Injection Spray Comparison of Diesel Fuel and Cold Pressed Rapeseed Oil Fuel

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Abstract

Diesel engines are popular not only for highway vehicles but also for working machines such as agricultural tractors. In this application it is also common to use fuels other than diesel. One of these fuels is cold pressed rapeseed oil. However, this vegetable oil has different physical properties than diesel fuel. This leads to different spray behaviour in an internal combustion engine, and subsequently to other emission levels. In this study the spray patterns of a diesel fuel Common Rail Injector are compared to spray patterns of cold pressed rapeseed oil with the same injector. The results are linked to engine emissions detected on an engine test bench.

Introduction

Exhaust gas emissions from agriculture machines are often neglected in public discussion, which is dominate by on-road vehicle emissions. For manufactures of non-road and agricultural vehicles, the emission levels for EU Stage I to EU Stage IIIA only the NRSC (**N**on **R**oad **S**tationary **C**ycle) is used to certify emission levels. Beginning with EU Stage IIIB in 2011 for high load engines and 2012 for low load engines respectively, the emission level is also verified by the NRTC (**N**on **R**oad **T**ransient **C**ycle). The EU Stage IIIA emission standard introduces a hard reduction of PM emissions of approximately 90% compared to EU Stage II, see **Figure 1**.

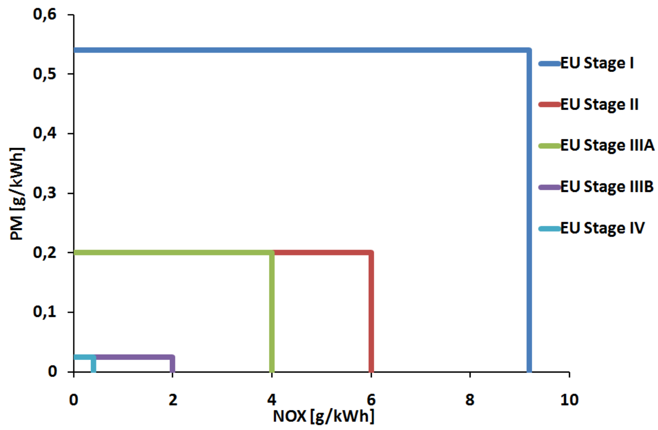

Figure 1. Relevant emission standards for non road vehicles (EU), [1]

The next emission level, EU Stage IV, which comes into action in 2014, will force a significant reduction of NO_X emissions at a consistently low PM level (EU Stage III). In addition to these new and challenging regulations, the continued use of diesel fuel for agricultural vehicles cannot be taken for granted by the manufactures. Due to the fact, that rapeseed oil (RSO) is available and can be used as an alternative to pure diesel fuel, new generations of engines should be able to achieve EU Stage IIIB and IV with this special fuel. The engine manufacturers are currently developing strategies to achieve these emission standards. One possibility is the use of exhaust after-treatment methods like SCR[1] or DPF[2], although the application of these techniques in conjunction with rapeseed oil is not yet possible in a reliable way due to ash accumulation. Another method is to extend the possibilities of modern Common Rail Injection to achieve the emission levels without cost intensive and as yet unreliable after-treatment methods. The challenge here is the different fuel behaviour of rapeseed oil regarding viscosity and surface tension.

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[1] SCR = Selective Catalytic Reduction
[2] DPF = Diesel Particulate Filter

Rapeseed Oil

Rapeseed oil belongs to the group of triglycerides regarding the chemical structure. It consists of a trivalent alcohol and additionally one, two or three fatty acids. The fatty acids differ in the amount of C-Atoms. Normally the length is restricted to between 16 to 22 C Atoms, see **Figure 2**.

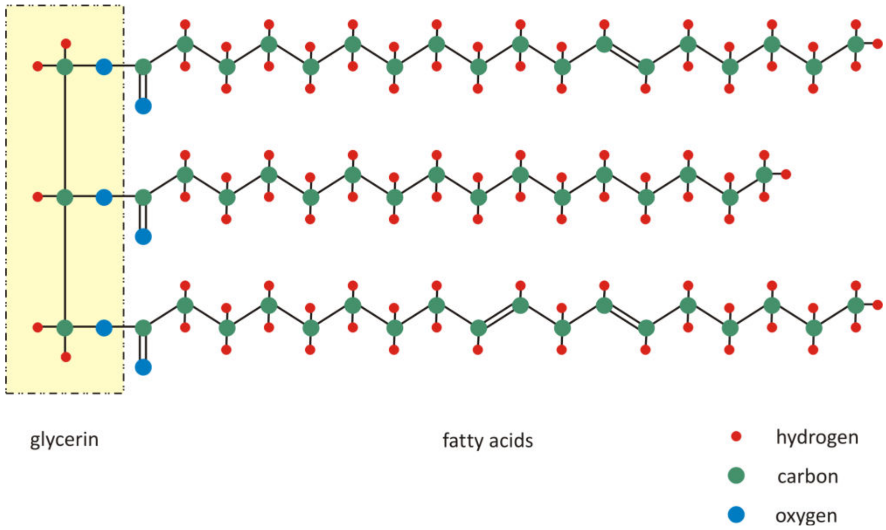


Figure 2. Chemical structure of rapeseed oil (RSO), [2]

In **Table 1** typical and important fuel properties are listed.

Table 1. Important Fuel Properties of Rapeseed oil (RSO), [3]

Physical property	Unit	**Diesel**	**Rapeseed oil (RSO)**
Density ρ (15°C)	kg/m^3	835	920
Kin. viscosity ν (20°C)	mm^2/s	3.08	78.7
Kin. viscosity ν (40°C)	mm^2/s	3.2	33.1
Surface tension σ (40°C)	mN/m	27	33
Gross caloric value	MJ/kg	42.6	37.7
Volumetric caloric value	MJ/dm^3	35.6	34.7
Cetan number	-	50-54	39-44
Flashpoint	°C	64	230
Sulphur	%m/m	0.035	>0.001

Due to the distinctly higher kinematic viscosity of rapeseed oil compared to diesel fuel, it needs to be heated before it can be used as fuel for non road engines. Rapeseed oil (RSO) reaches the kinematic viscosity level of diesel from a temperature level starting at approx. 100°C. In general, RSO is not heated higher than 70° C, due to polymerisation which starts at approx. 75°C. This clearly implies that for the atomization process the temperature level is a significant influencing variable. Apart from this the flashpoint of RSO is also very different to that of diesel. This behaviour can be attributed to the different saturated liquid line, see **Figure 3**. The decelerated evaporation of RSO leads to a delayed fuel mixing process in the combustion chamber of the combustion engine. Hence, problems with the combustion in low load operation can be expected, which can result in higher CO-emissions for example.

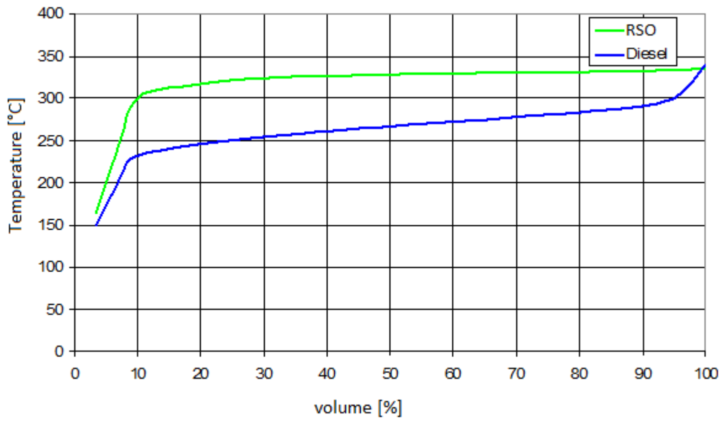


Figure 3. Saturated liquid line RSO and diesel

Test faculty

For the studies a high pressure research chamber is used. The chamber was designed to cope with pressures of up to 120 bar under cold conditions. Under these conditions it is possible to simulate the air densities which are found in modern diesel engines, even when they are highly super- or turbocharged. Pressurization of the injection chamber is achieved using pure nitrogen.

For visual investigation the chamber has 5 optical accesses, see **Figure 4**. There are 4 windows on the sides of the pressure chamber. Their dimensions are 120mm x 80mm. The lower window, with a diameter of 160mm is used to observe the whole spray of an injector and not only one jet. This is necessary for observation of asymmetrical spray development and spray to spray deviations. The injector is mounted on a special plate which can be moved sideways. Thereby on can observe sprays jets with approx. 130 mm length through the side-windows and more than 160 mm sprays from bottom of the chamber.

The tests described in this study have been performed at cold conditions (293 K) and under pressures of 40 bar.

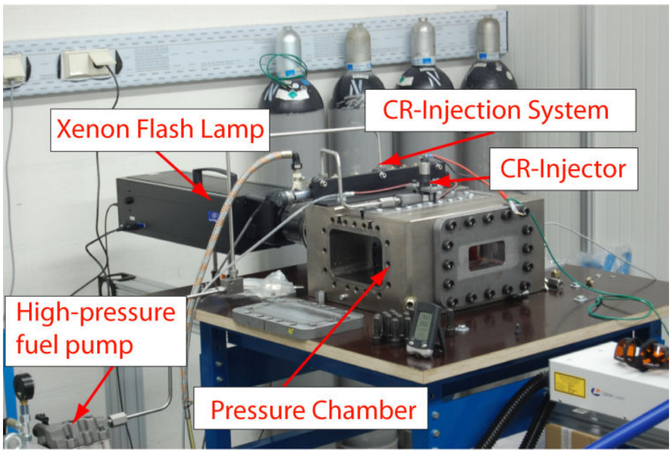


Figure 4. Research Chamber with Mie-Scattering apparatus

In the experiments the macroscopic spray characteristics using the Mie-Scattering Technique were investigated.

Fuel injection system and test set up

A modern Common Rail Injection system was fitted to the research chamber. The high pressure pump is oil lubricated. For that reason it is possible to investigate alternative fuels. The maximum pressure level which can be achieved is 2400 bar. The injector is a single circuit injector used in a John Deere 6 Cylinder Engine with a maximum Power output of 142kW (720Nm Torque). The injector is a sac-hole injector with 6 spray-holes and an outlet-diameter of 160µm. The k-factor, according to the Blessing definition - equation 1, is equal to 1 [4].

The L/D-Ratio is 5. The injector has an upper entry radius (HE Rounding) of 60µm, see **Figure 5**. To get the inner-nozzle data, a special polymer cast investigation was performed.

$$k = \frac{D_{out}[\mu m] - D_{in}[\mu m]}{10} \tag{1}$$

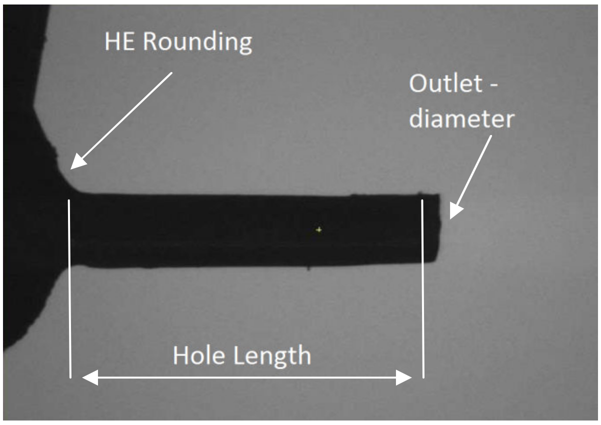


Figure 5. Nozzle-cast with technical data

The injection duration is set to 900µs for all experiments. In engine operating conditions this is the exact timing for diesel fuels. When operating the engine with RSO, the injection duration is slightly shorter to get the same power output for the engine. In order to better compare the macroscopic spray data, the injection duration was held constant.

The engine operating point investigated was a low load point at 900 rpm and 72Nm. At this operating point the CO-emissions are 5 times higher when using RSO instead of diesel, see **Figure 6**.

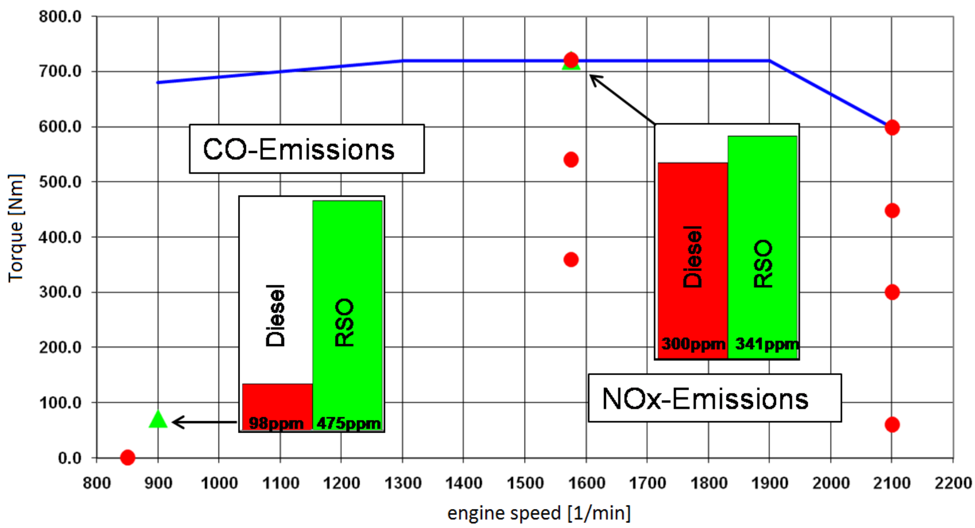


Figure 6. Engine map with NRSC Test Points and selected emissions (measured at test bench), [6]

The rail pressure at this operating point is set to 400 bar for diesel and 600 bar for RSO. These values were investigated in the constant volume vessel to gain a better understanding why the CO-emissions arise in such a manner.

For the investigations with RSO the tank was equipped with heating elements to achieve the same temperatures as in the engine. Due to problems which can occur with polymerization, the temperature of RSO in the tank was held at a constant level of 60°C. To avoid a cooling of RSO in the rail and the conduction from the rail to the injector, the conductors were also equipped with a heating filament with a temperature of between 54-60°C.

Mie-Scattering Technique

In order to investigate the macroscopic spray behaviour, a Mie-Scattering Technique was used. For illumination a helical xenon-flash lamp with illumination energy of 450J and a 19.9ms light pulse width was used. The spray parameters were recorded with a High-Speed CMOS camera. For all investigations the frame rate was set to 15'000 fps. The spatial resolution was set to 960 pixels for the horizontal resolution and 416 pixels for the vertical resolution, respectively.

The macroscopic spray parameters investigated with this technique are shown in **Figure 7**.

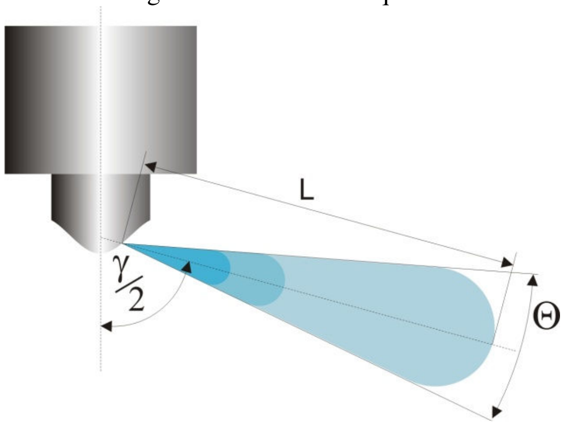


Figure 7. Investigated macroscopic spray parameter (Length L, Spray angle Θ)

Investigation results - Macroscopic spray parameters

All results shown in this study were performed in a cold chamber ($T_{chamber}$ = 293K) with a pressure level of 40 bar. The fuel temperatures for the experiments and some physical data for diesel and RSO are shown in the table below.

Table 2. Physical properties of test fuels

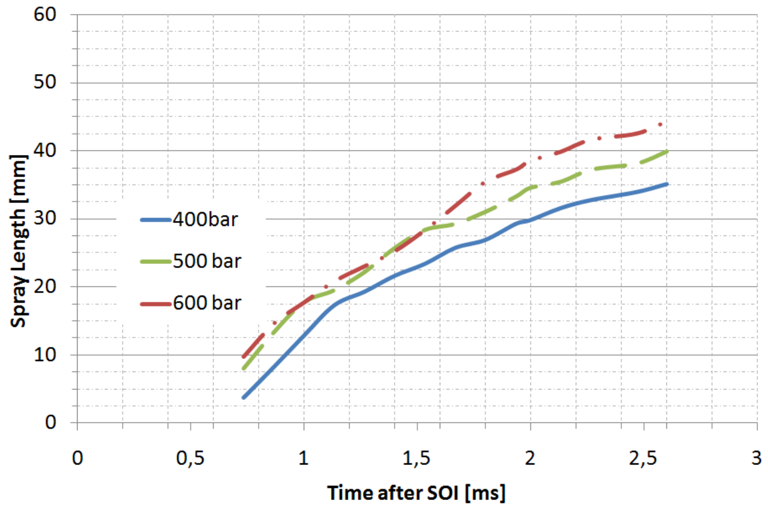
	Fuel temperature K	**Surface tension mN/m**	**Kinematic viscosity mm^2/s**
Diesel (400, 500 & 600 bar)	20°C	27	3.08
RSO 400 bar	51°C	approx. 32	approx. 24.5
RSO 500 bar	52°C	approx. 31	approx. 24
RSO 600 bar	58°C	approx. 27	approx. 20

Regarding **Table 2** it is obvious that the macroscopic spray parameters differ significantly. Even without taking the experiments into consideration it is clear that, in operating an engine with RSO, measures must be obtained to adjust the spray behaviour to pass the EU Stage IIIB and IV emissions level. This adjustment can involve the heating of RSO, a different injection strategy or, for example, raising the injection pressure in conjunction with high exhaust gas recirculation (egr).

Comparison of diesel and RSO

An analysis of the injection process has to be performed before the injection strategy is changed for RSO-operating mode. The macroscopic spray parameters are of particular interest.

Figure 8 shows the spray length in dependence of rail pressure. As already mentioned, the focus of these investigations was to show the differences in the low load operating point (900 rpm / 72 Nm), see **Figure 6.** It can be seen that the spray length for diesel is higher than that for RSO. Regarding the spray length at 500 bar, a decrease of 10mm in spray penetration compared to diesel can be observed. Another important point concerning the general spray behaviour is the delay when a spray is formed. In the case of diesel fuel, the delay time is approx. 600µs after the solenoid of the injector is energized. The first spray when using RSO is formed approximately 1000µs after the solenoid is energized. This can be attributed clearly to the higher kinematic viscosity of RSO during the experiments. The lower spray penetration of RSO is a result of higher surface tension, leading to lower Weber-Numbers, and higher kinematic viscosity. A visual comparison of this behaviour is shown in the appendix.



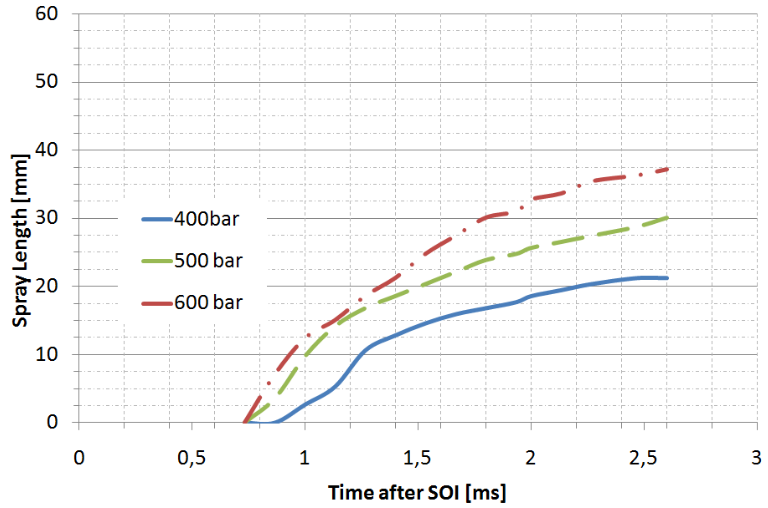


Figure 8. Spray length for diesel (upper) and RSO (lower)

One additional effect lowering the spray penetration is the constant solenoid energizing time of 900µs. In the case of RSO, the needle of the injector opens later and subsequently less fuel is injected, which also leads to a decrease in the spray penetration.

The influence of higher viscosity and higher surface tension, leading to a delayed droplet break up, can also be observed in the spray angle, see **Figure 9**. The spray angle for RSO is always smaller than that for diesel. A decreased spray angle in combination with a decreased penetration length leads to less air entrainment into the fuel spray. Subsequently, the mixing process is lower, and zones of higher equivalence ratios can be observed. In this case, both the ignition delay and the CO and soot generation are increased. One further aspect is the possibility of incomplete combustion, which can occur as a result of the combination of the spray parameters, lower evaporation and, of course, of the distinctly higher flashpoint, see **Table 1**.

Regarding the spray characteristics of the experiments performed in a cold chamber in respect of engine behaviour, evaporation tests should be performed, because the macroscopic spray parameters between the 400 bar diesel and 600 bar RSO spray similar similar characteristics, see **Table 3**.

Table 3. Results after 2.6 ms after solenoid energizing

	Spray penetration length mm	**Spray cone angle** [°]
Diesel 400 bar	35.1	22
RSO 600 bar	37.2	23

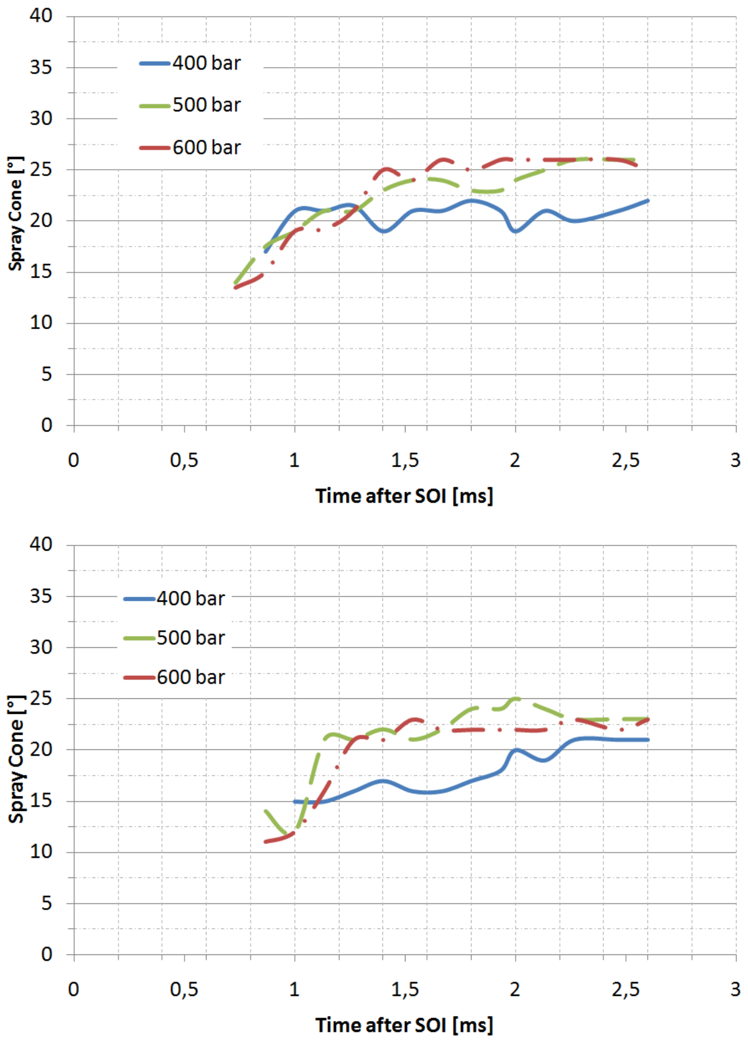


Figure 9. Spray cone diesel (upper) RSO (lower)

All previously shown results were obtained from spray jet #1, see **Figure 10**. Comparing these results to spray jet #4, for example, the general observed behaviour is the same, but the absolute data varies. This is shown to be the case for diesel case in **Figure 11** for the spray penetration length.

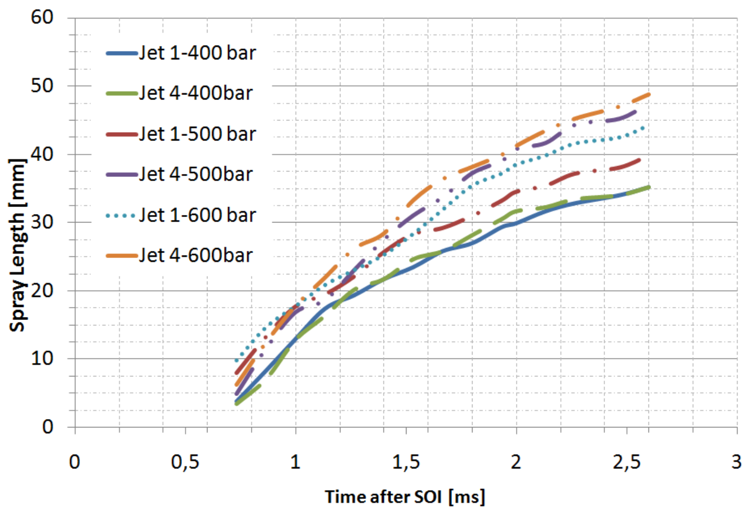


Figure 10. Spray penetration length - jet#1 and jet#4

One can also see that spray jet #1 is significantly wider than spray jet #4. This can also be observed for other spray cone angles.

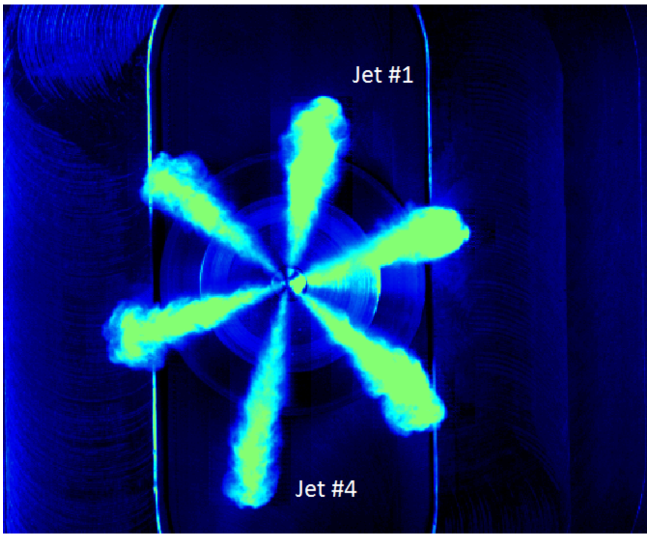


Figure 11. Full - Spray pattern of investigated Common Rail Injector

Regarding the differences in the spray characteristics it can be seen that focusing on only one spray, experiments can lead to uncertain results. The injector used is a modern Common Rail Injector which should not exhibit such differences in the spray process. Only by considering all sprays of a multi-hole injector can differences be recognized and integrated in the engineering process.

Conclusions

At the Institute of Internal Combustion Engines (LVK) of the Technische Universität München experiments handling the macroscopic spray data of RSO and diesel fuels with a modern CR-Injector were performed. The experiments were motivated by CO problems in low load operation for a heavy duty agricultural engine. The results clearly show that the physical spray parameters for RSO and diesel have a strong influence in the macroscopic spray parameters like penetration length and spray angle. As expected, the penetration length of diesel fuel in each experiment is higher than the penetration length of RSO. This behaviour is explained by the higher viscosity of RSO compared to that of diesel.

Regarding the engine calibration for the low load operation, the macroscopic spray parameters for diesel (400 bar) and RSO (600 bar) have a good accordance. The problems with CO emissions can also be explained by the physical data for the different fuels. First, the saturated liquid line of RSO displays different to that for diesel. A significantly higher temperature is needed to force the vaporization of RSO than for diesel. If the temperature is as low as under diesel fuel conditions, the evaporation is significantly lower. This leads to a longer ignition delay and can cause an incomplete combustion process which subsequently leads to high CO emissions.

The investigations were done with the whole spray patterns of a CR injector. Remarkable differences between the spray jets could be observed. For engine multi-hole injector investigations of the macroscopic parameters, it is recommended that all jets are observed to detect the spread of the results.

Based on the results shown in this paper, it can be concluded that the change from diesel to RSO has considerable effect on the engine behaviour, and, of course, on the emissions during the NRTC and NRSC - test cycles. For that reason it is necessary to perform fuel-specific engine calibration to satisfy the emissions levels also for RSO operation.

References

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Appendix

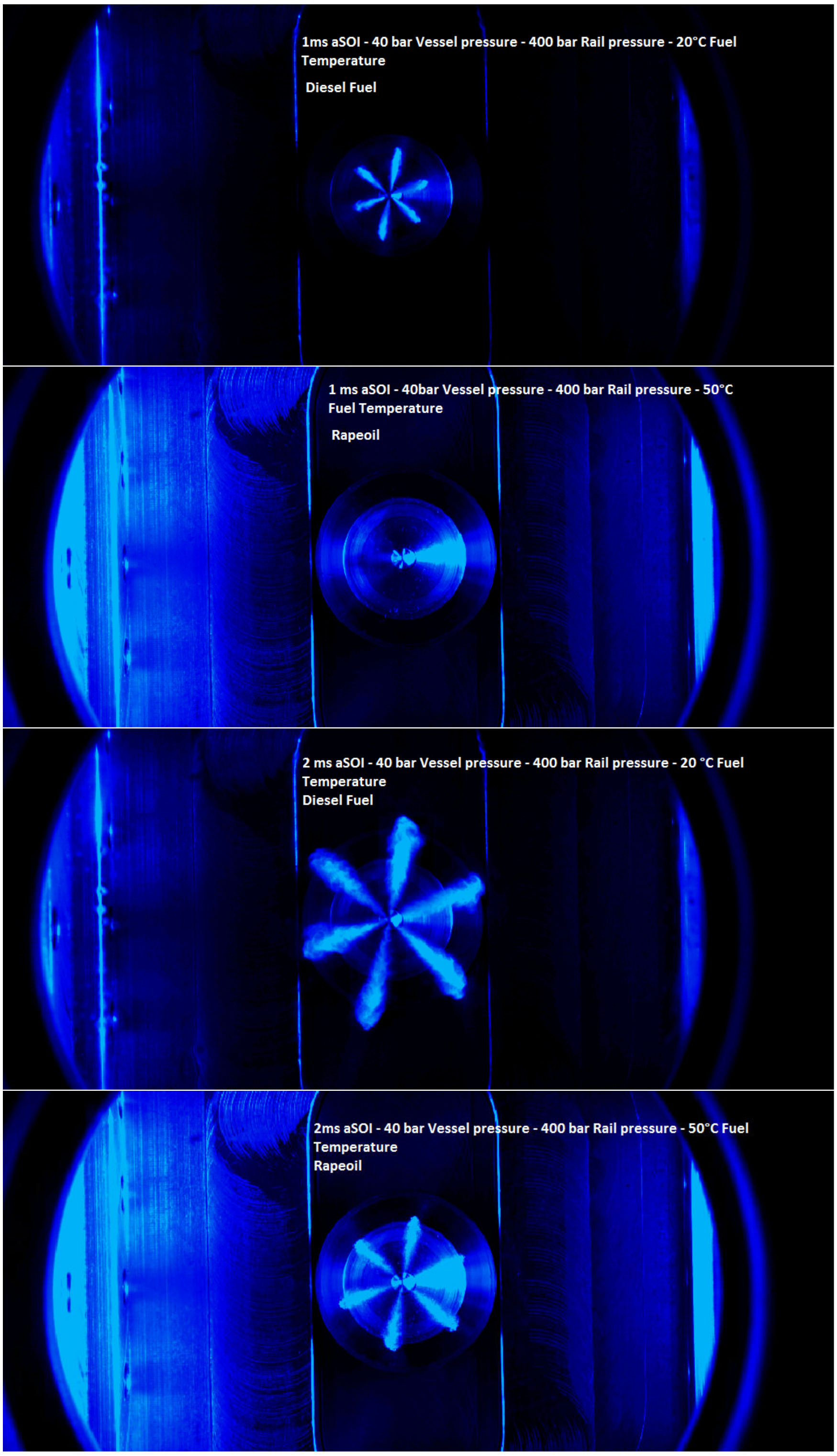

Figure 12. Visual comparison of diesel and RSO spray patterns