Influence of fuel mixture on spray formation in diesel processes

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Abstract

Earlier investigations of gasoline fuels carried out, that even small fractions of high boiling components have major effect on the spray characteristic and the evaporation behaviour [1]. For diesel fuels the high boilers fraction in bio-diesel fuels is increased compared to the mineral oil fuel. European law provides a blend of the bio diesel cut up to 10% until the year 2020.

A detailed analysis of the spray formation and evaporation of several different bio diesel fuels was carried out. The fuels investigated are miscellaneous first generation bio-diesel fuels like FAME-Diesel. Furthermore, pure plant oils have been used according to measurement series performed in low pressure vessels [2-4] or in optical accessible ic-engines. Measurements were performed in an optical accessible heated high pressure cell, allowing to change separately ambient pressure and temperature conditions. A modern Piezo-actuated injector was used in this measurement series. Ten different fuels have been investigated while ambient pressure, ambient temperature and injection pressure were varied. Mie scattering (integral illumination) was used to acquire the differences in liquid fuel propagation and evaporation. In order to get a direct relation to the engine conditions different precalculated engine load points were applied.

In a first comparison pure plant oils and diesel blend with a high content of plant oil as well as a reference diesel were investigated. In pure plant oil the fraction of high boilers is dominant. It was found that this fraction continues to dominate the spray characteristics of diesel oil blends down to a 10% volume fraction of plant oil, so that only marginal differences in comparison to pure plant oil can be found. In contrast to mineral oil diesel, that shows constant penetration depth at a full load operating point 200µs after start of injection due to evaporation, the penetration of these sprays still increases 1 ms after start of injection.

In a second comparison different blends of diesel fuels with FAME-components and pure FAME-diesel were compared to the CEC RF-06-03 reference diesel without FAME-components. The influence of the bio-components was found in a linear response of the maximum penetration depth and the amount of FAME in the diesel blend. The maximum penetration depth of FAME-diesel increases by a factor of two compared to the reference diesel.

The results figure out that low volatile fuel components have big impact on the spray formation and evaporation process under realistic diesel engine conditions. As bio-components for diesel fuel that are currently used and discussed mainly or to a relevant part consist of low volatile components, these components will alter the spray formation and evaporation process in diesel engines significantly.

Introduction

Injection systems are one of the key components in modern combustion engines. The characterization of those systems inside of an engine is limited, due to the restricted optical accessibility and the coupled interaction of several parameters influencing the spray-propagation, evaporation and combustion. For that reason optical accessible high temperature and high pressure vessels, called injection chambers, are used as an instrument for research on this topic. In the following an injection chamber is the major tool for investigation on mixture formation in a Diesel process.

The mixture formation and the injection strategy in direct injecting Diesel engines influences significantly the combustion process and thus the power generation, noise development, exhaust emission and efficiency of

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the engine. Earlier investigations of gasoline fuels carried out, that even small fractions of high boiling components have major effect on the spray characteristic and the evaporation behaviour [1]. For diesel fuels the high boilers fraction in Bio-Diesel fuels is increased compared to the mineral oil fuel. European law provides a blend of the Bio-Diesel cut up to 10% until the year 2020. Thus, a significant alteration of the spray- and evaporation behaviour can be expected.

Materials and Methods

The Injection Chamber

The analysis of the mixture formation of biogenic Diesel fuels was performed inside a high temperature and high pressure injection chamber according to Table 1. The chamber is a permanently scavenged, heated and pressurized cell in cube design with full optical access from five of the six sides. On each side you can mount whether an optical access or an injection system. This allows different versions of optical measurement techniques, like for example Mie-scattering, PDA/LDA or LIF, to be derived to investigate the injection process.

The body of the cell (shown in fig. 1, marker 1) is continuous flown through from the four upper edges of the cube, where electrical heaters are installed (2). Leaving the chamber by the four downward edges the scavenging gas is cooled down by four high pressure coolers (3). Due to the continuous scavenging the gas flow speed in the chamber is less than 0.1 m/s, so the gas motion is not influencing the spray behaviour.

The ambient conditions in the chamber can be set up to 10 MPa and 1000 K separately. Table 1 illustrates that in the chamber every load point from idle running to full load before combustion starts can be adjusted. Furthermore, the scavenging gas could be either nitrogen, normal air or a mixture of them so combustion at ignition start conditions and with a certain EGR is possible. The addition of other kind of gases, like CO_2 in the gas supply is also optional.

Currently two systems, one for diesel application (4) and one for gasoline fuels (5), are available to provide fuels to the injectors mounted in the chamber up to 28 MPa (gasoline) and 250 MPa (diesel). Both systems are built highly chemical resistant, this allows the use of various kind of fuels with additives for the different investigations.

In order to be comparable to a real engine, the injector mount can be tempered from 243 K to 383 K, which includes the temperature of a cooling mantle inside the cylinder head were the injector body is mounted (6). Due to that, a constant and known fuel temperature, detailed measured in a former investigation [12], is adjusted.

Figure 1. Test rig of the optical injection chamber

Table 1. Technical data of the injection chamber

maximum pressure	10 MPa
maximum temperature	1000 K
maximum scavenging flow rate	110 $m^3_N \cdot h^{-1}$
scavenging medium	N_2, air, CO_2 or mixtures
clearance of the optical accesses	125 mm
Inner vessel volume	10 liters
maximum fuel pressure	250 MPa (Diesel)
fuel temperature	243 K to 383 K
injection repetition rate	0,3 Hz to 3 Hz

The Injector and the experiment operation program

To keep the results comparable, all investigations were made with the same injector. A Bosch CRI 3.0 piezo-injector from a BMW 3.0 ltr, six-cylinder engine from 2006 was used. In this motor the injector has an 8-hole nozzle with constant angles between the spray-cones. In series the injector is driven up to 160 MPa, on a test bench are 200 MPa possible.

The motor load points for the investigation were calculated on the base of an actual diesel engine. The load points were simulated from cold start at cold environment conditions up to maximum motor load. Nine different motor load points with two different pressure levels each were chosen as shown in Table 2.

Table 2. Operating points of the measurement program

name	**p_G[MPa]**	**T_G[K]**	**p_F[Mpa]**	**T_F[K]**	**Comment**
cold start -10/ 800	3	713	80	263	FAME only
cold start -10/ 1200	3	713	120	263	FAME only
cold start 25/ 800	3	753	80	298	FAME only
cold start 25/ 1200	3	753	120	298	FAME only
partial load 1/ 1200	4,5	753	120	363	FAME and rapeseed oil
partial load 1/ 1600	4,5	753	160	363	FAME and rapeseed oil
partial load 2/ 1200	4,5	873	120	363	FAME and rapeseed oil
partial load 2/ 1600	4,5	873	160	363	FAME and rapeseed oil
partial load 3/ 1200	6	753	120	363	FAME and rapeseed oil
partial load 3/ 1600	6	753	160	363	FAME and rapeseed oil
partial load 4/ 1200	6	873	120	363	FAME and rapeseed oil
partial load 4/ 1600	6	873	160	363	FAME and rapeseed oil
full load 1/ 1600	9	873	160	363	FAME and rapeseed oil
full load 1/ 2000	9	873	200	363	FAME and rapeseed oil
full load 2/ 1600	9	953	160	363	FAME and rapeseed oil
full load 2/ 2000	9	953	200	363	FAME and rapeseed oil

For the investigation of the influence of biogen fuel components on the diesel process two measurement series were performed. The first series consists of FAME/diesels blends were the concentration of FAME was varied from 100% (B100) to 10% (B10) and the CEC reference fuel without FAME additions. The chemical composition together with some physical properties in comparison with the CEC reference Diesel is shown in Table 3.

Table 3. Characteristical values of biogen diesel fuels and diesel

characteristic value	**diesel fuel [5]**	**rapeseed oil [6]**	**FAME [7,8]**
density (at 15° C) [$kg \cdot m^{-3}$]	820 - 845	900 - 930	860 – 900
Cetane number [-]	min. 51	40	min. 51
Distillation range			
at 250° C [%]	< 65	-	-
at 350° C [%]	min. 85	-	-
at 360° C [%]	max. 95	-	-
Viscosity (at 40° C) [$mm^2 \cdot s^{-1}$]	2,0 - 4,5	38	3,5 – 5,0
flash point [°C]	> 55	220	min. 120
FAME-fraction [vol %]	max. 7	-	> 96,5

The second series consists of rapeseed oil and blends with diesel compared to CEC reference Diesel. Here the blends were varied from 100% rapeseed oil down to 10% rapeseed oil.

All measurement series were also compared to an early version of a spray model based on the measurement series already performed on the test rig. This model regards the spray propagation without evaporation. According to former references the spray propagation without evaporation is independent from the used fuels of this series because of the very similar density. For that reason the propagation can be described by a square root function like earlier investigations showed [9-11] in dependency of fuel pressure and gas ambient pressure. In contrast to the earlier models this has a shifted origin due to limited velocity at the nozzle exit. The limited nozzle exit velocity becomes important if you differentiate the equation for the spray penetration over time. The comparison of the measured curves to the model shows clearly at which point, also in time and location, the evaporation starts.

The measurement technique

To measure the spray propagation behaviour the Mie-scattering was chosen. The spray is illuminated integrally via 4 flashlights mounted on the sides of the injection chamber. The camera, a sensitive CCD-camera, is mounted on the top of the chamber. 32 pictures were taken at every of the 16 exposure points in between 25 µs and 1 ms after visible start of injection (vSOI). To synchronize camera, injector control unit and flash lamps a centralized trigger system controlled by a PC interface and the picture acquisition Software is used.

The evaluation was performed by automated image processing software. The examination consisted of penetration depth, spray cone angle, area within spray, spray border length and distance of the centre of gravity. All spray cones were evaluated so 256 values per exposure point were recorded. The base principle during the evaluation with the image processing software is shown in fig. 2. A recorded raw image is first background corrected then the greyscale image is transferred in a 1 bit image for the further examination. In order to get a statistical data content in one image, outline plots or frequency scale images are used. In these pictures the difference between the several, in this case 32, taken images can be seen in one image. Later on in the chapter results and discussion the visualization of the measured operating points is always performed by frequency scale images.

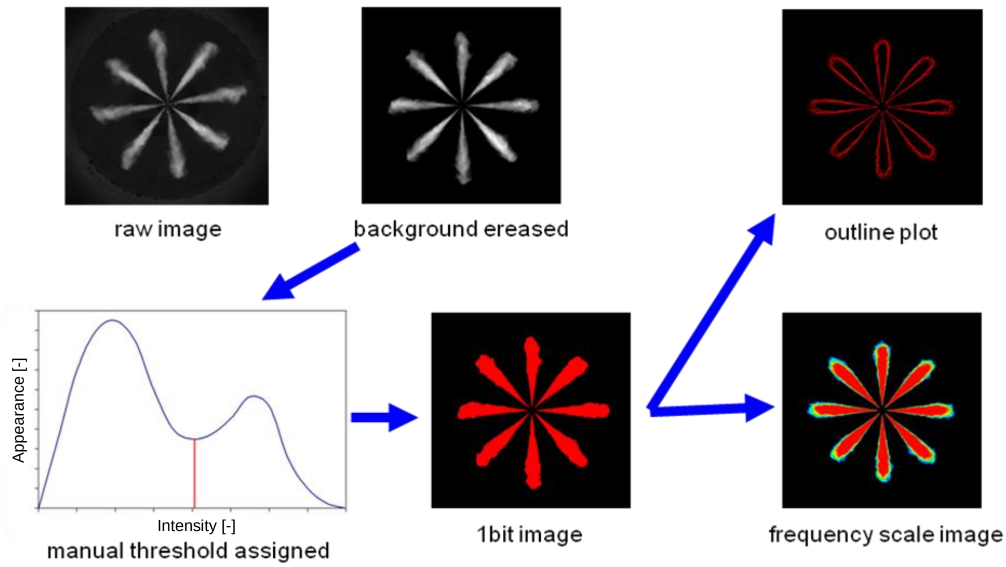

Figure 2. Principle of image evaluation within image processing software

Results and Discussion

FAME and diesel blends

The addition of different amounts of FAME to mineral Diesel fuel is exemplarily shown by one of the measured operating points a partial load point with 6 MPa ambient pressure and 873 K gas temperature in the chamber. A significant difference during the spray propagation process could be observed at every measured operating point, but the behaviour was similar to that partial load point shown below.

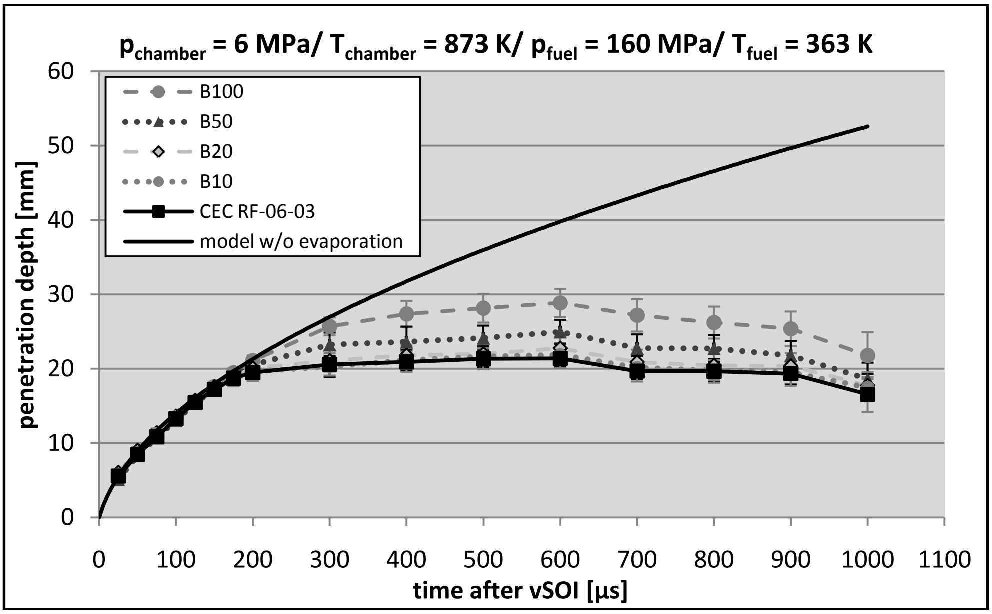

Figure 3. Penetration depth of Diesel fuels with varying FAME additions

The values represented, fig. 3 show that the fuel behaviour during the spray propagation phase up to 200 µs is not influenced by the different mixings. This means the evaporation of the fuel starts at approximately 200 µs after visible start of injection (vSOI) compared to the propagation model.

The graph in fig. 3 also shows the varying evaporation and there the differing penetration depth of the fuel mixtures. It becomes apparent that higher boiling FAME addition results in a higher maximum penetration depth of the fuel liquid phase. The penetration depth of the CEC reference Diesel is with a maximum of 22 mm round about one quarter lower than the maximum penetration of pure FAME with 28 mm.

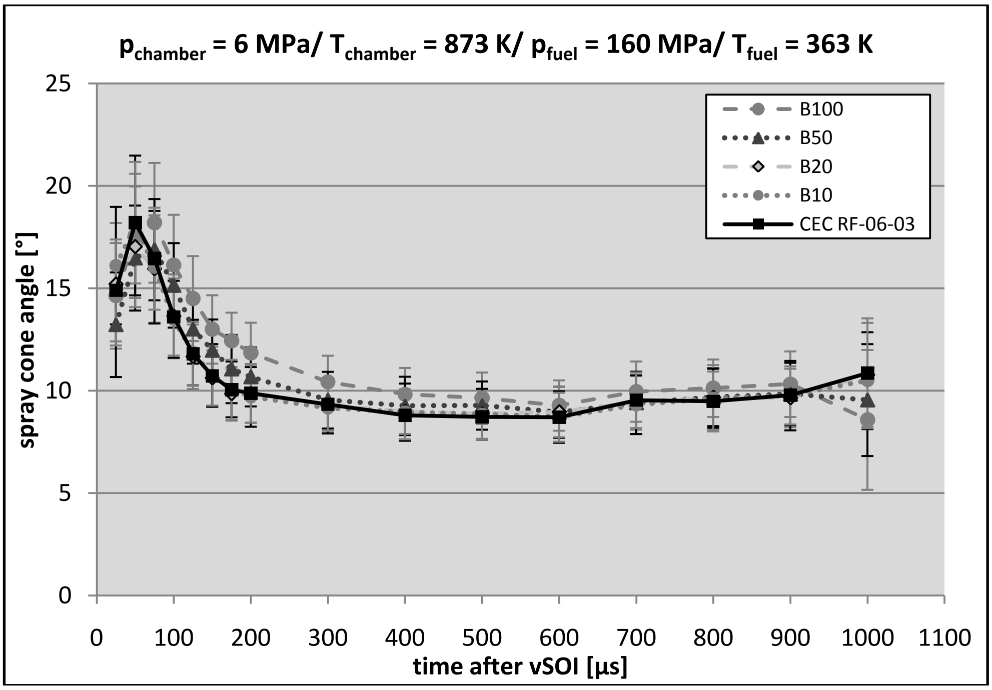

Figure 4. Spray cone angle of Diesel fuels with varying FAME additions

Figure 4 shows the spray cone angle of the FAME Diesel blends. All blends reach their maximum value of 17° at about 50µs after vSOI. After that all fuels fall down to 10° at 200µs. Between the exposure point at 200 µs and the end of measurement at 1 ms, the level of the spray cone is nearly constant.

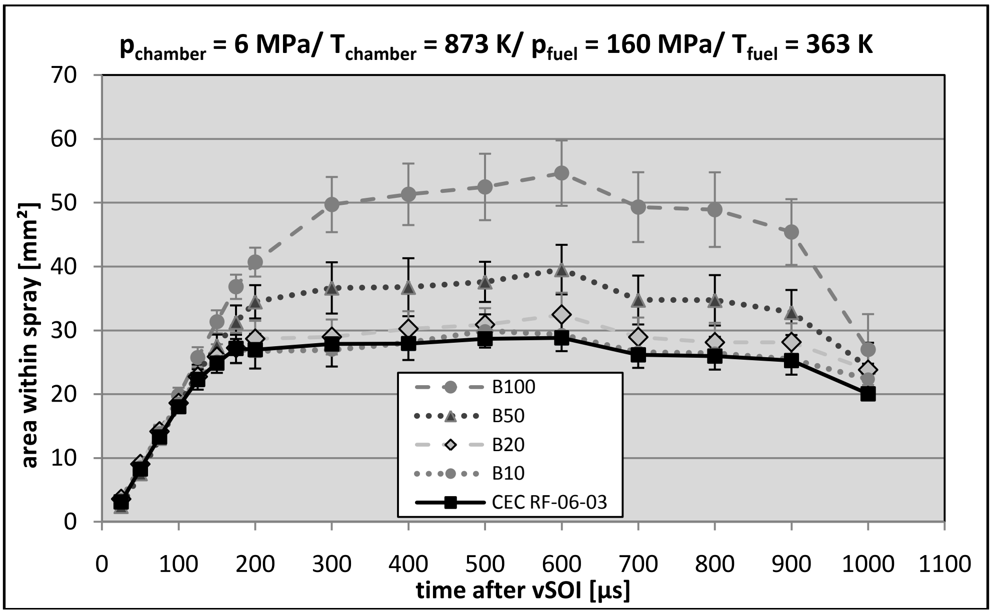

Figure 5. Area within spray of fuels with varying FAME additions

In fig. 5 the results of the area within spray measurements reflect the results of the penetration depth measurement in an intensified way because of the square dependency of area effects. The area within the spray of the B100 blend varies significantly compared to other Diesel fuels. The maximum area of pure FAME is 55 mm per spray cone. That is nearly twice as much as the area of CEC reference Diesel with up to 29 mm² in maximum.

What becomes clear by the analysis of the penetration depth and the spray area is the fact, that lower additions of FAME up to B20 have marginal influence on the spray behavior. By addition of higher concentrations of FAME to mineral Diesel an influence of the increased high boiler fraction can be detected during the evaporation process. The spray propagations phase before evaporation is independent of the mixture.

Fig. 6 summarizes the increase effect by the addition of FAME to mineral Diesel. Here the linear dependency of penetration depth and the exponential increase of area within spray are pointed out.

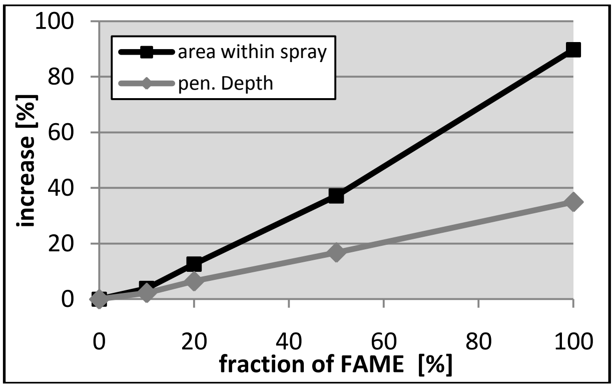

Figure 6. Increase of penetration depth and area within spray over fraction of FAME

The results of the FAME measurements are summarized in frequency scale images in fig. 7. A noticeable increase of the penetration depth can be observed at those images. At 200µs a rounded spray tip can be seen at the pure rapeseed FAME while the spray with lower fraction of FAME show sharpened spray tips which indicates the evaporation effects. Also the alteration in the area within spray can be seen from 400µs on.

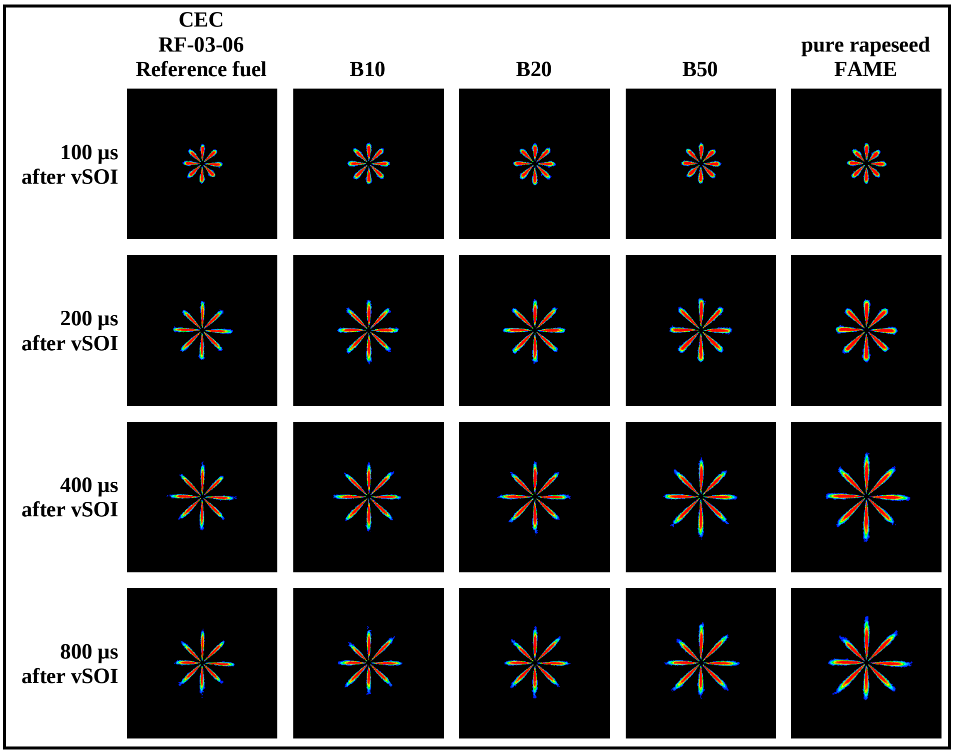

Figure 7. Frequency scale images of spray with different FAME concentrations

Rapeseed oil and diesel blends

In order to investigate the effect of high boilers on the mixture formation of Diesel fuels in a more detailed way, further measurement with mixtures of pure rapeseed oil were performed. The influence on the spray behaviour of the rapeseed oil in mineral Diesel is very distinctive at every measured load point. One extreme load point, which is chosen for the representation in the following, is a full load point, were diesel shows quick evaporation and pure rapeseed oil nearly no evaporation within the measured time interval. The ambient pressure at this load point is 9 MPa with a scavenging gas temperature of 953 K and a rail pressure of 200 MPa.

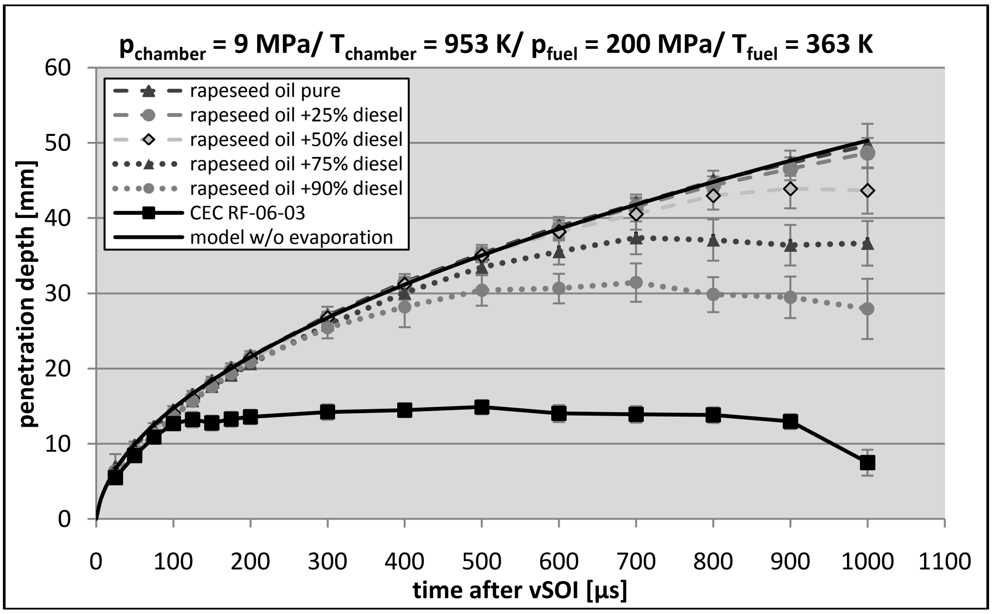

Figure 8. Penetration depth of Diesel fuel blends with rapeseed oil

The penetration results in fig. 8 demonstrate, that pure rapeseed oil shows a spray propagation not reduced by evaporation during the measurement interval of 1 ms. At the last exposure point the penetration depth is still increasing. So pure rapeseed oil is also a reference for a non evaporating spray which can be described by a square root function, what was already mentioned in the previously chapter. Furthermore, every measured blend shows the propagation behaviour but with an earlier starting evaporation inside the measurement interval depending on the fraction of diesel fuel added. As a matter of fact, even small amounts of high boiling rapeseed oil shifts the evaporation to a significant later point in time. So the conclusion is that the high boilers have a dominant effect on the spray breakup and evaporation process and therefore on the mixing process, the flame development and the formation of soot and NO_x.

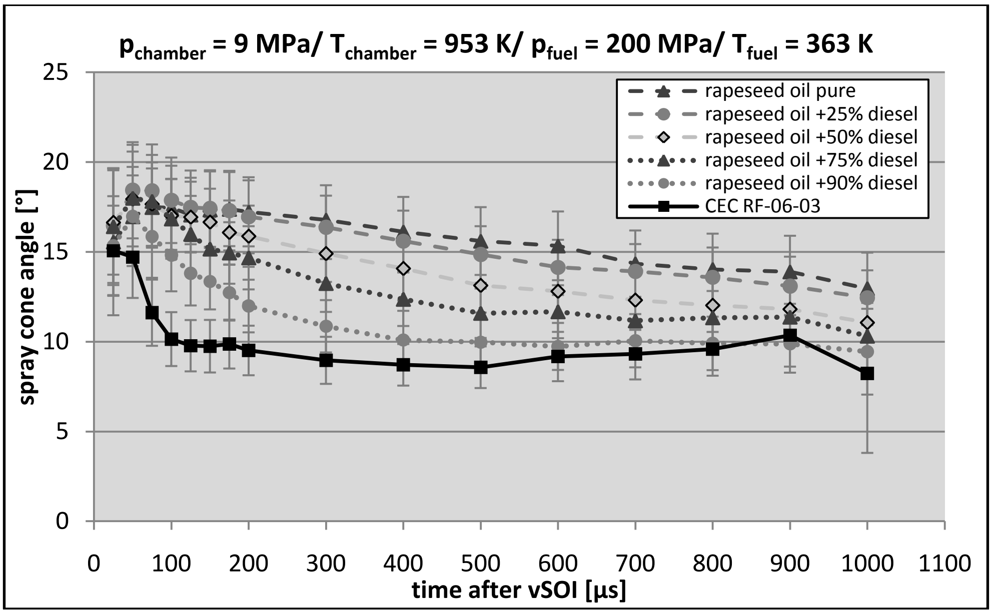

Figure 9. Spray cone angle of Diesel fuel blends with rapeseed oil

Fig. 9 demonstrates the spray cone behaviour of the Diesel fuel blends with rapeseed oil. The cone angle measured for the blends are generally higher than those measured for the reference diesel. Additionally, the behaviour versus time is different: The rapeseed oil leads to a constant decrease of the cone angle starting at the angle maximum of about 18°. For CEC reference Diesel, there is, after a maximum of 15°, a quick decrease of the angle to a constant value. This point differs from the measurements with FAME blends in the former chapter.

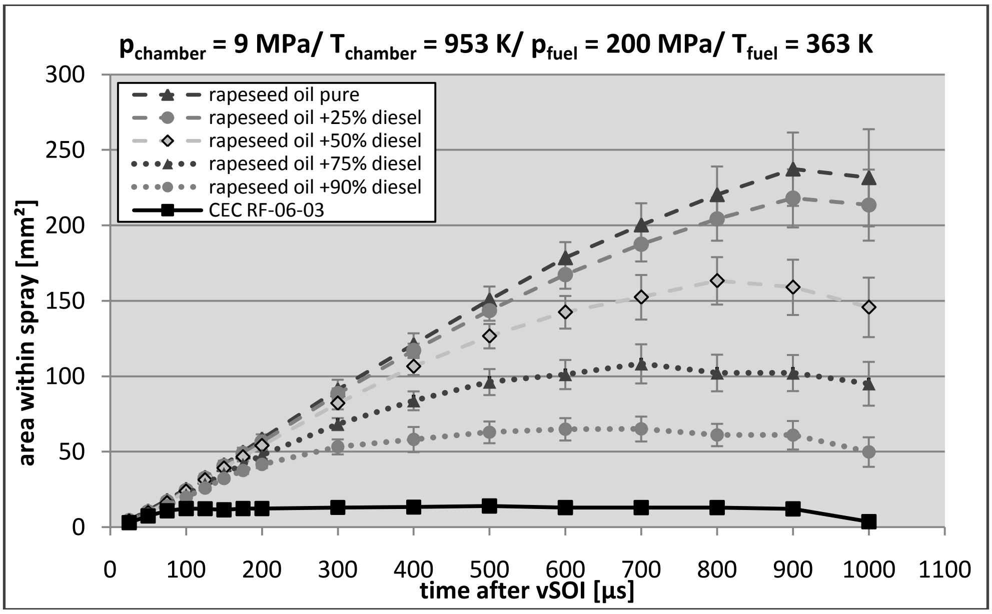

Figure 10. Area within spray of Diesel fuel blends with rapeseed oil

The results for the area within spray of rapeseed oil blends (fig. 10) reflect the results of the spray con angle and the penetration depth. Due to the high boiling rapeseed oil a huge alteration of the area within spray can be seen. The fact, that pure rapeseed oil shows no evaporation leads to high increase of the maximum penetration depth and the maximum area within spray. The spray area is 17 times higher for the pure rapeseed oil in comparison to diesel while the penetration of rapeseed oil is 4 times higher than the penetration of diesel. The addition of high boiling components which are way out of the distillation range of diesel fuel causes a non linear effect on the increase of these two values (fig. 11).

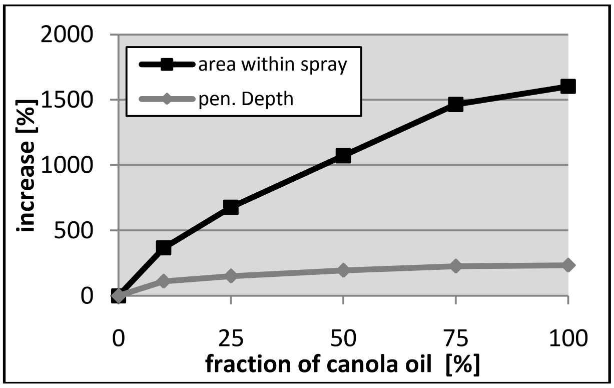

Figure 11. Increase of penetration depth and area within spray over fraction of rapeseed oil

Fig. 12Figure 12 shows the frequency scale image of the rapeseed oil/ diesel blends. The high increase of the area within spray and the penetration depth can be found at 800 µs after vSOI.

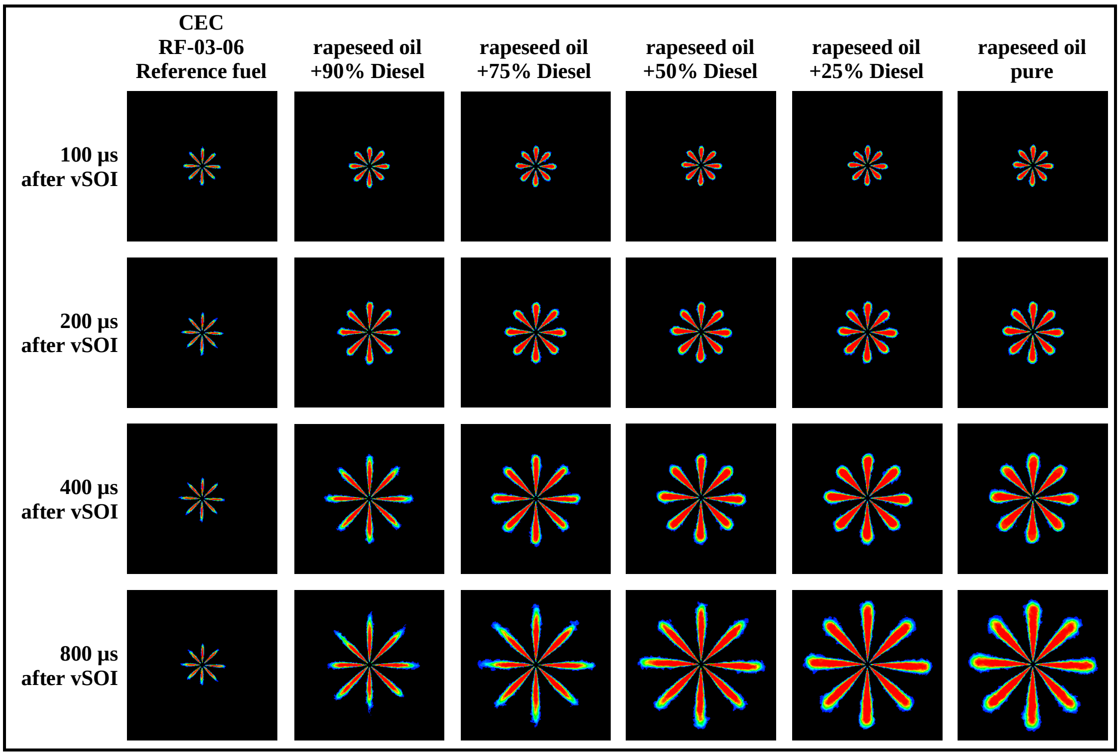

Figure 12. Frequency scale images of spray with different rapeseed oil concentrations

Conclusion

All measurements point out that in the propagation phase the velocities of the sprays are very similar and can be described by a square root function over time with a shifted origin due to the differentiation at the start of injection. Until evaporation takes place all injected fuels follow this graph.

Both measurement series clearly carried out, that the high boiling components of diesel fuels have a major effect on the spray behaviour. Biogen fuel components like FAME, or pure plant oils consist of low volatile molecules. Where the rapeseed oil is slightly higher boiling than diesel fuel, the pure rapeseed oil is complete out of the distillation range.

Depending on the fraction of FAME the maximum penetration depth and the maximum area within spray, which are reached in the stationary spray state, increase. While FAME fuels reach the stationary spray state in all partial and full motor load points, it depends on the amount of rapeseed oil and the motor load point whether the rapeseed oil Diesel blends reach the stationary spray state. The spray of pure rapeseed oil, for example, didn't become stationary during measurement time, even not at the highest motor load point.

The amount of low volatile components has an effect on spray behaviour. When the boiling behaviour of the low volatile components is near the distillation range of diesel fuel, a linear effect in maximum penetration depth can be seen. If the boiling range is not near the distillation range of diesel, the effect is non-linear.

Acknowledgement

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