How biodiesel/diesel fuel blends affect spray breakup and emissions

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Abstract

In the current study the influence of biodiesel blends in diesel fuel as well as the pure biodiesel and diesel fuels on the spray breakup in a cold chamber and on the emissions on a single-cylinder diesel engine was examined.

Blending biodiesel FAME B100 with diesel B0 leads to a reduction in filter smoke number (FSN) and unburned hydrocarbons (HC). The lowest HC and FSN values were measured when pure biodiesel FAME B100 was used. An increase in NOx emissions is observed at very high proportions of biodiesel of 50 % or with pure biodiesel FAME B100.

The current study showed that the cause of the changed emission results due to biodiesel blend can be explained not only in chemical terms (increased oxygen fraction in the biodiesel), but also partly in physical terms. At high proportions of biodiesel, the greatly increased viscosity of the biodiesel is an important variable influencing the formation of NOx. The effect of profile relaxation leads to a larger spray cone angle, which results in an increased thermal zone for the formation of NOx.

Introduction

Fossil fuels are increasingly being supplemented by biofuels, both for reasons of climate protection and because of their scarcity. Since February 2009, the new European diesel standard permits the use of biodiesel as a blend component in diesel fuel at a proportion by volume of up to 7 % (B7). A further increase in proportion by volume is likely over the next few years. The sharp increase in the use of biodiesel is the motivation behind this study to better understand the physical mechanisms of action of biodiesel in the process of injection spray breakup and the chemical mechanisms of action which lead to the observed reduction in emissions.

Current studies into biodiesel give a differentiated picture. According to Suh et al. [1], the penetration of diesel and biodiesel does not differ to a significant extent. However, the physical properties of biodiesel, the higher viscosity and surface tension, lead to poorer atomization of the spray. Park et al. [2] and Kawano et al. [3] also note that the atomization quality of the biodiesel is much less. Hüttl et al. [4] observed that the injection speed of the biodiesel is reduced and according to these authors, this is probably due to the increased friction of the higher-viscosity fuel in the spray holes. This is why the penetration of biodiesel at the start of injection is less than the penetration of diesel; the situation is reversed as the injection process continues, due to higher surface tension and thus larger droplets and higher impulse. According to Zhang et al. [5], the higher density of the biodiesel fuel leads to a spray with greater penetration. The spray cone angle is reduced, probably due to the higher viscosity. Zhang et al. [5] even observed that the spray cone angle of biodiesel is only half that of the spray cone angle of diesel. The physical properties of the biodiesel fuel lead to a poor atomization of the spray [5] and so to a lower flame temperature which results in reduced NOx emissions.

This contrasts with the studies [1], [6], [7] and [8], where use of biodiesel leads to increased NOx emissions. [9] suggests the rising oxygen content of the biodiesel as a cause. The higher oxygen content initiates further exothermic oxidation reactions leading to an increase of combustion temperature. Yuan [10] notes that it is primarily rising cylinder temperature of the biodiesel which is responsible for rising NOx emissions. The reasons for this higher cylinder temperature were determined as earlier start of injection and decreased spray cone angle of biodiesel fuels. There were many reasons for the earlier start of injection; for example, higher density, higher bulk modulus and higher viscosity. The decreased spray cone angle of biodiesel increases the spray penetration which consequently increases the degree of widespread combustion in the chamber.

Soot and HC generation by the biodiesel drop sharply compared to diesel. In this regard, the current studies ([1], [3], [5], [8] and [9]) show a uniform picture and give the rising oxygen content of the biodiesel as a cause.

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Materials and Methods

The experimental part of the study consists of two parts: the spray diagnostical tests and the combustion tests.

The part of the study investigating spray diagnosis was carried out in the cold chamber at L'Orange (**Figure 1**). The cold chamber is a high-pressure cell with a constant volume of 34 l. It is filled with the inert gas nitrogen. The test nozzle D_{basic} is a 6-hole nozzle with a design corresponding to that of the serial common-rail nozzle of a large diesel engine and with a flow value Q100 of 5,100 ml/min. The set internal chamber pressure of 15 bar at an injection pressure of 1,400 bar leads to the density which prevails in the combustion chamber of the large diesel engine under part-load, with the result that the spray breakup recorded in the cold chamber is comparable with the spray breakup in the combustion chamber. Using the optical unit of the test bench, which consists of a high-resolution CCD camera and illumination by stroboscope (xenon flash), this study provides shadow images of the injected spray (**Figure 2**). Various geometrical variables are automatically measured and evaluated from the photographs of the injection spray. The spray cone angle and elevation angle are measured close to the nozzle at a distance of ten times spray hole diameter (SL-Ø) and remotely from the nozzle at a distance of sixty times spray hole diameter (SL-Ø). The nozzle mask, which can be seen in **Figure 2,** is for screening off 5 injection holes of the 6-hole test nozzles, so that a single jet can be examined optically without interference. This does not obstruct flow through the screened-off spray holes. 5 shadow images of the injected fuel are taken every 50 µs after the start of injection which has been optically determined. Mean values are formed from the images (one point in the diagram, **Figure 7**).

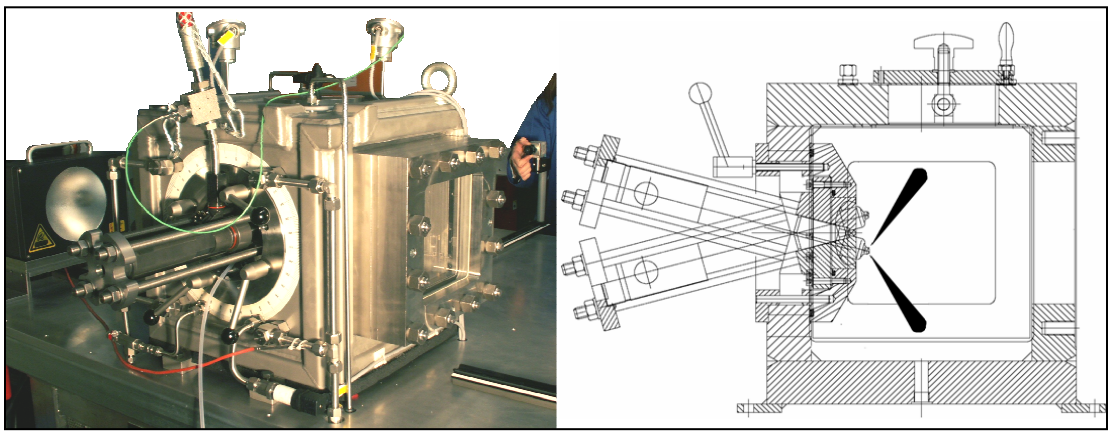
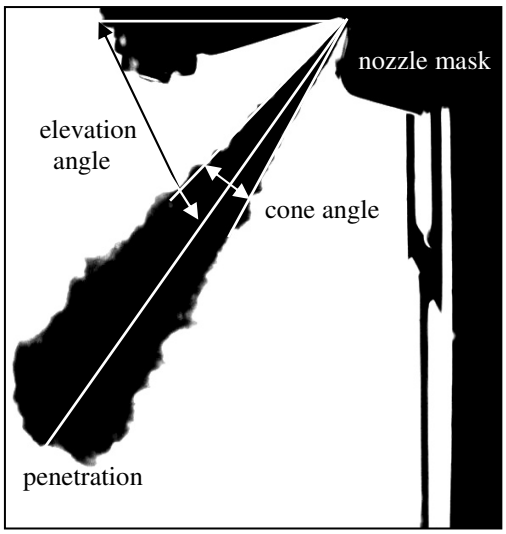
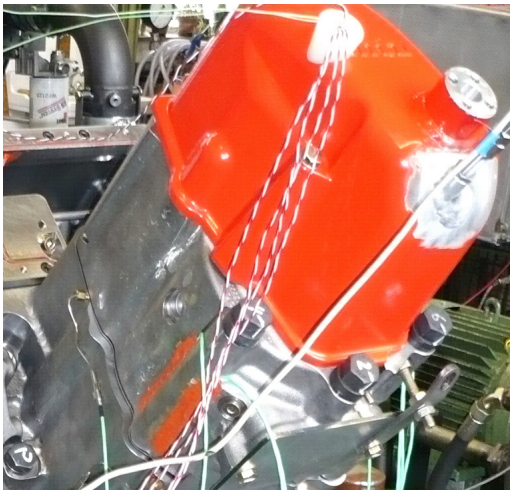


Figure 1. Cold chamber



S spray area
P penetration
Q_{100} nozzle flow rate for Δp=100bar
n number of nozzle spray holes
t time after the optical start of injection

Figure 2. Shadow images and the measured and calculated spray breakup properties



piston stroke:	210mm
cylinder bore:	170mm
piston bowl:	W

Figure 3. Single-cylinder BR4000 diesel engine (MTU Friedrichshafen)

The combustion tests were conducted on a single-cylinder BR4000 diesel engine from MTU Friedrichshafen with 4.8 l cubic capacity at cycle points 1, 7 and 4 (**Figures 3 and 4**). The set values for load pressure, air ratio etc. were based on the serial production standard for a full engine.

The study looked at diesel B0 and biodiesel FAME B100 as well as biodiesel/diesel blends B5, B10, B20 and B50. The designation BX stands for X % proportion by volume of biodiesel in the diesel fuel.

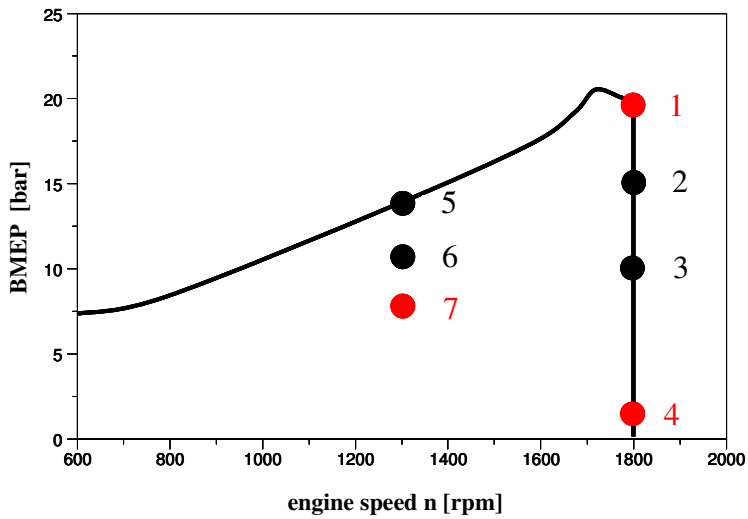


Figure 4. Cycle points

Results and Discussion

At all three cycle points, there is an approx. proportional decrease in filter smoke number FSN in relation to the percentage proportion of biodiesel B100 in diesel B0 (**Figures 5 to 7**). The pure biodiesel B100 generates the lowest filter smoke number FSN. The drop in filter smoke number FSN is probably due to the heavily increased proportion of oxygen in the biodiesel (**Figure 8**) which among other things, encourages exothermic oxidation reactions. These are also responsible for the reduction in unburned hydrocarbons. The HC result for biodiesel B100 is likewise the lowest. However, the influence of the biodiesel blends is not as pronounced as for filter smoke number FSN. In line with expectations, an increased temperature in the combustion chamber due to more intensive exothermic oxidation reactions leads to increased generation of NOx. However, this applies only to the high proportion of biodiesel B50 and the pure biodiesel B100 compared to diesel B0 at cycle points 1 (**Figure 5**) and 7 (**Figure 6**). The NOx emissions of the biodiesel blends B5, B10 and B20 is below the NOx value for diesel B0 at all cycle points, despite the increased proportion of oxygen.

This suggests another effect which may be physical rather than chemical, so spray photographs are observed as the evaluation continues in order to clarify supposed physical influences.

The comparison of spray diagnosis in **Figure 9** shows the differences in breakup of the injected fuel which depends on the physical properties of the fuel. Close to the nozzle, it is primarily the consequences of the interaction of the fuel and the nozzle spray hole which are seen. At a distance from the nozzle, spray breakup is predominantly determined by the interaction of the injected fuel with the environment.

Measured close to the nozzle, it is above all the spray cone angles of the fuels which differ. The higher density of the biodiesel blends (**Figure 8**) means that a reduced spray cone angle is likely [11].

The spray cone angle for small proportions of biodiesel B5, B10 and B20 is in the non-ballistic range (needle does not throttle, t > 300 µs after start of injection), approx. 10 % smaller than the spray cone angle of diesel B0.

The elevation angle of the biodiesel blends B5, B10 and B20 is likewise smaller than the elevation angle of diesel B0, and it approximates more closely to the geometric elevation angle of the spray holes. According to Ganippa et al. [15], this is a consequence of reduced flow interference (including turbulence and cavitation) in the spray hole, which is linked to the increased density of the fuel.

Although density increases significantly as the proportion of biodiesel rises steeply to 50 % and 100 % in the case of pure biodiesel B100 (**Figure 8**), it can be seen that the spray cone angle does not continue to decrease, but rather increases to the level of diesel B0. Disturbance of the fuel flow in the spray hole also increases with B50 and B100 so that the elevation angle close to the nozzle rises again.

This effect in B50 and B100 probably occurs as a result of steeply rising fuel viscosity, the effect of which overcompensates for the effect of density at elevated proportions of biodiesel. The steep increase in viscosity (**Figure 8**) at an elevated proportion of biodiesel in the fuel leads to increased shear forces in the spray hole and thus to greater friction between the fuel and the spray hole [11]. The external velocity vectors of fuel flow flow become smaller as a result of the high level of friction, and the velocity profile at the outlet of the spray hole thus moves away from the rectangular shape towards a trapezoidal shape. The higher the friction in the spray hole, the greater the velocity gradient at the outlet of the spray hole. An exchange of impulses takes place at the spray hole outlet between the inner and outer velocity vectors [12, 13], leading to the greater breakup of the spray close to the nozzle measured in the higher spray cone angle. This process is called progressive profile

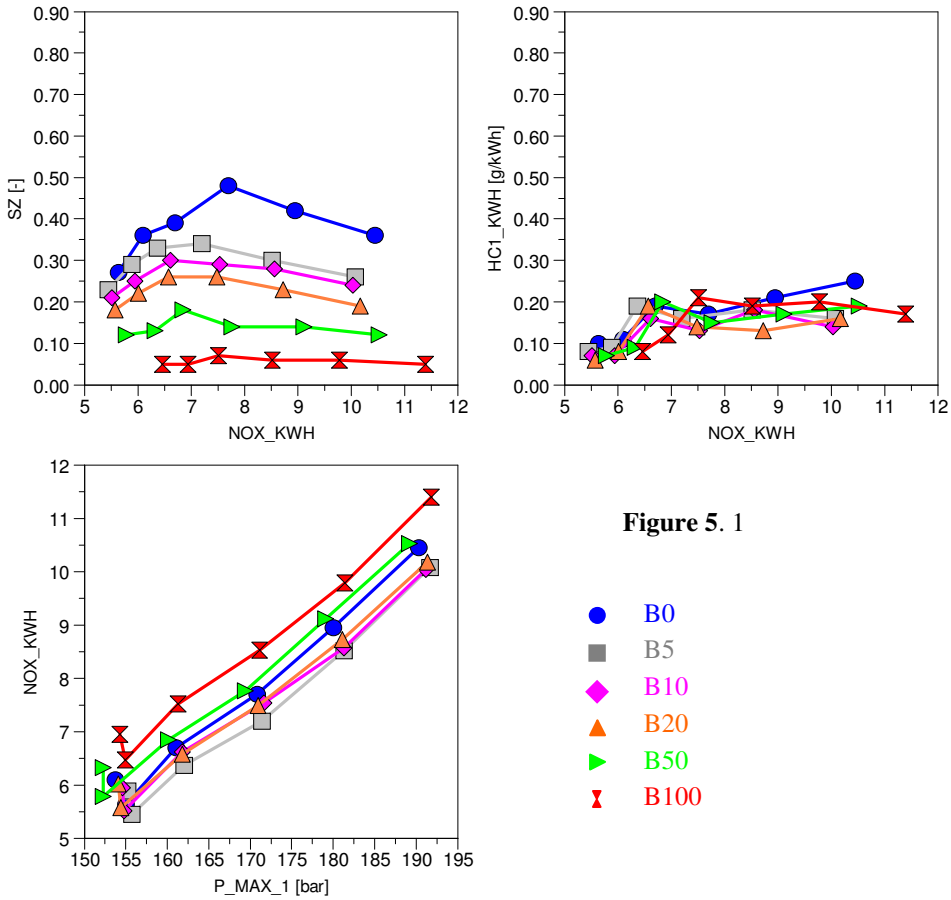
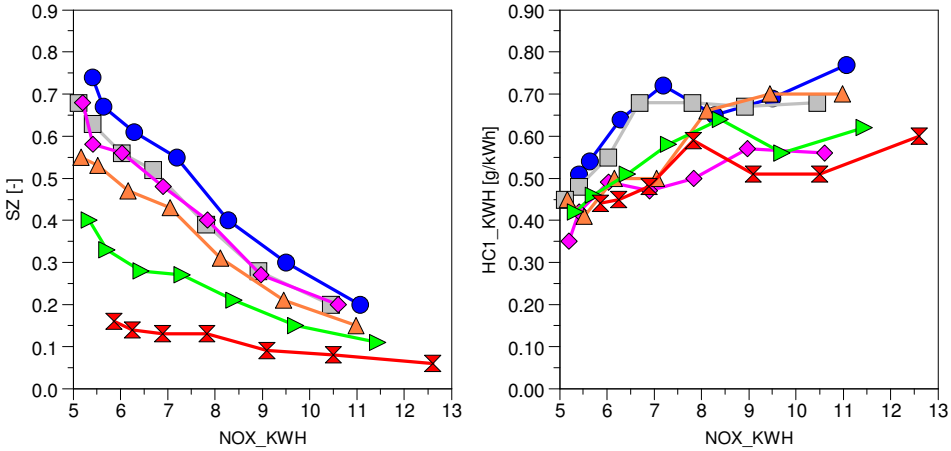


Figure 5. 1



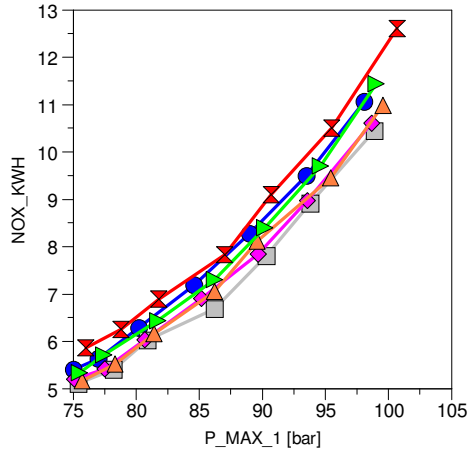
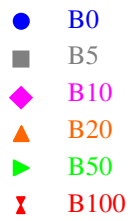
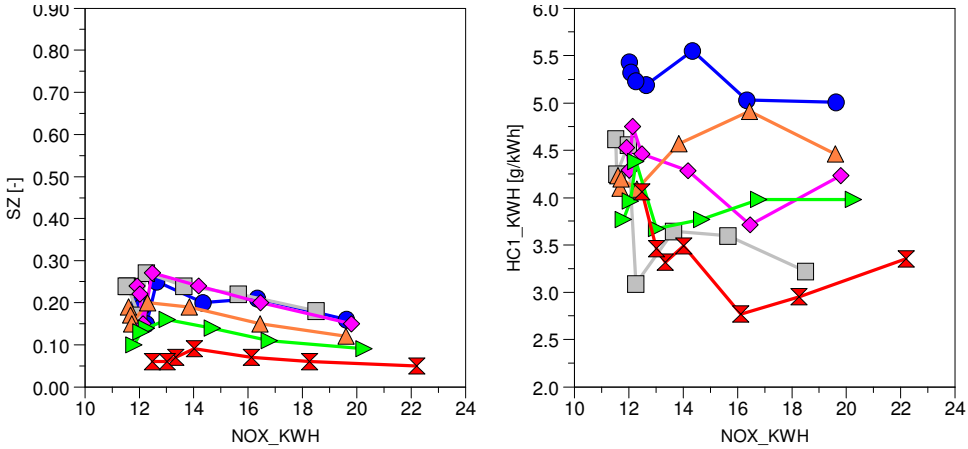


Figure 6. 7





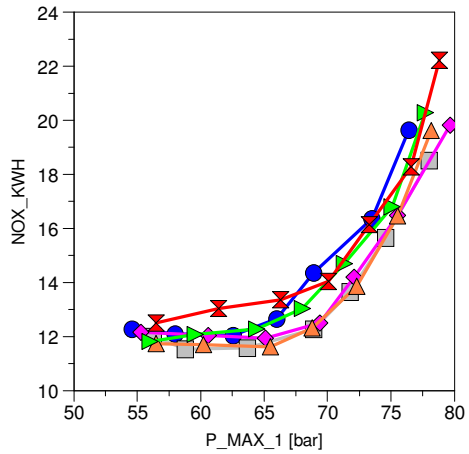


Figure 7. 4

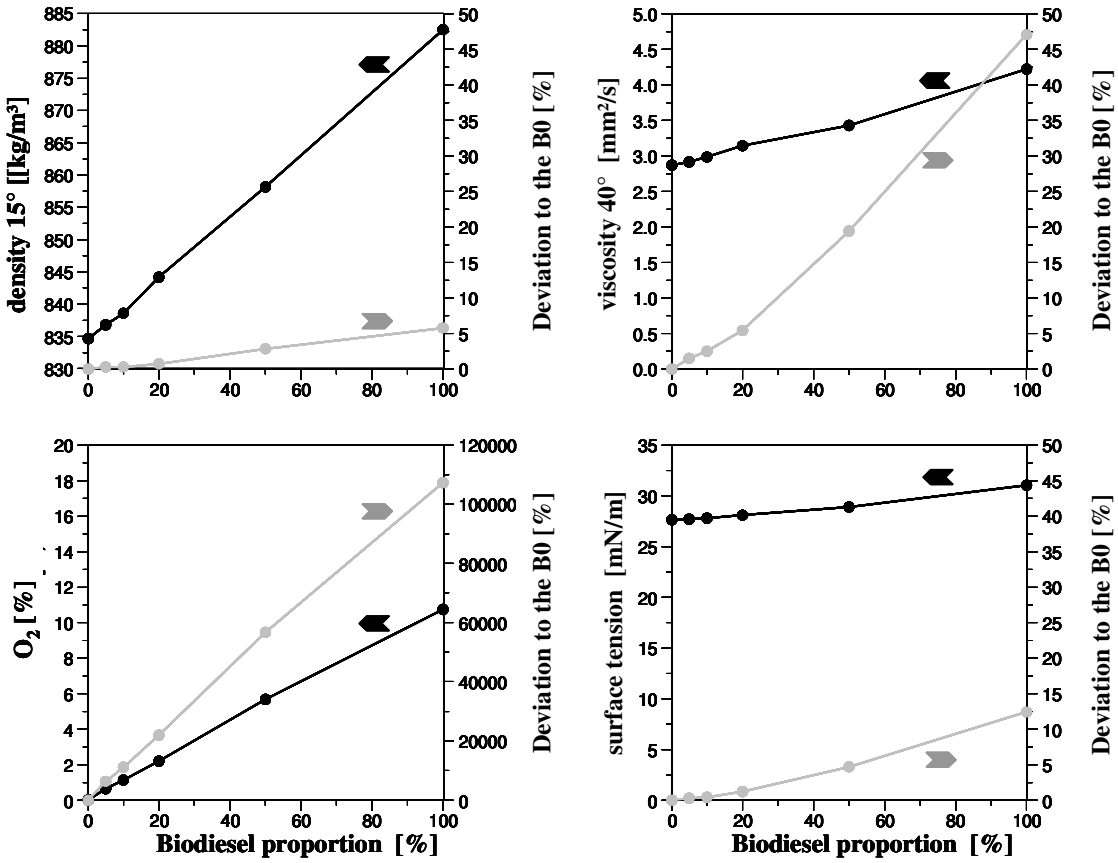


Figure 8. Data specifications of biodiesel, diesel and the blends

relaxation (**Figure 10**). **Figure 10** also shows the example of so-called degressive profile relaxation to compare the change in spray cone angle - something which is rare in practice.

The occurrence of profile relaxation at the spray hole outlet and its intensity have a key influence on primary spray breakup close to the nozzle. As injection continues, this leads to intensive radial spray breakup and to a fractured spray surface. The diffusion zone (**Figure 11**) is thus expanded in the whole of the spray zone by more intensive pulsation at the spray hole outlet and the greater spray cone angle of B50 and B100. The size of the diffusion zone has a key influence on the oxidation of the soot and thermal NO generation. More soot particles are oxidized in the expanded diffusion zone which contributes to a reduction in filter smoke number FSN (**Figures 5 to 7**). At the same time, more NOx emissions form thermally at the outside edge of the diffusion zone where temperatures are very high and plenty of nitrogen and oxygen is present.

The strength of the impulse exchange in the case of profile relaxation depends on the size of the velocity gradient and can even lead to annular detachments at the edge of the spray (**Figure 12**).

This study showed that the physical composition of the biodiesel/diesel blends has a key influence on spray breakup, on the formation of the fuel/air mixture and on the resulting emissions produced.

Conclusions and Outlook

Physical properties of biodiesel and its blends have a significant influence on the spray breakup and the emissions output.

1. The NOx-emissions correspond with the extent of the spray cone angle and the spray elevation angle.

The NOx-emissions of biodiesel blends B5, B10 and B20 are below the NOx-value for diesel B0 at all measured cycle points, dispute the increased proportion of oxygen. The spray cone angle for B5, B10 and B20 is probably due to the higher density approx. 10% smaller than the spray cone angle of diesel B0. The elevation angle of B5, B10 and B20 is also smaller than the elevation angle of diesel B0. Smaller spray cone angle indicates less oxygen intake into the spray and the reduced elevation angle indicates less radial flow disturbances that result in a reduced diffusion zone.

2. Although density of B50 and B100 steeply rises, it ca be observed that the spray cone angle does not continue to decrease, but rather increase to the level of diesel B0. Disturbance of the fuel flow increases so that the elevation angle rises too. These effects are caused by the steeply rising fuel viscosity, which overcompensates the density influence and enhances the shear forces and radial disturbances of the fuel flow. Rising viscosity leads also due to a pulsing progressive profile relaxation of the injected fuel to the larger spray cone angle. An intensified oxygen intake and a larger fissured diffusion zone lead to a higher NOx-emission of B50 and B100.

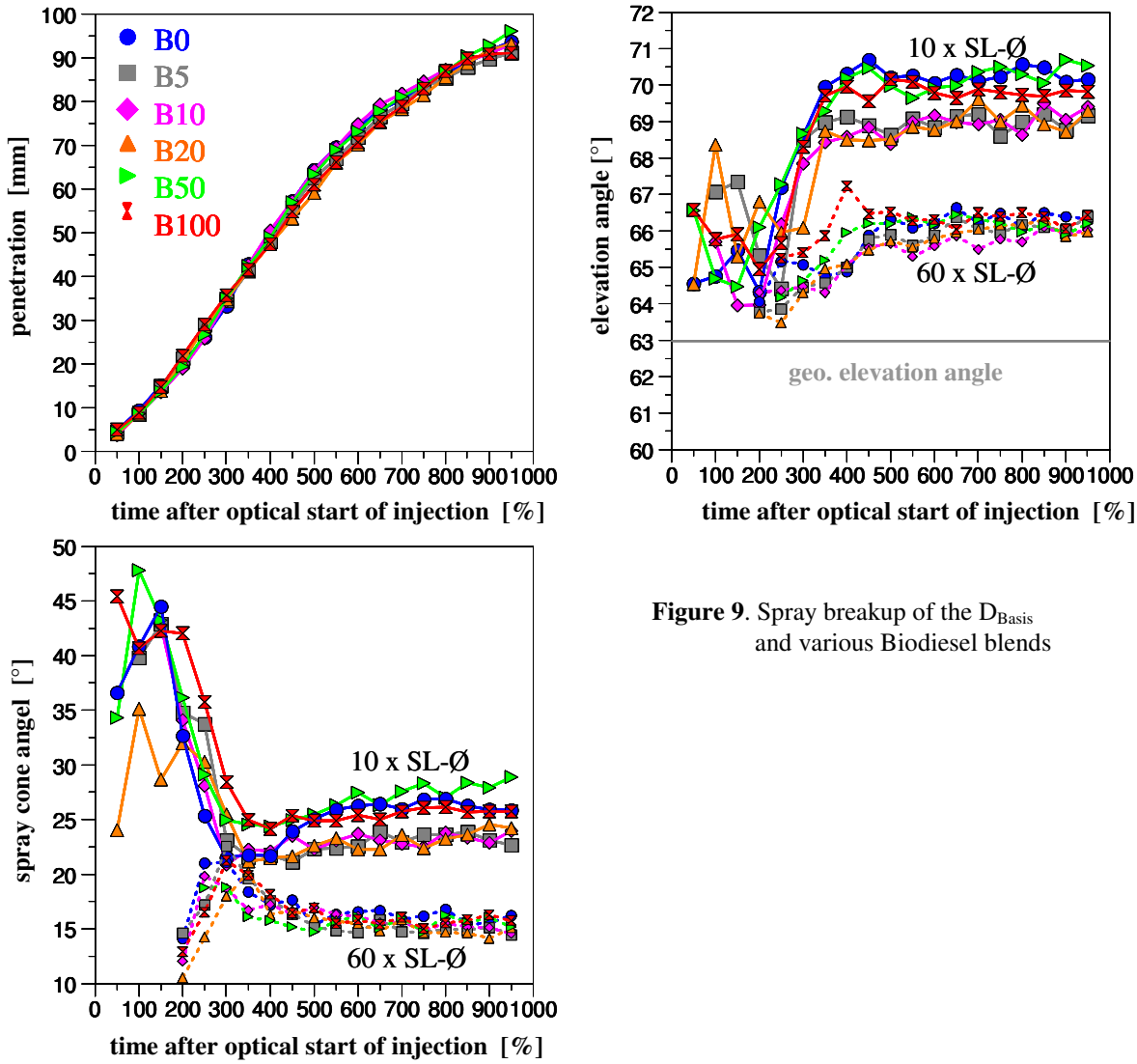


Figure 9. Spray breakup of the D_{Basis} and various Biodiesel blends

The pure biodiesel B100 generates the lowest FSN and HC results. The decrease is approx. proportional to the percentage proportion of biodiesel in diesel blends - probably due to the increased proportion of oxygen in the biodiesel.

In future studies the influence of the injection system especially of the nozzle geometry on the spray breakup and the emissions of the biodiesel fuel and its diesel blends is to be examined.

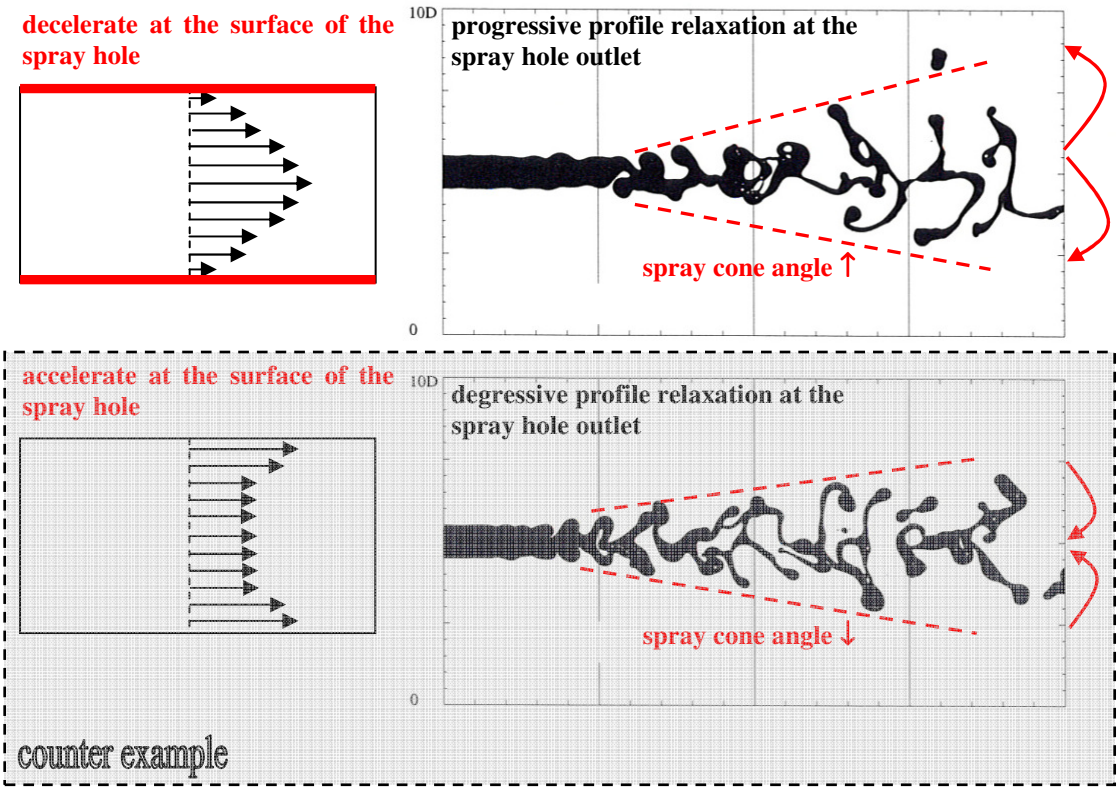


Figure 10. Profile relaxation [14]

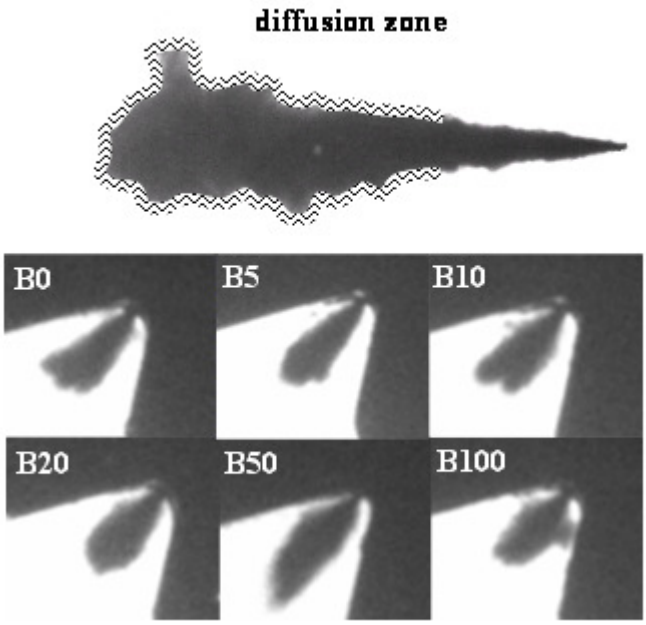


Figure 11. Comparison of the spray breakup with B0, B5, B10, B20, B50 and with B100 60µs after the optical start of the injection and the diffusion zone

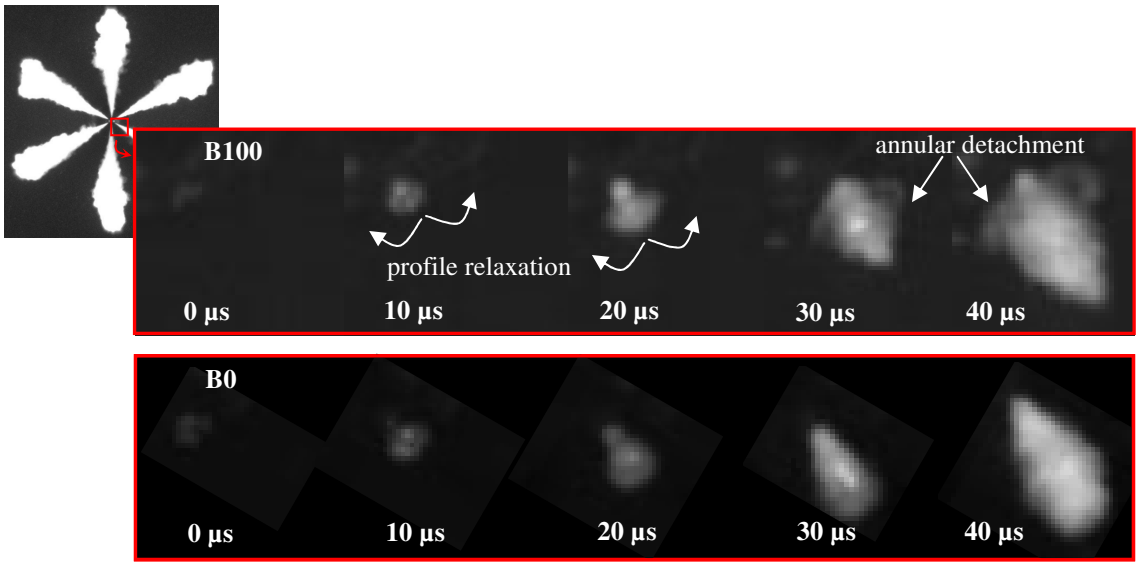


Figure 12. Images of the profile relaxation at 1800bar injection pressure and 10bar in the cold chamber for B100 and B0

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