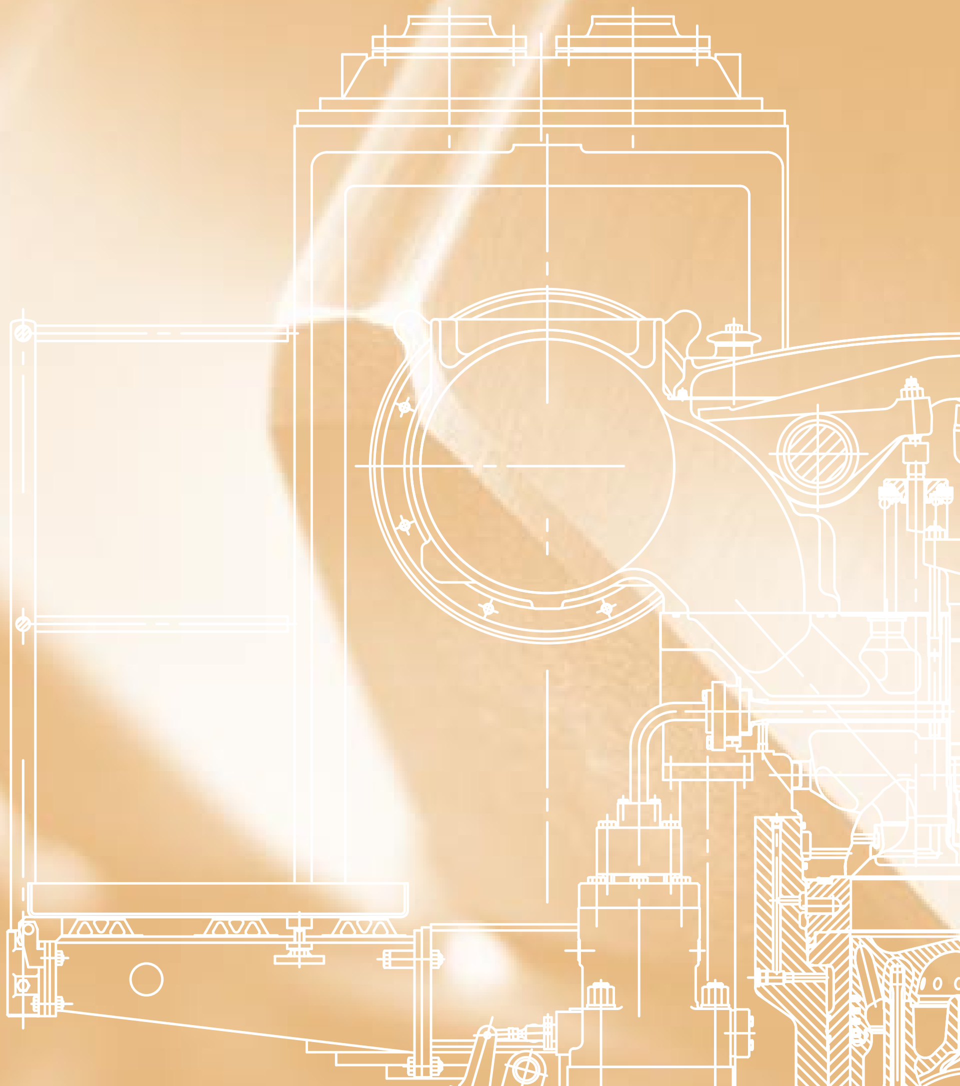
Green Power

From Diesel Engines Burning Biological Oils and Recycled Fat



MAN B&W Diesel

Abstract

The paper presents MAN B&W Diesel group's advances in the field of renewable energy from workshop and field testing to commercial operation of medium-speed Diesel engines with a variety of liquid biofuels including biological oils and recycled fat.

Worldwide commitment to the continuous growth of renewable energy production is giving increasing room for the use of liquid biofuels in internal combustion engines. Larger bore medium-speed Diesel engines are best suited to burn low cost liquid biofuels such as some crude vegetable oils, waste oils and recycled fat.

MAN B&W carried out initial workshop tests to determine biofuel compatibility with Diesel engines and to compare respective performance and emission data with the results of most commonly used mineral fuels (MGO, HFO).

Biofuels have been found to match the minimum quality requirements for operation in medium-speed Diesel engines although some aggressive waste and residual oils/fats have acidity above the accepted operating limits for conventional injection systems.

The tests showed no major deviations in Diesel engine's combustion and injection patterns as well as no significant changes on the engine performance and reduction of main noxious emissions with the exception of NO_X.

Commercial operation topping 15,000 hours revealed good long term operational reliability for biofuels.

The possibility of combining sound economics and superior eco-friendliness is driving the development and optimisation of Diesel engine's biofuel combustion to affirm this prime mover as one of the best available technologies for renewable power generation applications.

Introduction

In the next five years liquid biofuels are set to play a major role in the carrying out of the European Union's policies and strategies on the promotion of the use of renewable fuels for its internal electricity and transport markets[1].

The use of liquid biofuels to replace diesel or Heavy Fuel Oil in internal combustion engines, such as the ones used to power vehicles and electricity generation plants, carries clear global environmental benefits. Combustion of biofuels in replacement of mineral fuels actually promotes a net reduction of greenhouse gas emissions (see the case of rapeseed oil illustrated at figure A1) and other combustion related pollutants, while allowing simultaneously for appropriate disposal of waste biological oils of residential, commercial and/or industrial origin. Other consensus arguments in favour of biofuels is its potential for local and regional development, promotion of social and economic cohesion, local job creation and improvement of regional fuel supply security by reducing the need for fuel imports.

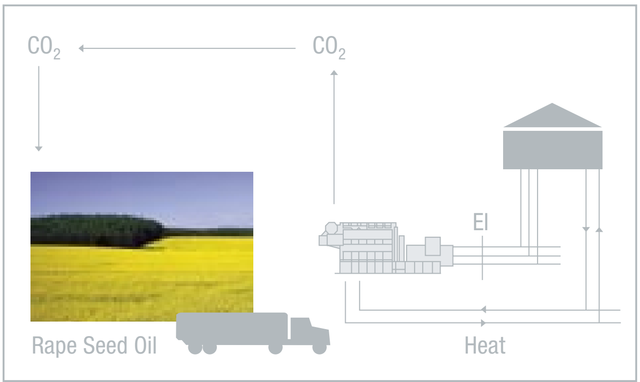


Fig. A1: CO_2 Balance for green-power generation from the combustion of rapeseed oil in medium-speed Diesel engines

A number of small bore high-speed engine manufacturers reported potential problems when using biodiesel[2] in concentrations above 5%, some related to deficiencies in handling and storage of these fuels, causing severe problems on the engine level including power loss and deterioration of performance, fuel leakage, corrosion, coking, blocking, lacquering and seizure of fuel injection equipment, filter plugging, formation of sludge and sediments, reduced service life, etc. Lower quality fuels such as raw vegetable oils have been reported as simply not acceptable for use in any concentration: in some high-speed engines these oils do not burn completely and finally cause engine failure by leaving deposits on the injectors and in the combustion chamber.

[1] Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of the electricity produced from renewable energy source in the internal electricity market.
Directive 2003/30/EC of the European Parliament and of the Council of 8 May 2003 on the promotion of the use of biofuels and other renewable fuels for transport.

[2] The expression biodiesel is the common designation for the various fuels collectively known as Fatty Acid Methyl Ester: the most common are RME (Rapeseed Methyl Ester), PME (Plant Methyl Ester) and SME (Soybean Methyl Ester) available in Europe and the US, respectively.

Due to its design and construction characteristics larger bore medium-speed Diesel engines are best suited to burn low quality liquid fuels such as crude vegetable oils and some waste and recycled biofuels, which are also the cheapest available biofuels in the world. The possibility of combining sound economics and superior eco-friendliness in the operation of its prime movers led MAN B&W to enter the development and optimisation of liquid biofuel combustion in its medium speed family of Diesel engines.

The paper hereinafter introduces innovative applications of raw biological oils and recycled fat in medium speed Diesel engines for power generation purposes, from early research and development work at MAN B&W Diesel in Holeby, Denmark to field tests.

It also presents the most recent results of the biofuel combustion development in larger bore Diesel Engines at MAN B&W Diesel's Augsburg centre of competence.

Finally the paper also presents green-power generation applications by commercial operation of Diesel engines with biofuels including vegetable oils (e.g. rape seed oil and palm oil) and recycled biofuel (e.g. waste cooking oil, frying fat).

Experimental Methods

Workshop tests conducted at MAN B&W Diesel Holeby, Denmark

From 1994 to 2003 a number of tests involving the use of liquid biofuels in medium-speed Diesel generating sets were conducted at workshops of MAN B&W Diesel Holeby's genset factory in Denmark. Several different fuels like rape seed oil, palm oil, fish oil and frying fat have been tested in different engine types (16/24, 23/30 and 27/38) for up to 100 running hours. During the third quarter of 2004 a number of tests with biofuel were also carried out in a single cylinder large bore research engine at MAN B&W Diesel's headquarters in Augsburg. The description of such tests and the properties of the tested biodiesel are presented in appendix A1.

The purpose of these tests was to determine whether the test engines were able to operate with these biofuels while carrying out at the same time performance tests including emissions measurements.

Properties of the tested biofuels

The below table A1 shows the physical and chemical properties of the liquid biofuels tested compared to most commonly used mineral fuels as Heavy Fuel Oil (HFO) and Marine Gas Oil (MGO).

Table A1: Properties of the biofuel tested at MAN B&W's Holeby workshop, Denmark. A comparison to most commonly used mineral fuels and the limit for HFO operation

Property	Unit	Palm oil	Rape seed oil	Fish oil	Used frying oil	MGO	HFO Limit
Density at 15°C	kg/m³	914.9	920.7	926.3	923	843	< 1010
Lower Cal. Value	MJ/kg	36.865	36.89	36.60	36.851	42.82	40.75*
Lower Cal. Value	MJ/ltr.		33.96	33.90	34.01	36.10	39.82*
Viscosity @ 40°C	cSt	40.2	33.8	29.6	37@50°C	3.42	< 700
Viscosity @ 100°C	cSt	8.33	7.88	7.23	11.3		< 55
Ash	%w	0.008	0.0079	0.008		< 0.001	< 0.2
Carbon	%w	76.6	77.7	77.5	77.2	87.7	86.8*
Hydrogen	%w	11.9	12	11.4	11.8	13.3	10.6*
Nitrogen	%w	< 0.1	1	0.1	< 0.05	< 0.1	0.4*
Sulphur	%w	< 0.05	< 0.05	< 0.05	< 0.1	< 0.05	< 5
Total Acid Number	mg KOH/g	10.6	2.4	13.1	3.9	< 1	< 1*
Cetane nr	Typical				52	> 40	> 20
Carbon Residue	%		0.57			< 0.2	< 22

**example*

Conduction of the tests and operating conditions

Emissions and fuel consumption were measured at 25, 50, 75 and 100% load operating points. For the tests carried out with the 8L16/24 test-bed the 100 % load point was omitted due to higher injection pressure resulting from the use of a l'Orange fuel injection equipment instead of the normally used Woodward one. Injection and combustion pressures were measured with a Kistler (piezo-electrical) pick-up respectively in the injection pump and in the cylinder cover. The exhaust gas flow was calculated based on the content of carbon dioxide (CO_2) in the exhaust gases and from the fuel consumption. The amount of exhaust flow was then used as a basis for calculation of the specific nitrogen oxides (NO_X) and carbon oxide (CO) emissions.

Fig. A2: Fritzens, Innsbruck/Austria
Engine: 6L21/31, Output: 1 290 kW
Fuel: Recycled frying fat

Properties of the tested biofuels

The various biofuels tested fell within the below standard specification for physical and chemical properties based on the experience of MAN B&W Diesel:

Table A2: Specification of biofuel for MAN B&W Diesel engines

Spezification		
Density (15 °C)	900–930 kg/m³	DIN EN ISO 3675, EN ISO 12185
Flash point	> 60 °C	DIN EN 22719
Lower calorific value	> 35 MJ/kg (typical: 36.5 MJ/kg)	DIN 51900-3
Viscosity (50 °C)	< 40 cST	DIN EN ISO 3104
Cetane number	> 40	FIA
Coke residue	< 0.4 %	DIN EN ISO 10370
Sediment content	< 200 ppm	DIN EN 12662
Oxidation stability (110 °C)	> 5 h	ISO 6886
Phosphorus content	< 15 ppm	ASTM D3231
Na + K content	< 15 ppm	DIN 51797-3
Ash content	< 0.01 %	DIN ISO 6245
Water content	< 0.5 %	EN ISO 12537
TAN (total acid number)	< 4 mgKOH/g	DIN EN ISO 660
Cold Filter Plugging Point	< 10 °C below lowest temperature in fuel system	EN 116

Commercial operation with biofuels

Table A3 below shows the reference list of commercial power plants featuring MAN B&W medium-speed engines operating with biofuels as raw vegetable oils, waste oil and recycled fat.

To secure continuous and economical operation of Diesel engines a large availability of biofuels is necessary. Due to a lower heating value of these fuels the annual fuel consumption of a 1 MW power module is close to 2,000 tons of biofuel. Such large quantities are available from oil- and food processing plants and from several waste collecting stations scattered throughout Europe.

Medium-speed Diesel engines' capacity of burning a wide variety of these fuels is therefore vital to secure continuous operation of the engines (above 8,000 hours/year).

Table A3: References

Reference	Engine type	Power output	Biofuel	Commissioning	Nr. op hours
Qlear, Holland/Switzerland*	9L16/24	760 kW	Vegetable oils / Waste cooking oil	June 2001	> 3,000
Mann Energie, Germany Aigremont, Belgium	9L16/24	760 kW	Raw and waste vegetable oil	June 2001	> 15,000
Qlear/EMACON, Austria	7L28/32H	1,575 kW	Waste cooking oil	January 2004	> 12,000
Fritzens, Austria	6L21/31	1,160 kW	Recycled frying fat	May 2004	> 14,000
Qlear, Italy	7L28/32H	1,575 kW	Recycled animal fat	January 2005	> 2,000
SPE Harelbeke, Belgium	14V52/55	85,000 kW	Palm oil	2005/2006	
Wiessner Distillery, Germany	5L27/38	2,888 kW	Palm oil	2006	
Belgium	18V48/60	17,400 kW	Waste oil	2006 contract signed	
Germany	12V32/40	5,529 kW	Palm oil	2006 contract signed	

**re-commissioned October 2004*

Results

Figure A3 below presents the graphics summarising the most relevant results of the tests conducted at MAN B&W Diesel Holeby's workshop. A comparison of engine performance parameters both for operation with crude palm oil and marine gas oil is depicted: maximum pressure in the cylinder and engine efficiency (measured as the specific fuel consumption) for different loads are presented.

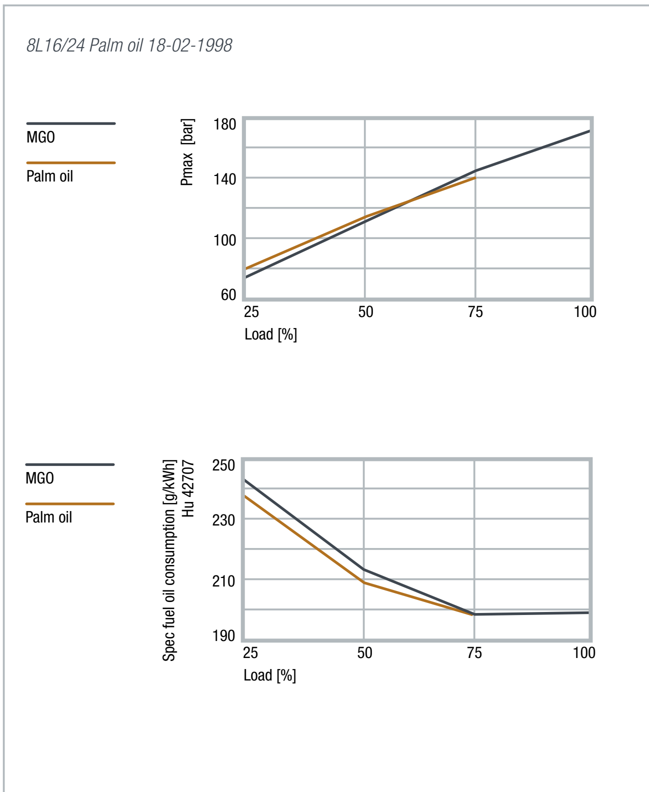
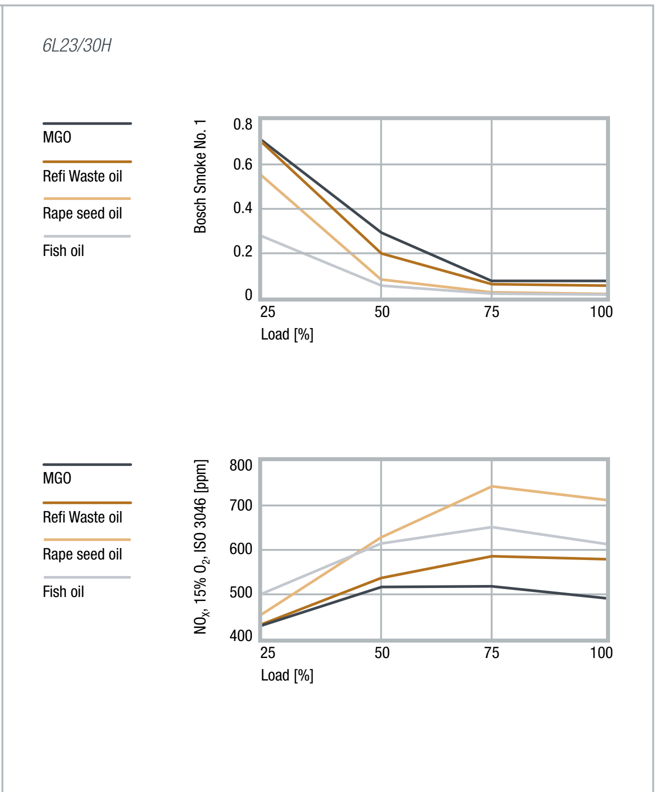


Fig. A3: Maximum pressure inside the cylinder and specific fuel oil consumption for different load steps: palm oil versus Marine Gas Oil operation



Levels of smoke and nitrogen oxides emissions for different load steps: biofuels such as rapeseed, fish oil and refined waste oil against Marine Gas Oil operation.

Discussion / Analysis

- >> Physical and chemical properties for the majority of the biofuels tested were within the minimum quality requirements for operation in medium-speed Diesel engines. Higher viscosity biofuels need to be heated up sufficiently to reduce viscosity to injection levels between 12 to 15 cSt (this corresponds to heating these biofuels up to a level of 60-80ºC).

- >> Biofuel has the following identifying features when compared to Marine Gas Oil: lower net calorific value, higher viscosity and density, lower stoichiometric air-to-fuel ratio because of higher oxygen content.

- >> Some waste and residual oils/fats have acidity (measured by the TAN - Total Acid Number) above the accepted operating limits for conventional injection systems.

- >> There is no major deviation in the combustion process when running Diesel engines with biofuels. The tests showed similar patterns in the rate of heat release during the combustion as well as measured maximum cylinder pressure rise with increased loads on engines running both with biofuels and Diesel oil.

- >> There is no substantial change on the engine efficiency and measured specific exhaust gas flows. Carbon dioxide specific emissions of biofuel combustion in Diesel engines are therefore very similar to the ones when using mineral fuels since the lower calorific value of biofuels is compensated by the lower carbon content of these fuels. In the case of vegetable oils one should account for the positive contribution to the carbon dioxide cycle since this greenhouse gas is captured back when growing the crop.

- >> While sulphur oxides are negligible and smoke emissions are significantly lower, nitrogen oxides emissions could experience however an increase by operation with biofuels. Installation of catalytic ‘DeNOx’ systems allow the abatement of these emissions down to the level of the strictest environment regulations (e.g. German Clean Air Act - TA-Luft).

- >> Reliable commercial operation of medium-speed engines with biofuels is proven by over 15,000 operating hours burning biofuels with FFA content of 2% (TAN 4).

Conclusion

MAN B&W medium-speed Diesel engines are biofuel compatible. Its fuel quality capabilities are far beyond the restrictions found in automotive applications.

Several commercial green-power plants have now been realised in Europe and good long-term operational reliability has been confirmed.
Availability of large quantities of biofuels is however necessary to ensure reliable and continuous power. The capacity of medium-speed Diesel engines to burn a wide variety of these fuels is therefore vital to secure continuous operation of the engines.

The possibility of combining sound economics and superior eco-friendliness is leading to the optimisation of Diesel engine's biofuel combustion to affirm this prime mover as one of the best available technologies for renewable power generation applications.

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Appendix A1

Workshop tests conducted at MAN B&W Diesel Augsburg, Germany

During the third quarter of 2004 a number of tests with a liquid biofuel (BF) were carried out in a single cylinder research engine at MAN B&W Diesel's headquarters in Augsburg.
The purpose of the tests was to compare the engine performance and emissions when running with this biofuel against the results of operation with most commonly used mineral fuels as Heavy Fuel Oil (HFO) and Marine Gas Oil (MGO).

Conduction of the tests and operating conditions

Measurements were taken between 10 and 100% load during generator operation. Charge air pressures and exhaust gas pressures on the single cylinder test engine were adjusted to be identical to the 6 cylinder engine 6L32/40.

Single Cylinder Research Engine 1L32/40 with external supercharging

- >> Bore: 320 mm
- >> Stroke: 400 mm
- >> Engine Rating: 480 kW at 750 rpm
- >> Mean effective pressure: max 30 bar
- >> Firing pressure: max. 250 bar
- >> Injection System: Common Rail
- >> Combustion Chamber: CD (serial)
- >> Injection Nozzle: 13x0.43-82º
- >> Valve Timing: Valve overlap: ~75º CA, Inlet valve close: ~905º
- >> Mass balancing: 1st and 2nd order

Table A5: Characteristics of MAN B&W single cylinder 1L32/40 test-bed

Fig. A4: Biofuel combustion development workshop testing.

Results

Figures below present the graphics summarising the most relevant results of the tests conducted at MAN B&W Diesel Augsburg's workshop. A comparison of the test engine performance parameters both for operation with Biofuel, Marine Gas Oil and Heavy Fuel Oil is depicted in figures A5 and A6: injection duration, injection delay and ignition delay for different loads are presented.

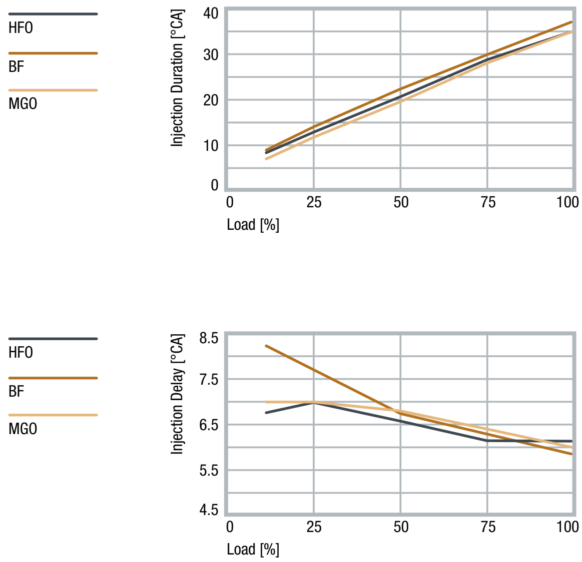

Fig. A5: Comparison of injection duration and delay for different engine loads

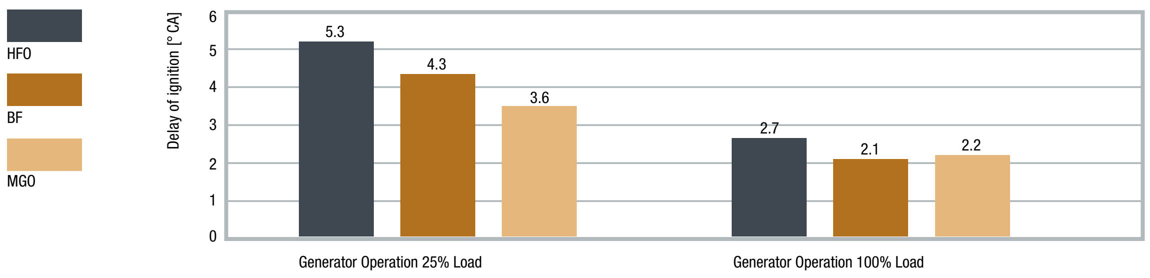

Fig. A6: Comparison of ignition delay for different engine loads

The resulting thermal efficiency and emissions of biofuel operation against the ones resulting from running the test engine with MGO and HFO is depicted in figure A7 below:

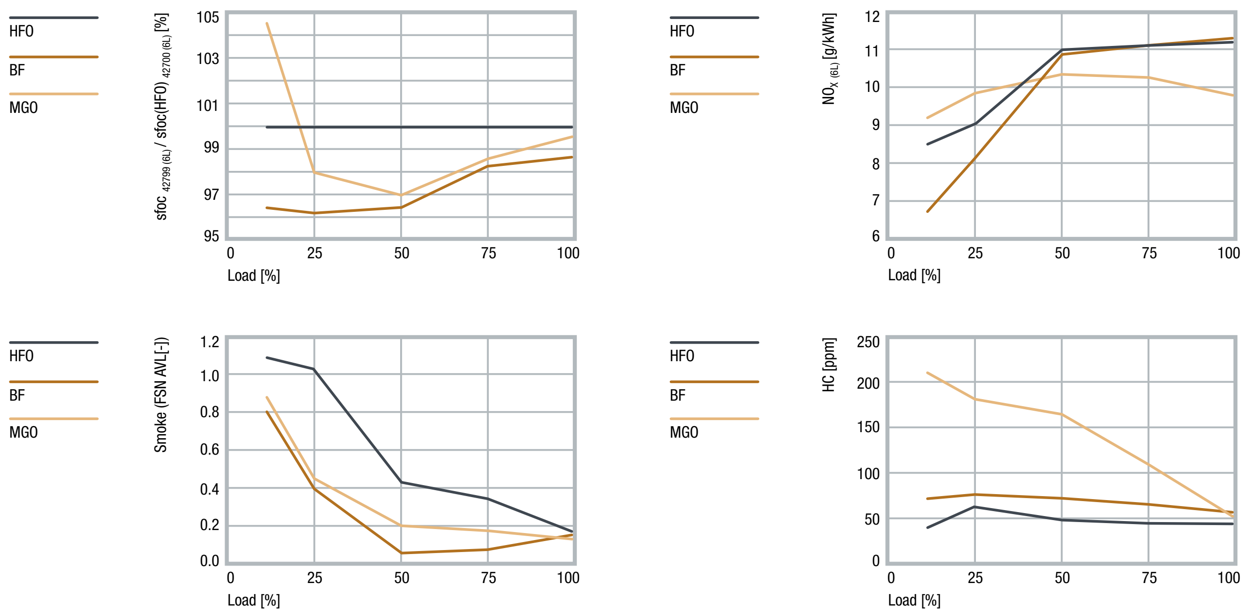

Fig. A7: Comparison of thermal efficiency and emissions for different engine loads

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