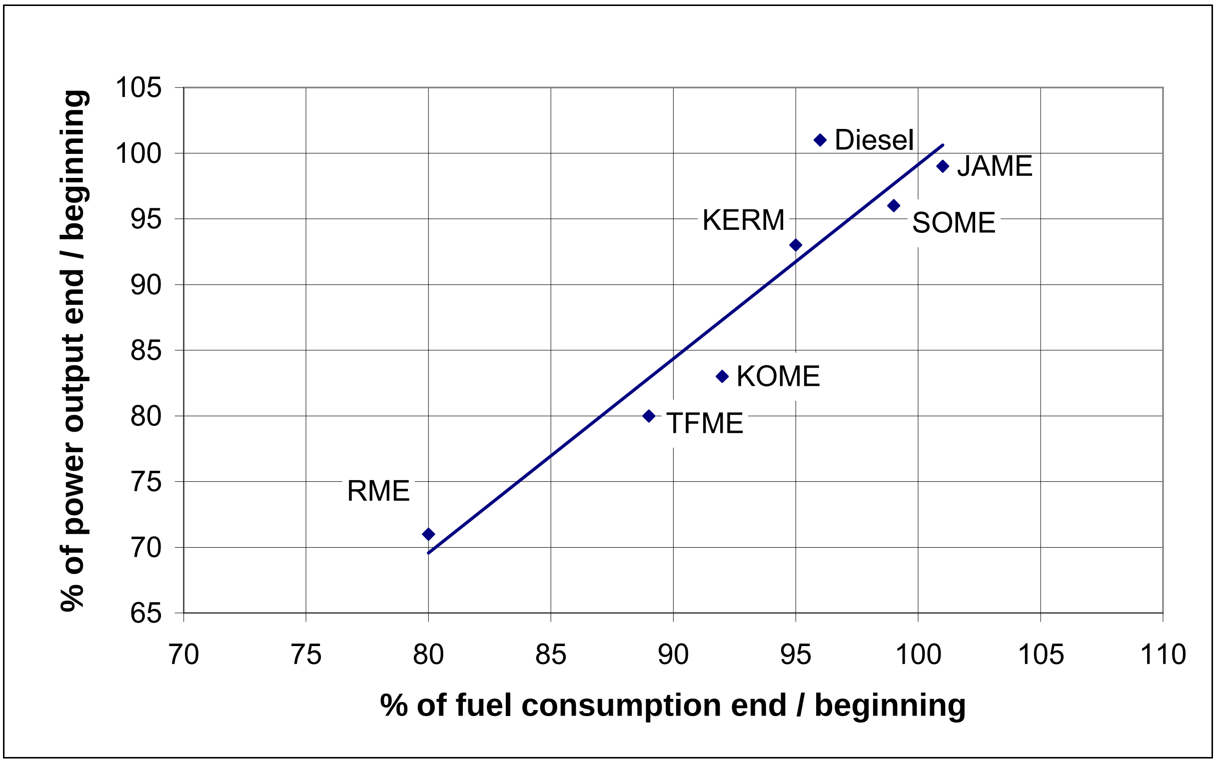



*Figure 14: Change of power output vs. fuel consumption after 256 hours*

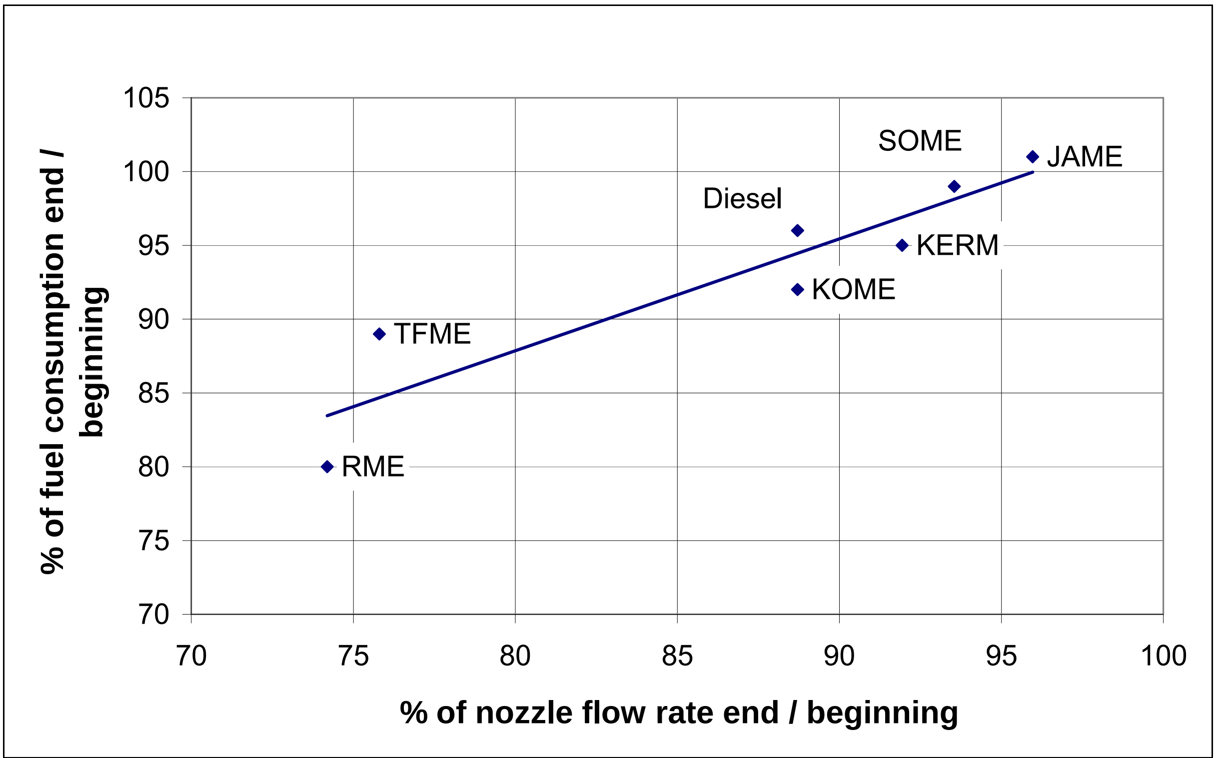



*Figure 15: Change of fuel consumption vs. nozzle flow rate after 256 hour*

## 3.3 Engine oil analyses

### 3.3.1 Viscosity

Viscosity at 100°C was determined immediately after taking the oil sample in the laboratory at FJ-BLT. In Table 17 the results are listed. Samples were taken at the beginning, at 48, 98, 146, 194 hours and at the end (256 hours run time). The trend of the engine oil viscosity is shown in Figure 16. A decrease of the viscosity could be observed in all cases which is caused by engine oil dilution with the fuel. The drop of viscosity is higher with RME and TFME. The other fuels show a slight increase until the end of the long term test.

*Table 17: Viscosity of the engine oil at 100°C*

| Sample no. | Run time [h] | Diesel | RME | TFME | KOME | SOME | KERM | JAME |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 14.33 | 14.27 | 14.22 | 14.68 | 14.27 | 14.23 | 14.42 |
| 2 | 48 | 13.88 | 13.98 | 14.03 | 14.27 | 14.10 | 14.21 | 14.19 |
| 3 | 98 | 13.79 | 13.78 | 13.92 | 14.15 | 13.98 | 14.08 | 14.17 |
| 4 | 146 | 13.84 | 13.73 | 13.85 | 14.14 | 14.09 | 14.15 | 14.36 |
| 5 | 194 | 13.80 | 13.62 | 13.85 | 14.13 | 14.14 | 14.08 | 14.49 |
| 6 | 256 | 13.97 | 13.57 | 13.84 | 14.16 | 14.37 | 14.17 | 14.29 |

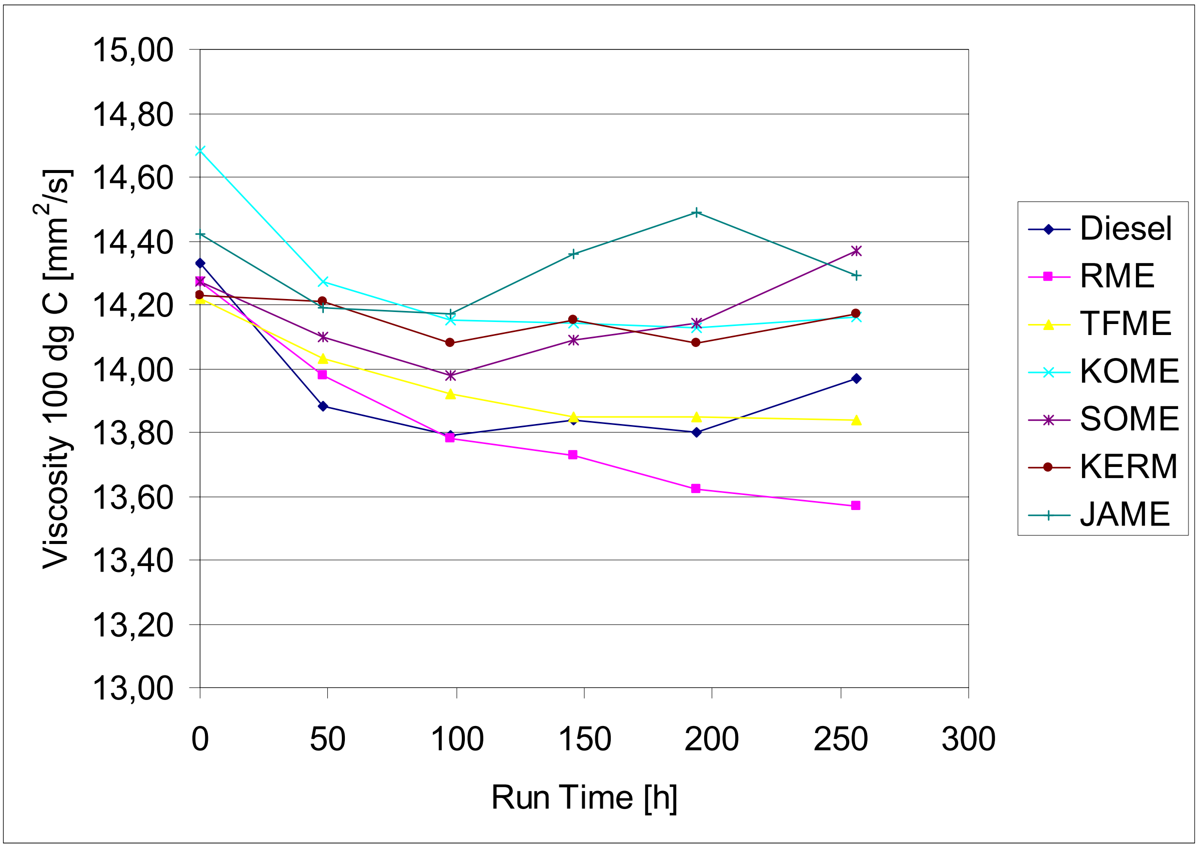



*Figure 16: Trend of the engine oil viscosity (100 dg C)*

### 3.3.2 Oil analysis

(Source: OMV and Oel Check)

Oil samples at the end of each 256-hours-test were analysed by an external laboratory. In Table 18 analyses of the oil samples are listed.

*Table 18: Oil analyses (Source : Oel Check Germany)*

| Parameter | Unit | Fresh oil | Diesel | RME | TFME | KOME | SOME | KERM | JAME |
|---|---|---|---|---|---|---|---|---|---|
| | Lab no.: | 315581 | 315580 | 315579 | 315578 | 315582 | 315583 | 315584 | 315585 |
| | Date: | 8.4.05 | 8.4.05 | 23.5.05 | 20.6.05 | 26.7.05 | 30.9.05 | 14.11.05 | 18.1.06 |
| **Wear** | | | | | | | | | |
| Fe | [mg/kg] | 0 | 45 | 17 | 11 | 32 | 23 | 21 | 25 |
| Cr | [mg/kg] | 0 | 3 | 1 | 0 | 1 | 0 | 1 | 1 |
| Sn | [mg/kg] | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 0 |
| Al | [mg/kg] | 0 | 8 | 4 | 5 | 10 | 10 | 9 | 6 |
| Ni | [mg/kg] | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| Cu | [mg/kg] | 0 | 5 | 2 | 2 | 4 | 3 | 3 | 3 |
| Pb | [mg/kg] | 0 | 5 | 4 | 3 | 4 | 4 | 4 | 5 |
| Mo | [mg/kg] | 0 | 11 | 1 | 1 | 1 | 0 | 2 | 1 |
| PQ- Index | | ok | ok | ok | ok | ok | ok | ok | ok |
| **Conta-mination** | | | | | | | | | |
| Si | [mg/kg] | 6 | 43 | 12 | 6 | 7 | 11 | 4 | 6 |
| K | [mg/kg] | 20 | 18 | 13 | 2 | 12 | 20 | 8 | 3 |
| Na | [mg/kg] | 3 | 3 | 3 | 7 | 4 | 3 | 5 | 0 |
| H2O | [%] | < 0.1 | < 0.1 | < 0.1 | < 0.1 | < 0.1 | < 0.1 | < 0.1 | < 0.1 |
| Glycol | | negat. | negat. | negat. | negat. | negat. | negat. | negat. | negat. |
| Fuel cont. | [%] | 0 | 0.20 | 0.80 | 0.50 | 0.40 | 0.50 | < 0.30 | 0.56 |
| Soot cont. | [%) | 0 | 0.11 | 0.14 | 0.04 | <0.1 | <0.1 | <0.1 | <0.1 |
| **Oil status** | | | | | | | | | |
| Viscosity 40 dgC | [$mm^2$/s] | 95.30 | 93.23 | 89.59 | 92.62 | 94.61 | 95.13 | 95.51 | 95.42 |
| Viscosity 100 dgC | [$mm^2$/s] | 14.23 | 13.90 | 13.54 | 13.85 | 14.06 | 14.14 | 14.10 | 14.17 |
| visc.index | | 154 | 152 | 153 | 153 | 152 | 153 | 153 | 153 |
| TBN | mgKOH/g | 10.34 | 10.26 | 11.23 | 10.61 | 10.46 | 10.72 | 11.37 | 10.20 |
| Oxidation | A/cm | - | 2 | 2 | 2 | 3 | 6 | 4 | 9 |
| Nitration | A/cm | - | 6 | 6 | 6 | 6 | 7 | 7 | 7 |
| Sulfation | A/cm | - | 6 | 12 | 9 | 6 | 8 | - | - |
| Dispersancy | [%] | 100 | 100 | 93 | 99 | 100 | 97 | 100 | 97 |
| **Additives** | | | | | | | | | |
| Ca | [mg/kg] | 2610 | 2934 | 4244 | 4418 | 3510 | 2861 | 3412 | 3808 |
| Mg | [mg/kg] | 27 | 69 | 25 | 23 | 35 | 31 | 39 | 25 |
| B | [mg/kg] | 0 | 2 | 3 | 1 | 0 | 0 | 0 | 0 |
| Zn | [mg/kg] | 1377 | 1317 | 1350 | 1206 | 1501 | 1142 | 1351 | 1346 |
| P | [mg/kg] | 1519 | 1360 | 1109 | 1363 | 1266 | 1035 | 1192 | 1208 |
| Ba | [mg/kg] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

A reduction of dispersancy can be observed at the samples of RME, TFME, SOME und JAME. The effect is very rare with diesel fuel. Maybe detergents/dispersant-additives were consumed by a higher content of polymer products. The fuel content of all samples is < 1 %. All other parameters are unobtrusive.

## 3.4 Component review

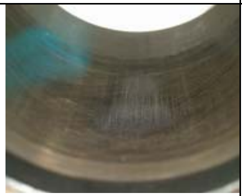
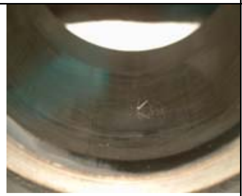
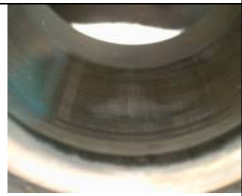
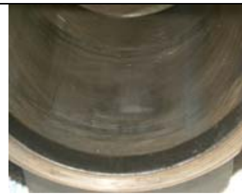
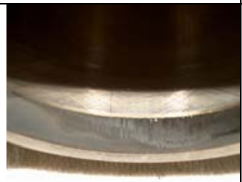
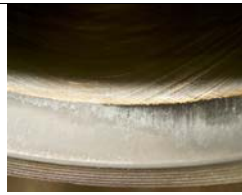
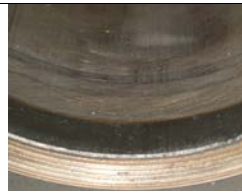
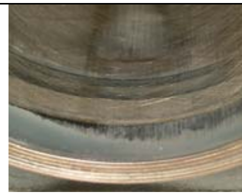
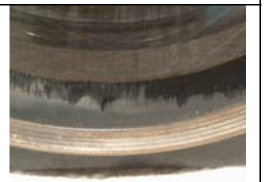
(Source: Peter Prinz-Hufnagel, Hatz, Germany)

The engine was dismantled after each 256-hours test. Piston, cylinder and nozzles were changed. All spare parts were inspected by the manufacturer.

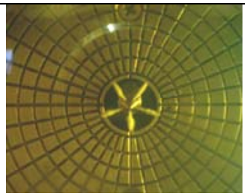
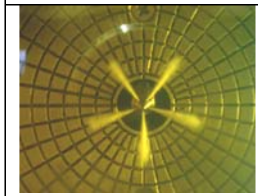
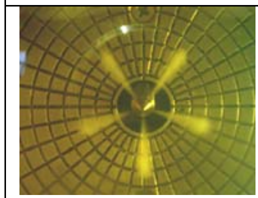
| **PISTON:** | | | | | | | |
|---|---|---|---|---|---|---|---|
| Test fuel: | **Diesel** | **RME** rapeseed oil m.e. | **TFME** animal fat m.e. | **KOME** coconut oil m.e. | **SOME** soy oil m.e. | **KERM** 70%RME/30% jet | **JAME** jatropha oil m.e. |
| Combus-tion chamber: |  |  |  |  |  |  |  |
| Shaft wear: Opposite pressure side: |  |  |  |  |  |  |  |
| Pressure side: |  o.k. |  o.k. |  o.k. |  o.k. |  o.k. |  o.k. |  o.k. |
| Bottom and gudgeon pin: |  |  |  |  |  |  |  |

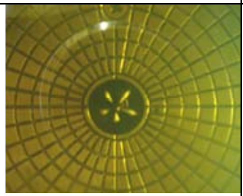
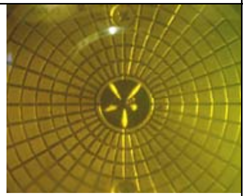
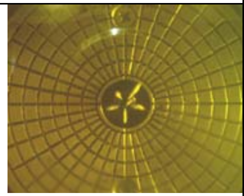
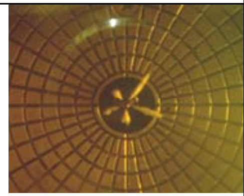
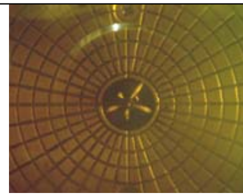
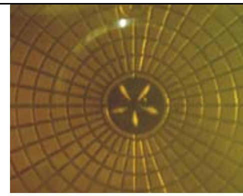
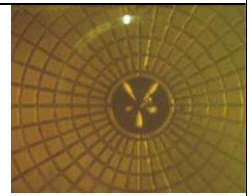
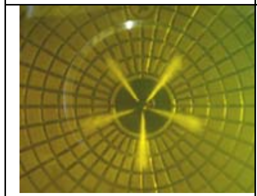
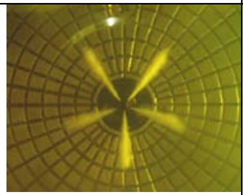
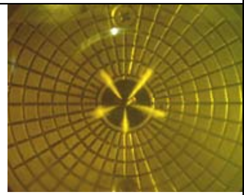
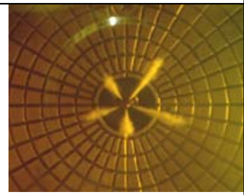
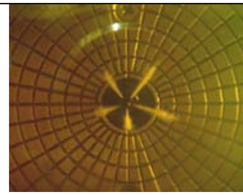
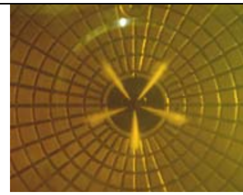
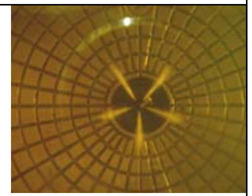
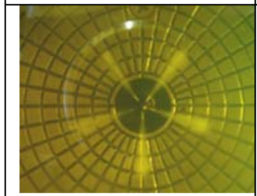
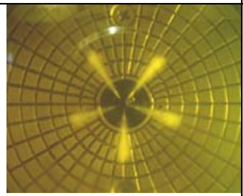
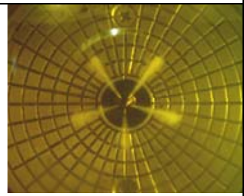
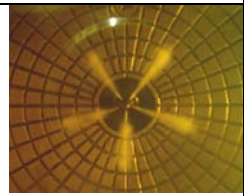
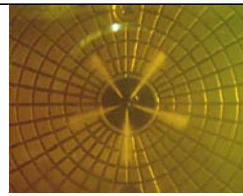
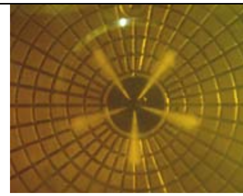
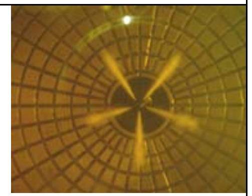
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Piston crown and piston ring area: |  |  |  |  |  |  |  |
| Coke deposit at piston crown: | | | | | | | |
| | heavy | heavy | heavy | heavy | heavy | heavy | heavy |
| Coke deposit inside first ring groove: | | | | | | | |
| | heavy | heavy | heavy | heavy | heavy | heavy | heavy |
| Coke deposit inside second ring groove: | | | | | | | |
| | heavy | heavy | heavy | light | light | heavy | light |
| Gudgeon pin free movable? | | | | | | | |
| | yes | yes | yes | yes | yes | Tight, but still moveable, violet coloured on each end | yes |
| *Comment:* | Second ring groove shows clearly visible yellow colour and coke deposit in the ring gap area | Second ring groove shows clearly visible yellow colour and coke deposit in the ring gap area; clearly visible yellow colouring on the piston shaft at pressure side, white ash deposits inside combustion chamber. | Second ring groove shows clearly visible yellow colour and coke deposit in the ring gap area; clearly visible yellow colouring on the piston shaft at pressure side | Second ring groove shows clearly visible yellow colour and coke deposit in the ring gap area; clearly visible yellow colouring on the piston shaft at pressure side, light brown combustion deposits. | Second ring groove shows clearly visible yellow colour and coke deposit in the ring gap area; clearly visible yellow colouring on the piston shaft as well as remarkable coke deposits and yellow colouring on land between first two rings at pressure side, light brown to white combustion deposits. | Second ring groove shows clearly visible yellow colour and coke deposit in the ring gap area; clearly visible yellow colouring on the piston shaft as well as remarkable coke deposits and yellow colouring on land between first two rings at pressure side, light brown to white combustion deposits. | Second ring groove shows clearly visible yellow colour and coke deposit in the ring gap area; clearly visible yellow colouring on the piston shaft as well as remarkable coke deposits and yellow colouring on land between first two rings at pressure side, white ash deposits inside combustion chamber.. |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **PISTON RINGS:** | | | | | | | | | | | | | | |
| **Gap clearance [mm]:** | | | | | | | | | | | | | | |
| Test fuel: | **Diesel** | | **RME** rapeseed oil m.e. | | **TFME** animal fat m.e. | | **KOME** coconut oil m.e. | | **SOME** soy oil m.e. | | **KERM** 70%RME/30% jet | | **JAME** jatropha oil m.e. | |
| | 0h | 256h | 0h | 256h | 0h | 256h | 0h | 256h | 0h | 256h | 0h | 256h | 0h | 256h |
| 1st Ring: | ~0,30 | 0,45 | ~0,30 | 0,30 | ~0,30 | 0,30 | ~0,30 | 0,30 | ~0,30 | 0,30 | ~0,30 | 0,30 | ~0,30 | 0,30 |
| 2nd Ring: | ~0,50 | 0,65 | ~0,50 | 0,65 | ~0,50 | 0,65 | ~0,50 | 0,65 | ~0,30 | 0,65 | ~0,30 | 0,65 | ~0,30 | 0,65 |
| 3rd Ring: | ~0,40 | 0,55 | ~0,40 | 0,60 | ~0,40 | 0,55 | ~0,40 | 0,55 | ~0,30 | 0,60 | ~0,30 | 0,60 | ~0,30 | 0,70 |
| Related sealing surface [%] | 1st Ring: | | 50(VK 1); 40(VK 2-4,6,7); 60(VK 5) | | | | | | | | | | | |
| | 2nd Ring: | | 30(VK 1,5,6); 25(VK2-4); 20(VK 7) | | | | | | | | | | | |
| *Comment:* | No unusual wear, run – in period of 1st compression ring seems to be elongated with FAME fuels | | | | | | | | | | | | | |

| **CYLINDER:** | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Overheat marks: | None | | | | | | | | | | | | | |
| Polished spots: | Piston shaft related area around TDC at opposite pressure side and around BDC on pressure side | | | | | | | | | | | | | |
| Deep honing grooves still visible? | yes | | | | | | | | | | | | | |
| **Roughness value Ra in [µm]:** | | | | | | | | | | | | | | |
| Test fuel: | **Diesel** | | **RME** rapeseed oil m.e. | | **TFME** animal fat m.e. | | **KOME** coconut oil m.e. | | **SOME** soy oil m.e. | | **KERM** 70%RME/30% jet | | **JAME** jatropha oil m.e. | |
| | 0h | 256h | 0h | 256h | 0h | 256h | 0h | 256h | 0h | 256h | 0h | 256h | 0h | 256h |
| | 0.5-0.9 | 0.185<br>0.101<br>0.465<br>0.429 | 0.5-0.9 | 0.163<br>0.153<br>0.439<br>0.354 | 0.5-0.9 | 0.330<br>0.220<br>0.352<br>0.304 | 0.5-0.9 | 0.276<br>0.285<br>0.385<br>0.175 | 0.5-0.9 | 0.372<br>0.394 | 0.5-0.9 | 0.343<br>0.218 | 0.5-0.9 | 0.215<br>0.282 |
| |  | |  | |  | |  | |  | |  | |  | |
| |  | |  | |  | |  | |  | |  | |  | |
| |  | |  | |  | |  | |  | |  | |  | |
| *Comment:* | Neither significant differences nor unusual wear marks visible | | | | | | | | | | | | | |

| **INJECTOR** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Nozzle opening pressure [bar]:** | | | | | | | |
| Running time [h] | **Diesel** | **RME**<br>rapeseed oil m.e. | **TFME**<br>animal fat m.e. | **KOME**<br>coconut oil m.e. | **SOME**<br>soy oil m.e. | **KERM**<br>70%RME/30% jet | **JAME**<br>jatropha oil m.e. |
| 0 h | 225+12 | 225+12 | 225+12 | 225+12 | 225+12 | 225+12 | 225+12 |
| 256 h | 216 | 221 | 220 | 220 | 219 | 213 | 222 |
| Spray behavi. at ~250 bar.: | 3 sprays normal, 2 slightly scattering | 3 sprays normal, 2 slightly scattering | 4 sprays normal, 1 scattering | 3 sprays normal, 1 heavily scattering, 1 sligthly scattering | 3 sprays normal, 1 heavily scattering, 1 sligthly scattering | 2 sprays normal, 3 sligthly scattering | 3 sprays normal, 1 heavily scattering, 1 sligthly scattering |
| |  |  |  |  |  |  |  |
| |  |  |  |  |  |  |  |
| | Small coke crater in front of one sprayhole, others o.k. | Small coke craters, white to yellow, white ash deposits, nozzle body colour turning into yellow | White coke deposits in front of 2 sprayholes, nozzle body colour turning into yellow | Extreme cratering, nozzle body colour turning into yellow | All sprayholes show few coke craters, white to yellow, nozzle body colour turning into yellow | Extreme cratering, nozzle body colour turning into yellow | Two sprayholes show small coke craters, white to yellow, white ash deposits, nozzle body colour turning into yellow |

| Nozzle flow rate [cm$^3$/ min/ 100 bar]: | | | | | | | |
|---|---|---|---|---|---|---|---|
| Running time [h] | **Diesel** | **RME** rapeseed oil m.e. | **TFME** animal fat m.e. | **KOME** coconut oil m.e. | **SOME** soy oil m.e. | **KERM** 70%RME/30% jet | **JAME** jatropha oil m.e. |
| 0 | 620 | | | | | | |
| 256 | 550 | 460 | 470 | 550 | 580 | 570 | 595 |
| **Spray pattern at three different protrusion phases (constant rack position; cam speed 1500 rpm):** | | | | | | | |
| Running time [h] | **Diesel 20.5 mm$^3$/H** | | | | | | |
| 0 |  | | | | | | |
| |  | | | | | | |
| |  | | | | | | |

| | **Diesel** | **RME** rapeseed oil m.e. | **TFME** animal fat m.e. | **KOME** coconut oil m.e. | **SOME** soy oil m.e. | **KERM** 70%RME/30% jet | **JAME** jatropha oil m.e. |
|---|---|---|---|---|---|---|---|
| | **840,2 kg/m$^3$ 20,7 mm$^3$/H** | **886,5 kg/m$^3$ 17,3 mm$^3$/H** | **875,7 kg/m$^3$ 19,3 mm$^3$/H** | **874,9 kg/m$^3$ 19,1 mm$^3$/H** | **885,9 kg/m$^3$ 21,2 mm$^3$/H** | **857,4 kg/m$^3$ 20,1 mm$^3$/H** | **878,7 kg/m$^3$ 19,7 mm$^3$/H** |
| 256h |  |  |  |  |  |  |  |
| |  |  |  |  |  |  |  |
| |  |  |  |  |  |  |  |

| | |
|---|---|
| *Com-ment:* | Main throttling effect, visible as different protrusion depth and angle of each single spray, obviously appears at a very early stage of injection at pressures few above nozzle opening pressure, whereas late spray pattern at high pressures is only influenced by carbon deposits in terms of forming slightly different spray angles at the same protrusion depth.<br>Spray behaviour is definitively not only influenced by external visible coke craters: The explanation for different relations between nozzle flow rates, overall fuel rate, visible cratering and spray behaviour must be an additional carbon deposit inside the holes, which influences the hydraulic diameter and therefore probably diminishes the flow rate of each individual sprayhole. |

## 3.5 Emission measurements

Emission measurements were carried out with 24 different fatty acid methyl esters in total. Carbon monoxide (CO), hydrocarbon (HC) and nitrogen emission were detected. A broad variety of Biodiesel test fuels were available which were produced in the laboratory of FJ-BLT. The iodine value of the fuels ranged between 12 (for coconut oil methyl ester) and 189 for linseed oil methyl ester. Most fuels were found in the range of 80 to 130.

A clear dependency ($R^2$ = 0,88) could be found between nitrogen emission and iodine value (Figure 17). But the gradient is not very steep: With the current engine the iodine value has to be reduced by 50 for a decrease of 1 g NOx /kWh. The nitrogen emission of the engine operated with Biodiesel with an iodine value up to 80 shows are less than with diesel fuel. Carbon monoxide emissions only show a slight dependency while hydrocarbon emission are independent from the iodine value (Figure 18 and Figure 19).

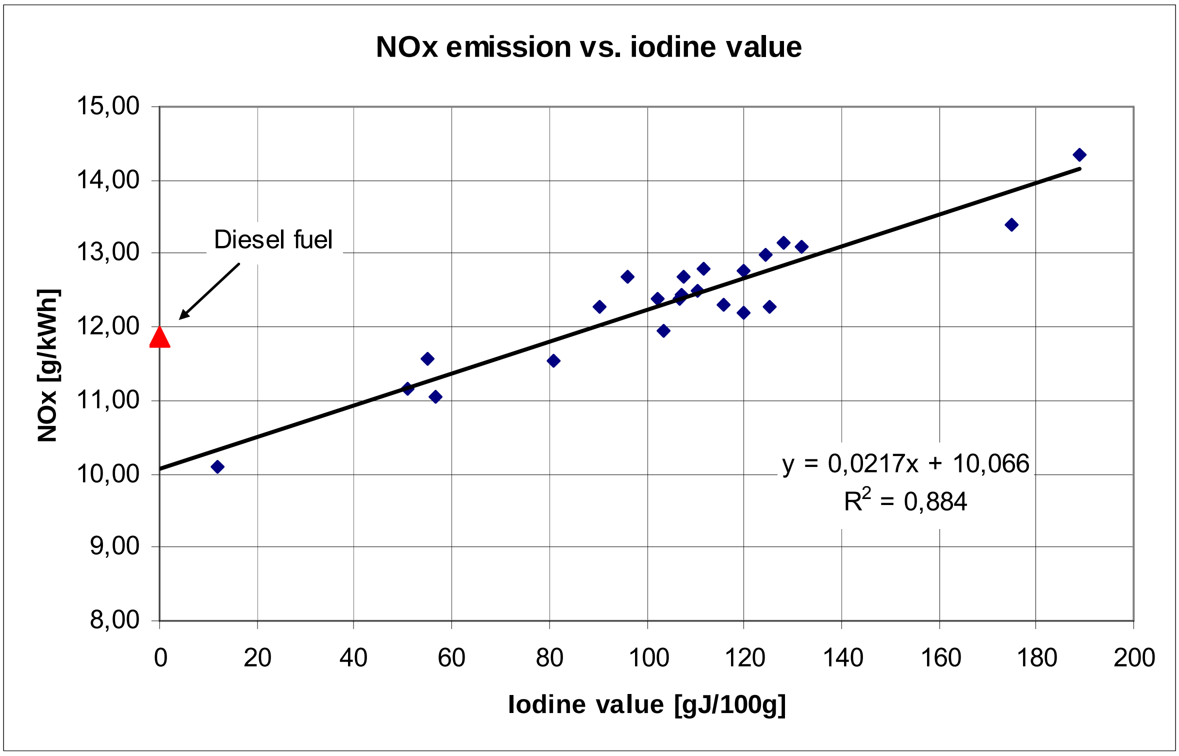



*Figure 17: Nitrogen emission vs. iodine value*

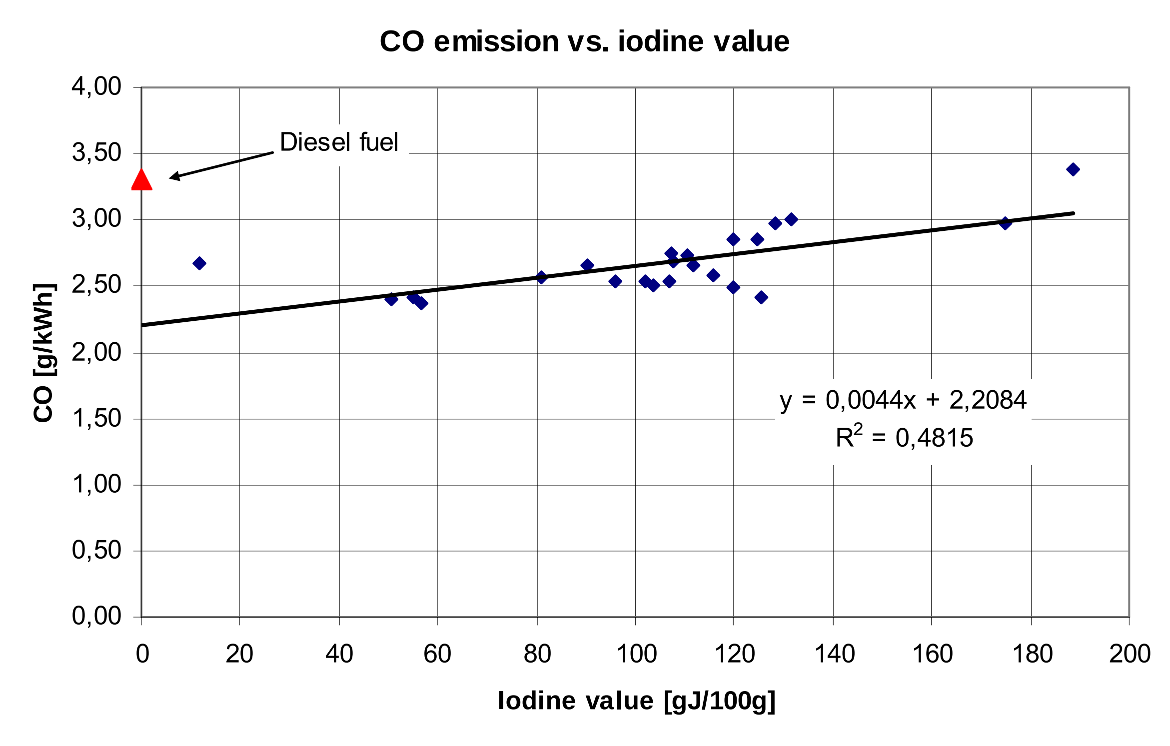



*Figure 18: Carbon monoxide emission vs. iodine value*

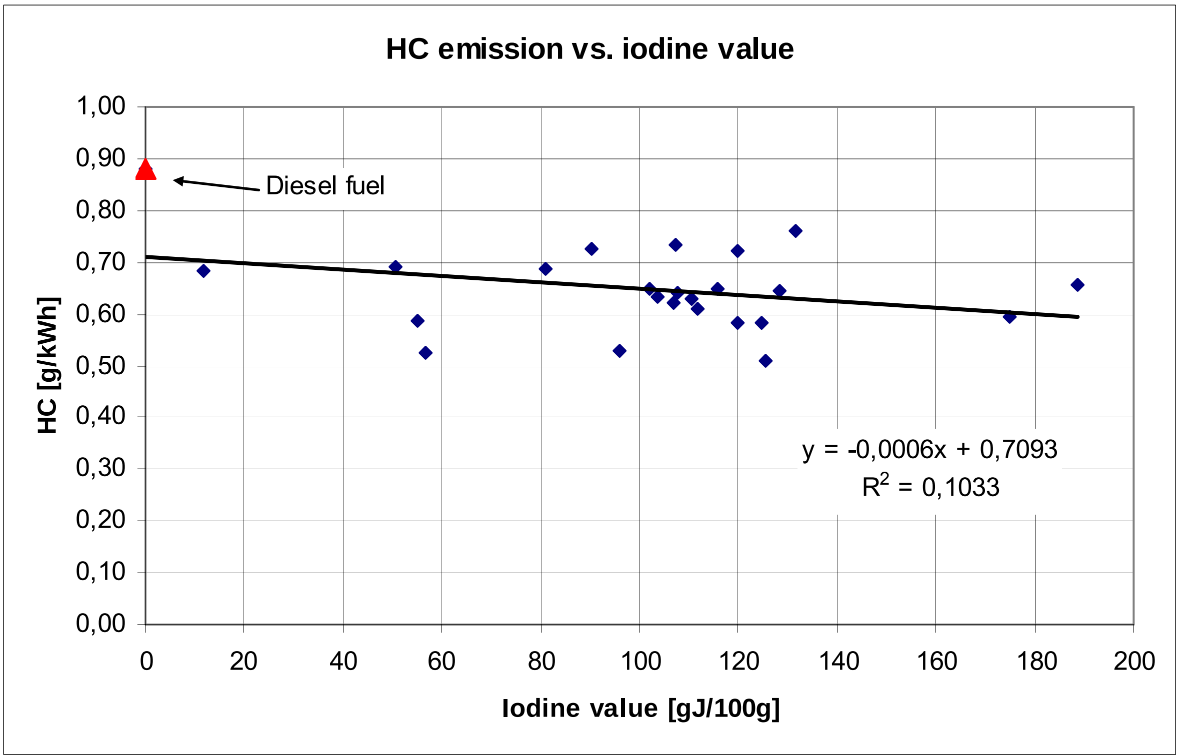



*Figure 19: Hydro carbon emission vs. iodine value*

# 4 SUMMARY AND CONCLUSIONS

Endurance tests were carried out with seven different test fuels in order to find influences of the fuel composition to the engine behaviour. A single cylinder engine (5.6 kW at 3000 rev/min) was operated 256 hours with varying load and speed with each fuel. Fossil diesel and six fatty acid methyl ester were used with iodine values between 12 and 125:

- Diesel fuel
- Rapeseed oil methyl ester (RME),
- Animal fat methyl ester (TFME),
- Coconut oil methyl ester (KOME),
- Soya oil methyl ester (SOME),
- a blend of 30% jet fuel and 70% rapeseed oil methyl ester (KERM) and
- Jatropha oil methyl ester (JAME).

Engine performance (power, fuel consumption) was determined at the beginning and at the end of each endurance test. Cylinder, piston and nozzle were changed at the end and inspected by the engine manufacturer. Oil samples were taken and the engine oil was analyzed.

Speed, torque and several temperatures were registered during the whole long term tests. Ambient temperature was controlled at approx. 32 – 33°C to ensure constant conditions. The average engine oil temperature was 104 (+/- 1) °C. A loss of the engine power during the 256-hours test could be observed mainly with three fuels: RME, TFME and KOME. It was caused by a drop of the fuel consumption and decreasing engine's efficiency.

The engine oil has shown an unobtrusive behaviour: The oil consumption ranged between 1.3 and 1.9 g/h. The trend of oil viscosity was found to be decreasing with all fuels. RME and TFME dropped most while the other fuels have shown a slight increase towards the end of the test. Engine oil analyses were done from the oil samples at the end. The fuel content was < 1% in all cases. No significant differences were found in wear, contamination or additive content. But dispersancy was decreasing mainly with RME but also with TFME, SOME and JAME. The effect is rare with diesel and could be caused by increasing content of polymer products.

The engine parts were inspected very carefully by the engine manufacturer. No remarkable differences were found in coke deposits of the piston, piston ring grooves and gap clearance of piston rings. Neither significant difference no unusual wear marks were visible at cylinders. Most differences were found at the injectors: Coke craters in front of sprayholes were higher with all Biodiesel fuels than with fossil diesel. Extreme cratering was found with KOME and KERM. The determination of the nozzle flow rate after 256 hours operation has shown a decrease with all fuels in comparison to a new nozzle. The highest change was found with RME and TFME. The spray behaviour is not only influenced by external visible coke craters: The explanation for different relations between nozzle flow rates, overall fuel rate, visible cratering and spray behaviour must be an additional carbon deposit inside the holes, which influences the hydraulic diameter and therefore probably diminishes the flow rate of each individual sprayhole.

Emission tests were carried out with diesel fuel and 23 fatty acid methyl esters with iodine values between 12 and 189. A clear dependence could be found between iodine value and nitrogen emission. An increase of the iodine value of 50 g iodine/100 g increases the NOx emission of 1 g/kWh with the current engine. Weak dependency was found between carbon monoxide while hydrocarbons are independent from the iodine value.

All in all differences between the investigated “innovative biodiesel” were considerable low. Under the selected testing conditions Biodiesel fuels have shown worse results in term of engine performance and carbon deposits in comparison to fossil diesel. Especially with RME and coconut oil methyl ester long term test results where surprisingly worse. RME results differ to experiences in practice so far. Biodiesel fuels with low iodine values have a positive effect on nitrogen emissions.