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Operating Performance of a Tractor Engine of Emissions Standard EU IV in Biodiesel Operation

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The use of pure biofuels in agricultural machinery offers the opportunity to reduce the use of fossil fuels. These engines are largely fuelled by self-consumption gas stations. Based on the introduction of new emission standards at the beginning of the decade it was determined that the engines have to comply with the emission limits regardless of the used fuel. At the Chair of Piston Engines and Internal Combustion Engines (LKV) of the University of Rostock it was investigated to what extent modern diesel engines for agricultural machinery are suitable for long-term operation with biodiesel fuel according to EN 14214.

1 MOTIVATION

Due to their high energy density, mainly liquid fuels of primarily fossil origin are used to power vehicles. In order to cut down the dependency on crude oil and greenhouse gas emissions at the same time, research has been carried out on alternative and renewable fuels for many years. With its action plan to promote biofuels, the EU Commission aims to replace 10 % of conventional fuels used throughout Europe with biogenic fuels by 2020. What is more, the Directive 2009/28/EC also stipulates a 10 % share of renewable energies in the transport sector, 5 % of which is to be produced from residual materials such as used fats [1].

A fleet operation with 100 % biodiesel (B100) in the agricultural sector is an approach that may significantly contribute to fulfilling the quota obligation. This is why this project aims to provide the proof in principal for the suitability of 100 % biodiesel for operating series engines of the emissions standard EU IV (non-road) for industrial and agricultural applications on a typical engine used for agricultural purposes, the Deutz TCD 3.6.

In doing so, primarily the potential deactivations of the Exhaust-gas Aftertreatment system (EAT system) due to fuel trace elements (P, K, Na, Ca, Mg) are being investigated in long-term operation. Detailed analyses of the Diesel Particulate Filter (DPF) include investigations regarding loading and continuous regeneration using the NO_2-based CRT effect. To ensure there is a fault-free operation for the end user with B100, the On-board Diagnostics (OBD) system function is also tested.

The main focus areas of the research project included: Firstly, an extensive functional test of the engine is carried out in stationary operation (C1 cycle and selected stationary load points) with reference DF (DIN EN 590) and biodiesel (DIN EN 14214). The effect on the functionality of the exhaust gas aftertreatment system is also recorded and analyzed during this process. Furthermore, a continuous test of 1000 operating hours is to provide information on the long-term durability of the engine and its EAT system.

The overall objective of the project is to gain general scientific insights into whether and under which conditions modern agricultural machines of the EU IV emission legislation (tantamount with US emissions standard Tier 4 final) can be operated with biodiesel so that suitable and tested drive units will be available in good time for the use of B100 for agriculture purposes.

Parameter	Unit	Data
Rated power	kW	100 at 2200 rpm
Maximum torque	Nm	500 at 1600 rpm
Displacement	l	3.6
Stroke	mm	120
Bore	mm	98
Approval fuel	-	DIN EN 590
Fuel injection system	-	CR maximum 1600 bar
EGR	-	Cooled high-pressure EGR
EAT	-	DOC, DPF, SCR, ASC
Emission standard	-	EU IV
Engine oil	-	Quality class Deutz DQC IV-10 LA

TABLE 1 Technical data of the four-cylinder test engine Deutz TCD 3.6 (© Deutz)

2 SETUP AND MEASURING TECHNOLOGY OF THE ENGINE TESTS

For the engine tests, a series engine TCD 3.6 was operated on an engine test bench with the described fuels. In the engine control unit, no adjustment was made to the fuels to analyse the effects of the fuel on the series engine. The technical data of the test item is shown in **TABLE 1**.

The engine has an exhaust gas aftertreatment system from the catalytic converter manufacturer Umicore, which has been developed to comply with the emissions standard, and consists of a Diesel Oxidation Catalytic Converter (DOC), a DPF, a Selective Catalytic Reduction (SCR) Catalytic Converter and an Ammonia Slip Catalyst (ASC), **FIGURE 1**. Upstream of the SCR catalytic converter there is an AdBlue dosing line, which consists of a dosing

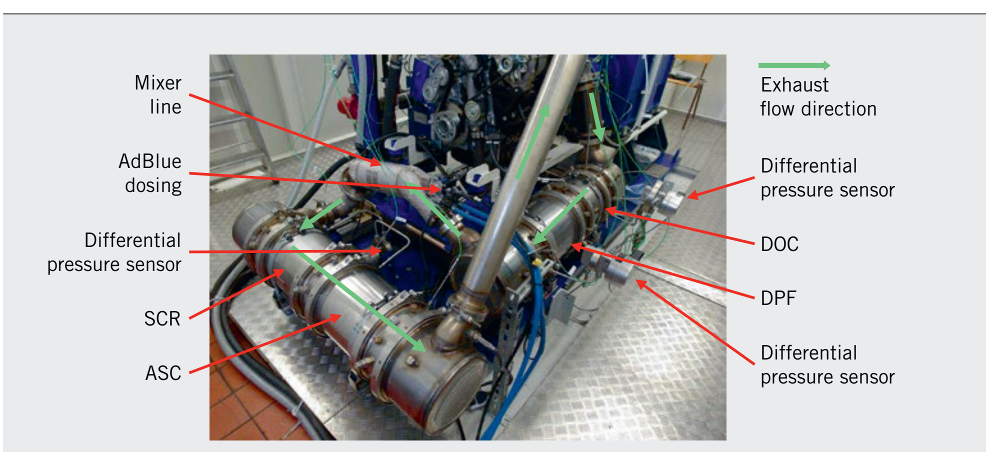

FIGURE 1 Setup of the exhaust aftertreatment system of the engine on the test bench (© University of Rostock)

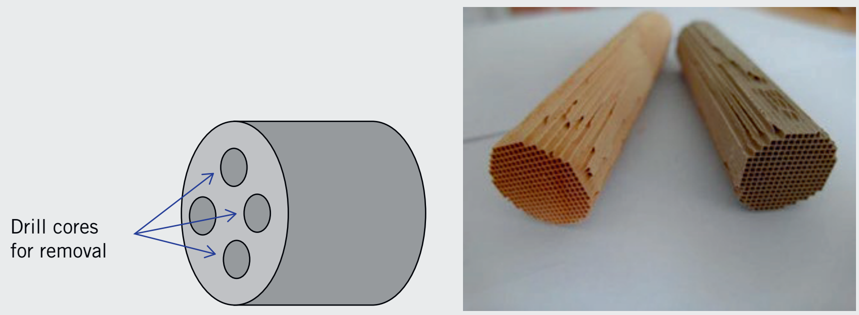

FIGURE 2 Representation of drill core removal and cores from the DOC and SCR (© University of Rostock)

valve, supply lines and a tank with pump. The mixer line is required to mix exhaust gas and AdBlue.

The components are modular in construction in close-to-series cannings. There are intermediate rings arranged between the individual EAT components in order to accommodate the measuring points, which contain all of the necessary measurement connections to accommodate the temperature, pressure and exhaust sampling probes. The EAT components and the intermediate rings are connected via V-band clamps, which allow for quick assembly and disassembly of individual components. The chosen setup of the EAT system is used to allow for extensive investigations of the short-term and long-term performance of the individual EAT components, in particular that of the DOC and the SCR, which were disassembled and assessed at regular intervals. During the 1000-h endurance test drill cores were removed at specified intervals and analysed, **FIGURE 2**.

For the exhaust gas analyses, four commercial exhaust measuring systems are used synchronously in parallel operation at a measurement rate of 1 Hz. The exhaust gas sampling points are located downstream of the turbine (ATL) upstream of DOC (raw exhaust gas), downstream of DOC/upstream of DPF, downstream of DPF/upstream of SCR and downstream of the SCR system (End-of-Pipe, EoP).

3 RESULTS

In order to characterize the performance of the engine, the full load curve and the engine characteristics were recorded for the respective fuels B100 and DF. This data illustrates the measuring points for the C1 test, **FIGURE 3**. As already described, the heating value has a special effect on the operating performance of the engine. Due to the low heating value and the related lower energy density of the biodiesel, the full load curve shows slightly less torque in B100 operation compared to DF operation. This results in the engine reacting to the lower heating value with a load point shift in the control unit, where the control unit fulfils the torque requirement with an increased quantity of fuel. This means that extra fuel consumption in biodiesel operation is recorded. **FIGURE 4** also shows the measured fuel consumption without heating value correction. If the fuel consumption is corrected by the heating value, the specific fuel consumption is relativized from B100 to DF.

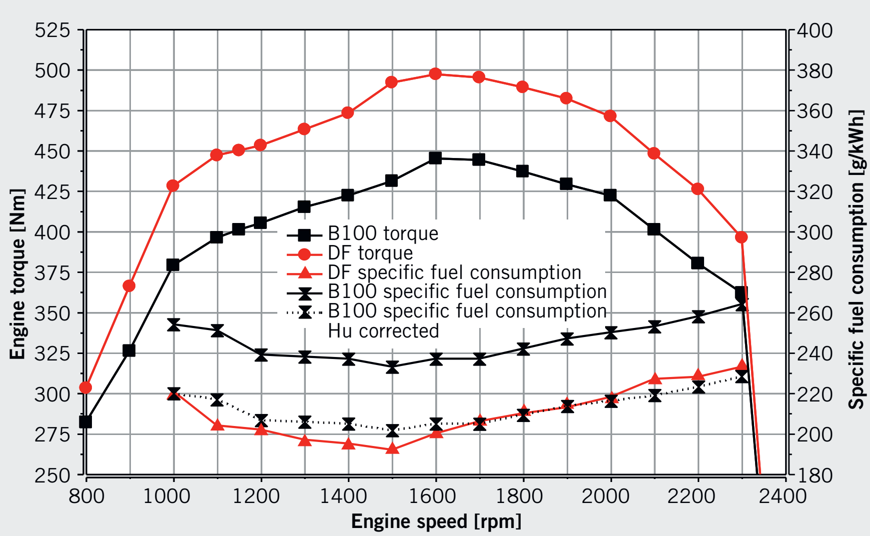

FIGURE 3 Torque curve and fuel consumption of DF and B100 (© University of Rostock)

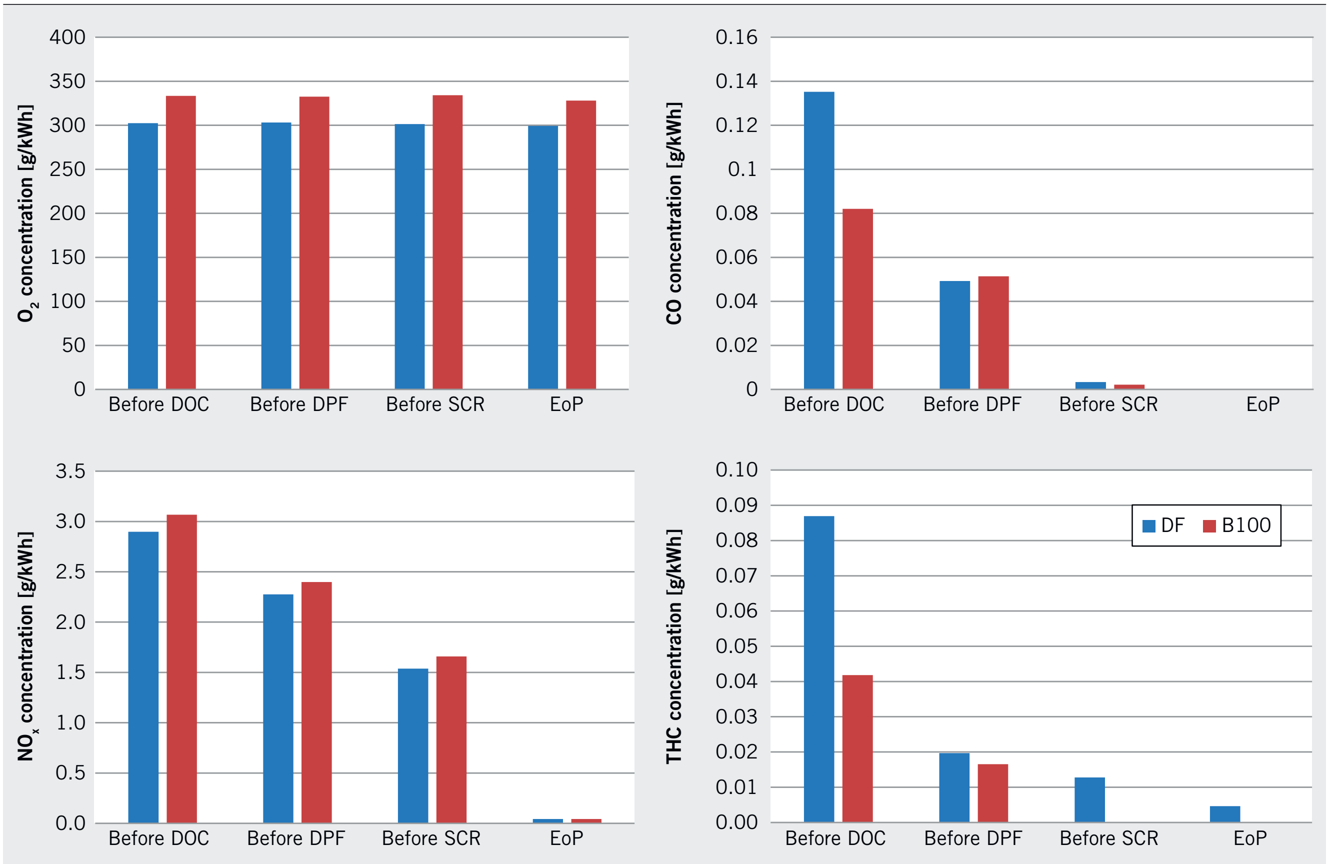

FIGURE 4 Exhaust gas concentrations for DF and B100 at load point 6 (n = 1600 rpm, M = 370 Nm) (© University of Rostock)

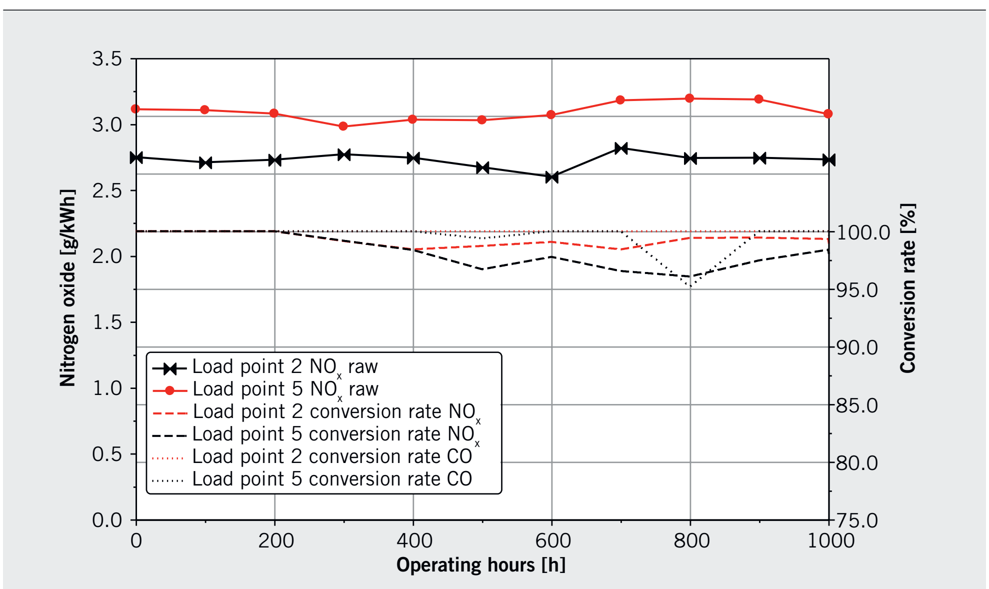

FIGURE 5 Nitrogen oxide concentrations and conversion rates throughout the operation time of 1000 h for B100 operation (© University of Rostock)

Due to the bonded oxygen in B100 fuel, the concentration of oxygen in the exhaust gas increases. Furthermore, the additional oxygen contributes towards an improvement in the oxidiation of unburned hydrocarbons (THC) and carbon monoxide (CO). Therefore, it was shown that the concentrations of CO and THC are lower in biodiesel. **FIGURE 5** shows an example of a load point with average load and speed (n = 1600 rpm and M = 370 Nm). It was possible to prove that the exhaust aftertreatment system operates reliably. The conversion rates of DOC and SCR exceed 90 % regardless of the fuel. The concentrations of CO and THC are end-

Emissions	Unit	DF	B100	B100 (after 1000 h)	Limits
CO	g/kWh	0.007	0.003	0.007	5.00
HC	g/kWh	0.026	0.011	0.030	0.19
NO_x	g/kWh	0.114	0.127	0.190	0.40
Particle	g/kWh	0.013	0.007	0.007	0.025

TABLE 2 Specific emissions from the C1 test with limit values (© University of Rostock)

of-pipe at the detection limit. Due to the downstream exhaust aftertreatment, the engine is also clearly capable of complying with the specified EU IV emissions standard with a considerable reserve even in B100 operation, **TABLE 2**.

In order to assess deterioration changes in engine operation and in the exhaust aftertreatment system, a continuous test of 1000 operating hours was carried out in biodiesel operation. **FIGURE 6** shows the nitrogen oxide concentrations of the raw exhaust gas as well as the conversion rates of nitrogen oxides and carbon monoxide are exemplary for the load points 2 (n = 2300 rpm, M = 310 Nm) and 5 (n = 1600 rpm, M = 442 Nm) throughout the operation time of 1000 operating hours. It is possible to record that there are no deterioration effects in the EAT system throughout the operation time in B100 operation.

Furthermore, the individual core samples were investigated after the 1000-h continuous test by Umicore. First of all, the specific surface area of the catalytic converters was analyzed. A BET analysis was carried out to do this. **FIGURE 6** shows the BET values of the SCR as a function of the operating hours. It shows that there are no anomalies throughout the operating time. In an additional step, the light-offs were determined in order to find out the conversion rates. The T50 and the T80 value for NO_x conversion are shown in **FIGURE 7**. T50 or T80 represent the temperature here which is required for a NO_x conversion of 50 or 80 %. The blue dashed line (fresh T50) represents the temperature for a 50 % conversion of the NO_x emissions in the initial state of the SCR. The red dashed line (30B600-T50) in the middle indicates a SCR hydrothermal aging at 600 °C for 30 h and is considered a limit. For the catalyst tested, this temperature coincides with the 80 % conversion point of the fresh catalyst (T80 (fresh)). The upper red dashed line (30B600-T80) indicates the limit for a hydrothermally aged catalyst at a conversion of 80 %.

It shows that the NO_x performance (T50/T80) up to 800 h is within the deterioration window. After 800 h, the performance drops slightly. The core sample of 1000 operating hours was then subjected to two regenerations at 600 °C for 30 min. This resulted in a performance increase that allowed the deterioration window for T50 and T80 to be complied with. It should also be mentioned at this point that no active regeneration or other heat modes were performed in the continuous test. It is assumed that with active regeneration strategies the performance of the SCR would be within the deterioration window.

4 SUMMARY

In order to operate diesel engines of the latest generation with alternative fuels in agricultural vehicles, the engines and their exhaust gas aftertreatment for the fuels must be approved. This involves corresponding engine tests. At the Chair of Piston Machines and Internal Combustion Engines (LKV) of the University of Rostock, fundamental tests with more than 1700 engine operating hours were carried out on an agricultural engine of the emissions standard EU IV in 100 % biodiesel operation as part of the project. The aim of the experiments was to provide fundamental evidence of the long-term suitability of EU IV industrial diesel engines and their exhaust gas aftertreatment systems for operation with biodiesel or biodiesel blends. Serving as a reference, the original condition of the test carrier was a Deutz TCD 3.6 in diesel operation. The full load curve and the stationary C1 test were points of reference. The subsequent extensive investigations with biodiesel operation took place without any modifications or software adjustments of the engine.

It was shown that the biodiesel results in an increase of the volumetric fuel consumption due to the lower heating value. If the consumption is corrected by the heating value, the differences are within the measuring accuracy. Changing the volumetric fuel consumption also changes the injection volume per operating cycle to the point that a shift in the operating point in the engine control unit is determined when operating with biodiesel. For example, the injection time for the individual injections is adjusted and injections are carried out earlier for higher injection volumes. The investigations showed that biodiesel has a positive effect on the composition of the raw exhaust gas (downstream of cylinder, upstream of exhaust aftertreatment). This is why the engine produces lower carbon monoxide and hydrocarbon raw emissions in biodiesel operation compared to diesel operation. Furthermore, lower smoke numbers (FSN) were determined for operation with biodiesel. This is an important knowledge for potential biodiesel application of the particulate filter. Compared to the reference operation with diesel, the nitrogen oxides in the raw exhaust gas had slightly increased in biodiesel operation,

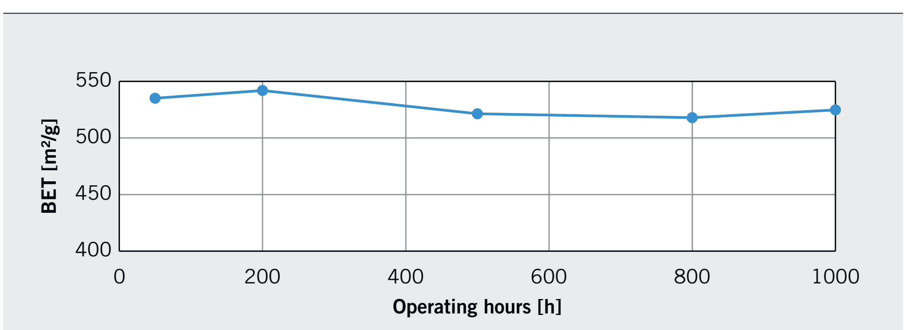

FIGURE 6 BET of the SCR throughout the operating time of 1000 h (© University of Rostock)

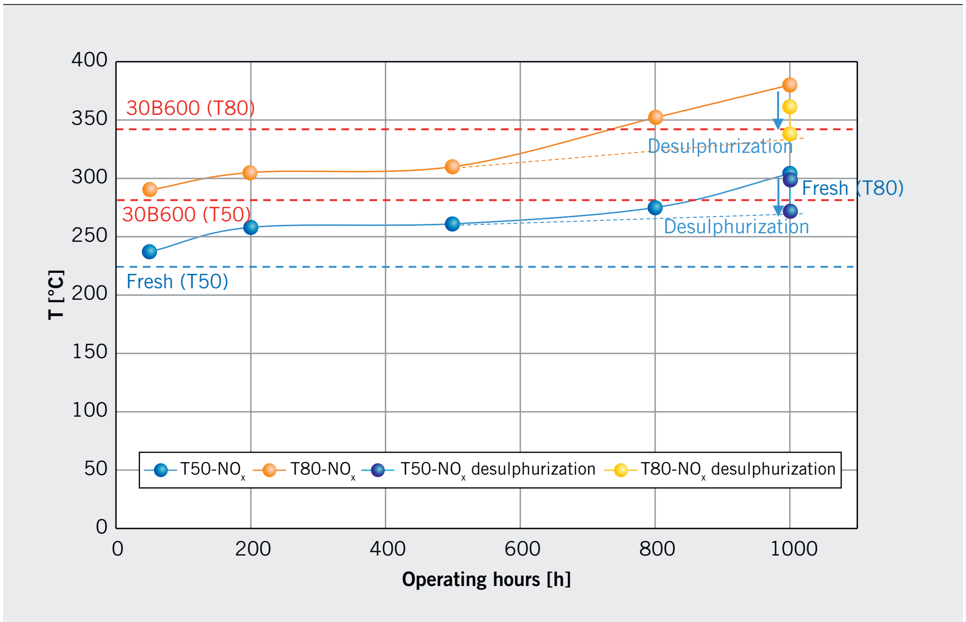

FIGURE 7 T50 and T80 value of SCR performance throughout the operating time of 1000 h (© University of Rostock)

which was also the case in earlier engine tests. These increased nitrogen oxide emissions in the raw exhaust gas were safely reduced to values below the EU Stage IV limit values thanks to the SCR catalytic converter. At the end-of-pipe, with the measuring point relevant for the exhaust gas test, no differences were determined between diesel operation and biodiesel operation. The exhaust-gas aftertreatment system, which consists of DOC, DPF and SCR system, operated in both diesel and biodiesel operation in accordance with its construction so that the end-of-pipe emissions could reliably comply with the emissions standard Euro IV and Euro V.

Detailed analyses of the DPF include investigations regarding loading and continuous regeneration using the CRT effect. Here it was shown that the loading of the DPF also decreases due to a reduction of the smoke numbers (FSN) in B100 operation. Furthermore, it was shown that the functionality of the DOC and the SCR catalytic converter is fully guaranteed when using B100. The conversion rates in stationary operation exceeding 90 % that are required to fulfil the emissions standard are reliably attained for the long-term. The test engine is stable over a long period of time in biodiesel operation, which was proven in a 1000-h continuous test. There was no change in engine performance throughout the operation time. The EAT system was just as reliable. Here too, the emissions standard Euro IV was successfully complied with after the 1000-h continuous test. Primarily the potential deactivations of the EAT system, due to fuel trace elements (S, P, K, Na, Ca), were not determined in long-term operation. In normal operation of the agricultural engine, the regeneration of the DPF takes place both in DF and in biodiesel operation via a CRT process without any additional exhaust heat strategies (heat modi). The investigations showed that it is possible to successfully repeat the standstill regeneration of the DPF in diesel and biodiesel operation. This ensures that the high EAT performance is available over a longer period. The continued development of mixture formation over the last ten years has led to a significant reduction of fuel entering lubricating oil in biodiesel operation.

The positive project results were an essential component for the approval of the current Deutz engine series for the EU IV emissions standard in the technical circular TR 0199-01218/4 fuels [2]. Since the EAT system tested is also basically used for engines with the emissions standard EU V, an approval of B100 also seems to be generally possible here.

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