Chapter 5
Effects of Biodiesel Usage on Injection Process Characteristics

A replacement of mineral diesel by biodiesel causes variations in injection process characteristics. Most notably, biodiesel usage influences the *injection pressure*, *injection timing*, and *injection rate*. Clearly, these effects depend to a great extent on *biodiesel properties* (raw material, production technology, ingredients, etc.), *operating regime*, and *ambient temperature*. This means that one has to deal with many highly interdependent influencing parameters. Consequently, the determination of these effects is a sophisticated process that is typically done only partially (e.g., only for one injection system type, for one biodiesel type, etc.) in individual research laboratories. Once such results are known, it is very difficult to estimate how these results can be used in slightly modified circumstances (e.g., when a somewhat different fuel is used). This is why one can often make only some general observations or guidelines. For example, many investigators show that in engines equipped with *mechanically controlled fuel injection systems (MCFIS)* the cyclic fuel delivery, pressure wave propagation time, average injection rate, and maximum pressure during injection are significantly affected when neat biodiesel replaces mineral diesel (Kegl 2006a; Luján et al. 2009a, b). In general, the injection pressure and injection rate are higher and the needle opens earlier for neat biodiesel (Caresana 2011; Kegl 2006a, b). For *electronically controlled fuel injection systems (ECFIS)* the situation is somewhat similar in the sense that various biodiesel types may result in various effects. Although in electronically controlled systems these effects are less exposed than in mechanical systems, numerous tests have to be performed in order to evaluate the influence of biodiesels for various injection pressure levels or injection time strategies (Boudy and Seers 2009; Luján et al. 2009a, b; Ye and Boehman 2010).

B. Kegl et al., *Green Diesel Engines*, Lecture Notes in Energy 12,
DOI 10.1007/978-1-4471-5325-2_5,

5.1 Injection Pressure

Fuel injection pressure has a significant effect on NO_x and soot emissions. In general, an increase of the injection pressure results in an increase in NO_x emission and a decrease in soot emissions (Song et al. 2012). Biodiesel influences significantly the fuel injection pressure; however, this influence is more exposed in MCFIS and less in ECFIS (Boudy and Seers 2009; Kegl 2006a; Kegl and Hribernik 2006; Luján et al. 2009a, b; Payri et al. 2012; Postrioti et al. 2004; Tziourtzioumis and Stamatelos 2012; Zhang and Boehman 2007; Ye and Boehman 2012; Yoon et al. 2009).

In *MCFIS* (*IDI, DI, and M systems*) fuel is transported from the pump through the high pressure tube to the injector, which is actuated by an adequate fuel pressure rise. The fuel transport path is therefore relatively long and plagued by phenomena like cavitation, pressure wave reflection, hydraulic losses, and so on. It should therefore be obvious that fuel properties like density, bulk modulus, and viscosity influence directly the pressure wave propagation and consequently the injection pressure (Kousoulidou et al. 2012; Kegl 2006a; Luján et al. 2009a, b; Ozsezen and Canakci 2010; Usta 2005). Furthermore, biodiesel effects related to the injection pressure depend also on the engine operating regime and fuel temperature.

In *ECFIS* (*unit injector systems, common rail systems*) the phenomena related to pressure wave propagation and reflection are rather minor since the transport way is rather short and the pressure is quite well controlled at some prescribed constant level (Song et al. 2012). Therefore, in these systems biodiesel effects are largely eliminated. In spite of that it is known that the operation of a *common rail system* generates a pressure wave in the injector's feed pipe, which can modify the mass flow rate through the injector. Therefore, fuel properties that affect these pressure waves can influence the injection process and, consequently, the total fuel mass injected, especially in multiple injection scenario (Boudy and Seers 2009). It may also be worth noting that the bulk modulus effect appears to be present in *unit injector systems*, but not in *common rail systems*, where a rapid transfer of the pressure wave practically does not occur (Kousoulidou et al. 2012).

Obviously, the situation depends significantly on the selected injection system type. However, minor design modifications, such as an addition of a snubber valve to the fuel transport way, may also influence the result. For example, numerical and experimental investigations on a bus diesel engine M injection system (Table 5.1) show that a change from mineral diesel to rapeseed biodiesel results in a higher injection pressure and earlier needle opening, if the design and initial conditions are kept constant (Kegl and Hribernik 2006; Kegl 2006a). If diesel and biodiesel blends are used, it can be observed that the mean injection pressure increases almost linearly (up to 7 %) with the increasing part of biodiesel in the blend.

However, the addition of a snubber valve to the high pressure path of the fuel changes the situation. Numerical simulation of injection characteristics for rapeseed biodiesel at fuel temperature of 40 °C and at rated condition revealed this influence. A comparison of the pressure after the HP pump p_p, the injection pressure p_{inj}, and

Table 5.1 Main specification of the tested M injection system (Kegl 2006a)

Injection model	Direct injection system with wall distribution (M system)
Fuel injection pump type	Bosch PES 6A 95D 410 LS 2542
Pump plunger (diameter × lift)	9.5 × 8 mm
Fuel HP tube (length × diameter)	1,024 × 1.8 mm
Injection nozzle (number × nozzle hole diameter)	1 × 0.68 mm
Needle lift (maximal)	0.3 mm

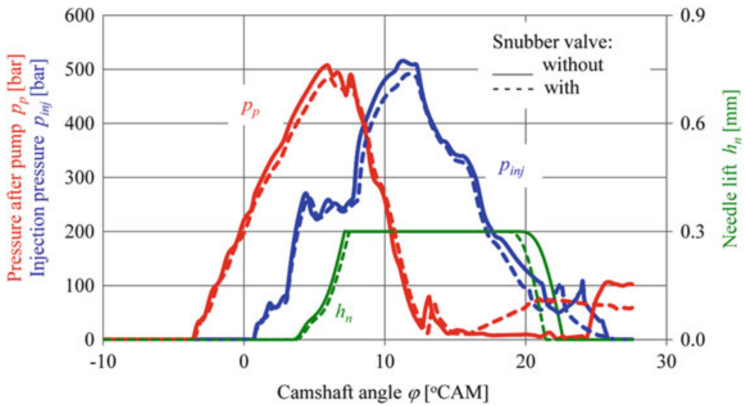

Fig. 5.1 Injection characteristics with and without the snubber valve

the needle lift h_n is shown in Fig. 5.1. When the snubber valve is present, the pressures p_p and p_{inj} are lower by about 20 bar, the injection duration is shorter by about 0.2 ms, and the fuelling is lower by about 10 mm^3/stroke.

5.1.1 Influence of Biodiesel Properties

The physical properties of biodiesel fuels typically differ significantly from those of mineral diesel. These differences lead to various effects, which are most notably present in MCFIS. The most significant effects result from the variations in the following properties:

- *Compressibility* or *bulk modulus*: by using biodiesel, the pressure rise produced by the pump in a MCFIS is achieved faster due to the lower compressibility (higher bulk modulus) of biodiesel.
- *Sound velocity*: when using biodiesel, the fuel transport pressure wave propagates faster toward the injector as a consequence of biodiesel's higher sound velocity; in a MCFIS the delay between the pressure rise after the HP pump and the injection pressure rise is notably shorter.

- *Viscosity*: higher viscosity of biodiesel reduces pump leakage in a MCFIS; this results in increased injection pressure and also contributes to faster and earlier needle opening.

All of these facts result in faster and earlier needle opening when using biodiesel. This fact has been widely accepted to explain the higher temperature peaks and higher rates of NO_x formation when diesel was replaced by biodiesel. Unfortunately, the physical and chemical properties of various biodiesel types may vary significantly, even if they conform to the corresponding standard. Therefore, the effects of biodiesel may also vary substantially in dependence of biodiesel type.

In Kegl (2006a) a mechanically controlled M injection system, Table 5.1, was used to estimate the influence of biodiesel usage on mean injection pressure. As expected, a replacement of mineral diesel (D100) by *rapeseed biodiesel* (RaBIO) with higher bulk modulus resulted in faster injection pressure rise. Furthermore, since higher viscosity of RaBIO reduces pump leakage, increased injection pressures were observed at almost all of the 13 operation modes tested (Fig. 5.2). Similar trends could be observed for RaBIO blends with mineral diesel (B25 denotes a blend of 25 % biodiesel and 75 % mineral diesel, and so on).

It should be noted however, that there might be exceptions. Some studies show that in engines with an MCFIS, the injection pressure may also be lower when mineral diesel is replaced by biodiesel. In the mechanically controlled Ruggerini RF91 fuel injection system, Table 5.2, the experimentally obtained injection pressure was lower with RaBIO than with D100 (Caresana 2011). The average difference observed was around 13 bar for neat RaBIO and 2 bar for the B20 (20 % biodiesel, 80 % mineral diesel) blend. An analysis of the experimental injection pressure traces revealed that just after the needle closing the pressure in the injection tube may fall below the vapor value, which leads to cavitation. In turn, cavitation may be the cause of lower injection pressure in the subsequent injection cycle. The residual pressure obtained with biodiesel was lower than that obtained with mineral diesel (Fig. 5.3).

In Tziourtzioumis and Stamatelos (2012) the influence of fuel properties on variation of the injection pressure was investigated on a HSDI turbocharged engine, equipped with an ECFIS, Table 5.3. The biodiesel used was produced from 40 % rapeseed oil, 30 % soybean oil, and 30 % waste cooking oil.

The results show that the rail pressure increases when biodiesel is added to mineral diesel (Fig. 5.4). This is explained by the ECU algorithm for the computation of the rail pressure. Namely, the rail pressure is computed as a function of the engine speed and fuel delivery per stroke. Since biodiesel has a lower volume heating value than pure diesel, more fuel needs to be injected into the engine cylinder, which causes a higher fuel delivery and thus increased rail pressures for the B70 fuel blend. In Fig. 5.4, the ranges of pressure wave oscillations in the rail tube are given at several engine speeds.

The influence of fuel properties on injection pressure was also investigated numerically for single and multiple injection strategies in an ECFIS (Boudy and Seers 2009; Song et al. 2012). From the results it follows that an increase of fuel viscosity, bulk modulus, or density results in a relatively small reduction of the

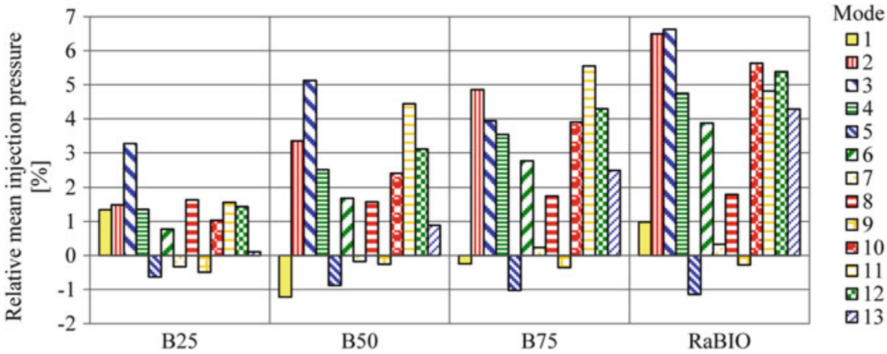

Fig. 5.2 Mean injection pressure at 13 ESC test mode for blends of RaBIO and D100 with respect to D100

Table 5.2 Main specifications of the tested engine (Caresana 2011)

Engine	Ruggerini RF5
Engine type	One cylinder, four stroke, NA, DI, mechanically controlled injection system
Displacement	477 cm^3
Compression ratio	18.5:1
Bore and stroke	90 × 75 mm
Maximal power	8.1 kW at 3,600 rpm
Maximal torque	25 Nm at 2,500 rpm

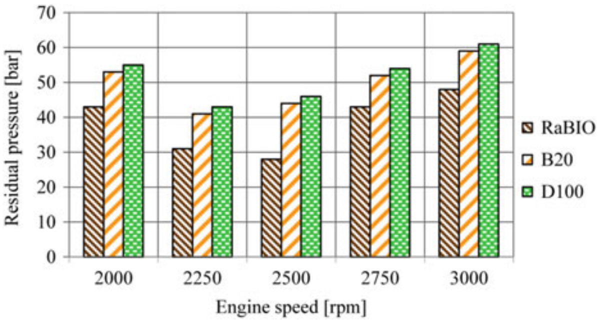

Fig. 5.3 Residual pressure for various tested fuels

pressure wave amplitude. In case of a single injection strategy, the variation in fuel properties are less influential, because the time interval between successive injections is large enough to allow the pressure wave to be damped out before the next injection event. In a multiple injection scenario, the fuel with higher density exhibits a smaller pressure wave amplitude. These differences can be observed even for various biodiesels. For example, the density of RaBIO is higher than that of *palm biodiesel* (PaBIO); consequently the *pressure wave amplitudes* in multiple injection strategy of RaBIO are smaller than those obtained with PaBIO.

Table 5.3 Main specification of the tested engine (Tziourtzioumis and Stamatelos 2012)

Engine	HSDI turbocharged diesel engine DW10 ATED
Engine type	Four cylinders, in line, electronically controlled injection system
Injection type	CPI Bosch EDC 15C2 HDI (1,350 bar)
Compression ratio	18:1
Bore and stroke	85 × 88 mm
Maximal power	80 kW at 4,000 rpm
Maximal torque	250 Nm at 2,000 rpm

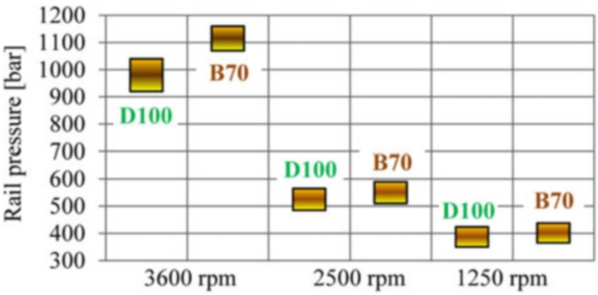

Fig. 5.4 Rail pressure and its oscillation range at various engine speeds

5.1.2 Influence of Engine-Operating Regime

The engine-operating regime is defined by the engine load and speed. In general, the injection pressure increases by increasing either the engine speed or load. A pressure rise is also typically observed when mineral diesel is replaced by biodiesel. However, investigations have shown that the actual situation may look somewhat different at some operating regimes.

Numerical simulations performed on a mechanically controlled M injection system of a bus diesel engine, Table 5.1, revealed that the higher bulk modulus and kinematic viscosity of biodiesel result in a higher mean injection pressure at almost all 13 modes of the ECS test (Fig. 5.5) (Kegl 2006a). There are, however, two modes at which the mean injection pressure decreased. The variation was small but notable. From Fig. 5.5 it can be seen that the lowest values of mean injection pressure with RaBIO are obtained at idle (mode 1) and at lower engine speeds and loads (modes 5, 7, 9).

For the RaBIO blends with D100 the situation is quite similar (Fig. 5.2). The mean injection pressure increases almost linearly with the increasing part of biodiesel (up to 7 %) (Kegl 2006a).

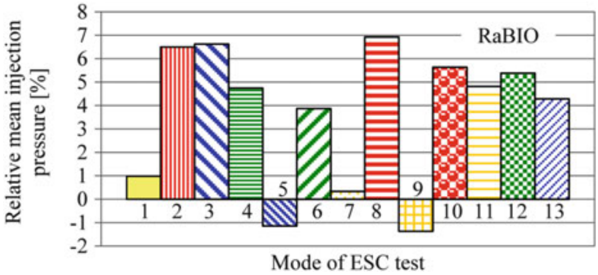

Fig. 5.5 Relative mean injection pressure at the 13 ESC test modes for RaBIO with respect to D100

5.1.3 Influence of Temperature

Fuel temperature influences the bulk modulus, density, kinematic viscosity, and sound velocity of biodiesels. In general, lower fuel temperature means higher bulk modulus, density, and sound velocity. Consequently, a variation in fuel temperature can contribute significantly to variations in all injection characteristics.

At lower fuel temperatures, the injection pressure of biodiesels rises earlier than that of mineral diesel. This is due to the fact that at lower temperatures the difference of bulk modulus between biodiesel and mineral diesel is larger than at higher temperatures.

In a mechanically controlled M fuel injection system, Table 5.1, the influence of fuel temperature on injection pressure was investigated experimentally by using RaBIO (Kegl and Hribernik 2006). The tests were performed at constant pump injection timing of 23°CA BTC at several operating regimes. The fuel temperature was measured at the end of the HP tube, just before the injector. At full load and 500 rpm the maximum injection pressure was reached at higher temperatures (Fig. 5.6). This changed when the speed was increased to 800 rpm (Fig. 5.7) and 1,100 rpm (Fig. 5.8). In the latter cases the pressure maximum was observed at lower temperatures. At lower load regimes, the influence of fuel temperature on the measured injection pressure was observed to be quite similar to that at full load (Kegl and Hribernik 2006).

By lowering the fuel temperature, the bulk modulus and kinematic viscosity of biodiesels typically increase. In general, this means that lower fuel temperature results in higher mean injection pressures. This can be observed at most ESC modes (Fig. 5.9). As one can see, the relative mean injection pressure increases progressively with lower fuel temperature (up to 15 % at −20 °C) (Kegl 2008).

It may be worth noting that some authors report that at higher fuel temperatures (over 80 °C), the variation of bulk modulus and kinematic viscosity does not influence significantly the injection pressure, injection timing, and needle lift history (Yamane et al. 2001).

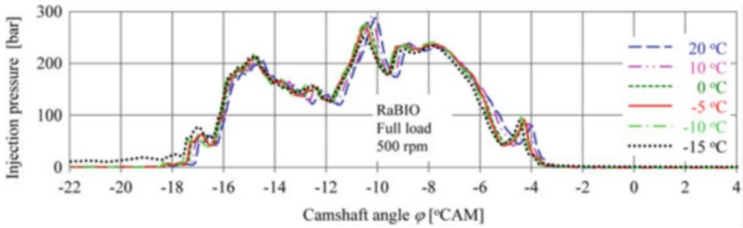

Fig. 5.6 Fuel temperature influence on injection pressure at full load and 500 rpm

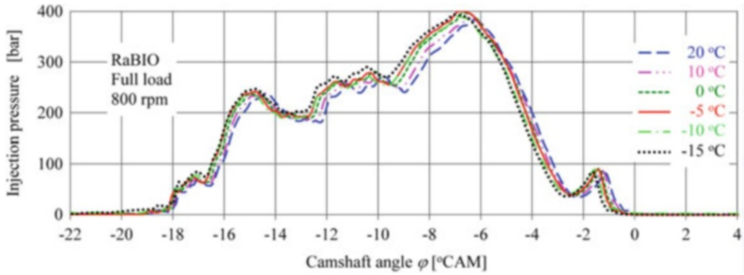

Fig. 5.7 Fuel temperature influence on injection pressure at peak torque

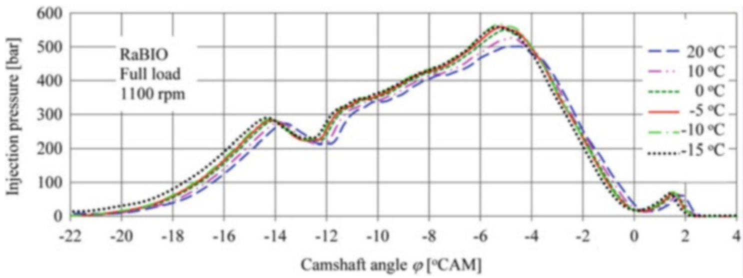

Fig. 5.8 Fuel temperature influence on injection pressure at rated condition

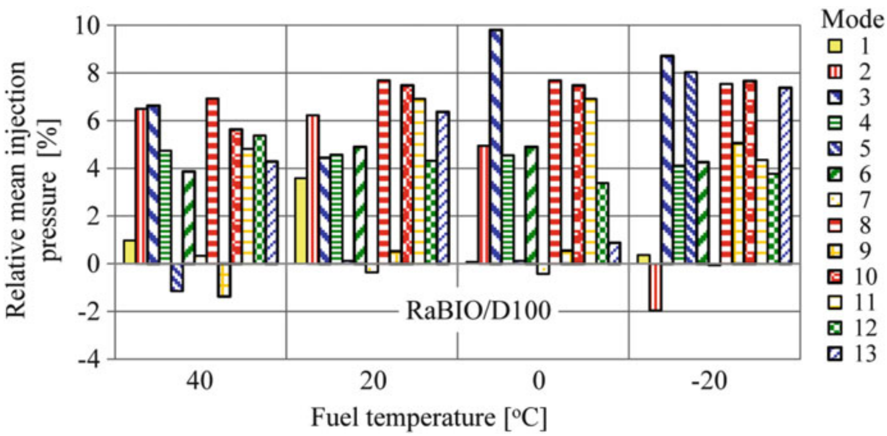

Fig. 5.9 Relative mean injection pressure variation of RaBIO with respect to D100

5.2 Injection Timing

It is well known that injection timing or start of injection is a very important parameter that significantly influences all engine characteristics. This is mainly due to the fact that injection timing influences the mixing quality of the air–fuel mixture and consequently also the combustion process, including harmful emissions. It is generally known that retarded injection decreases the maximal pressure in the cylinder and leads to lower peak rate of heat transfer and consequently to lower combustion noise. Since the delayed injection leads to lower temperatures, the NO_x emissions are also reduced. On the other hand, retarded injection leads to an increase in fuel consumption. Smoke emission may also increase, though trends vary significantly between different engine types. For example, for direct injection diesel engine at high load, the HC emissions are low and vary only modestly with respect to injection timing. At partial loads, the HC emissions are higher and increase as the injection start is shifted significantly from the optimum. This trend is especially evident at idle.

By changing the injection timing and introducing biodiesel fuel, it is necessary to carefully monitor some of the engine characteristics in order to prevent harmful mechanical and thermal stress of the engine. Above all, these characteristics are the *injection pressure*, *in-cylinder pressure*, and *exhaust gas temperature*. All these parameters, as well as ambient pressure and temperature, fuel temperature, cooling water temperature in the inlet and outlet of the engine, intake air pressure and temperature, oil pressure and temperature, intake air mass flow, and oxygen level in the exhaust gases, have to be measured to find the optimal injection timing.

In ECFIS, the start of injection can easily be controlled directly by the ECU, which can be programmed according to various fuel types. When biodiesel replaces diesel, the consequences are not exposed as much as in a MCFIS. In spite of that, they are measurable and have to be taken into account (Song et al. 2012). For example, at the same operating conditions and at the same injection fuelling, *soybean biodiesel* (SoBIO) usage results in a slightly shorter injection delay and consequently in slightly advanced injection timing, compared to mineral diesel (Yoon et al. 2009). The reason for advanced injection timing is mainly due to the higher bulk modulus of biodiesel.

In MCFIS, the start of injection can hardly be controlled directly, because it depends on sophisticated transport phenomena in the pump, high-pressure tube, and the injector. However, the start of injection is closely related to the start of injection pump delivery, which can be set easily to any desired value. For this reason, the start of injection pump delivery or injection pump timing is frequently used as the primary variable to set the injection timing (Kegl 2006b). Compared to mineral diesel, biodiesels exhibit a higher bulk modulus, which results in higher sound velocity. This leads to a more rapid transfer of the pressure wave from the pump to the injector needle and to an earlier needle lift (Boehman et al. 2004; Kegl and Hribernik 2006; Kegl 2006a). Therefore, the injection timing should in general be advanced practically at all operating regimes (Ozsezen et al. 2008).

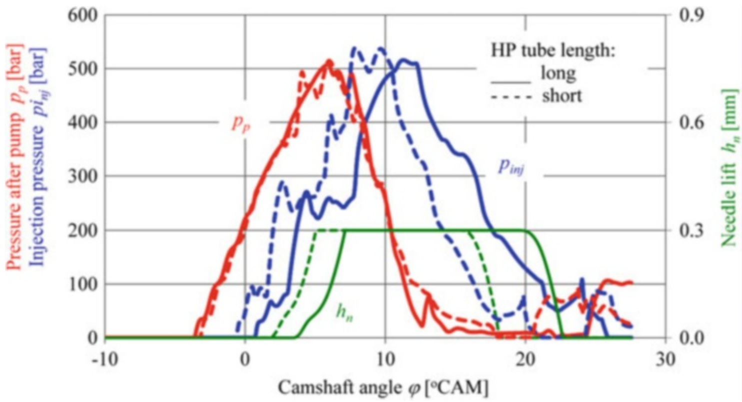

Fig. 5.10 Injection characteristics using RaBIO and various HP tube lengths

It is worth noting that for a MCFIS rather minor design variations, such as the addition of the snubber valve, HP tube length variation, etc., may also lead to significant injection timing variation that may depend on the fuel type. For example, numerical and experimental RaBIO usage investigation on a mechanically controlled M injection system, Table 5.1, revealed that if the HP tube is shortened, e.g., by about 50 %, the pressures p_p and p_{inj} may increase up to 20 bar (Kegl and Hribernik 2006; Kegl 2006a). Furthermore, the injection duration shortens by about 0.4 ms and the fuelling is lower by about 15 mm^3/stroke (Fig. 5.10). Furthermore, the HP tube shortening advanced the injection timing by about 0.3 ms.

5.2.1 *Influence of Biodiesel Properties*

Fuel injection timing is most notably influenced by the physical properties of the fuel, especially by density, bulk modulus, and kinematic viscosity. Clearly, in mechanically controlled injection systems these effects are much more exposed than in electronically controlled systems.

Biodiesels typically exhibit higher *density, bulk modulus, viscosity*, and *sound velocity*. This leads to faster pressure wave propagation. In MCFIS this leads to earlier needle lift and advanced injection timing (reduced injection delay). Earlier injection typically leads to an increase of the maximum in-cylinder pressure, increased in-cylinder temperature, and higher exhausts emissions (Pandey and Sarviya 2012). Higher viscosity of biodiesels results in reduced fuel losses during the injection process which also contributes to faster evolution of the injection pressure and advanced injection timing. Another point worth notion is the *vapor volume* that depends on the residual pressure in a MCFIS. Biodiesels typically exhibit lower vapor values. This also decreases the injection delay and thus advances the injection timing. This effect is observable for neat biodiesels and for biodiesel blends with mineral diesel.

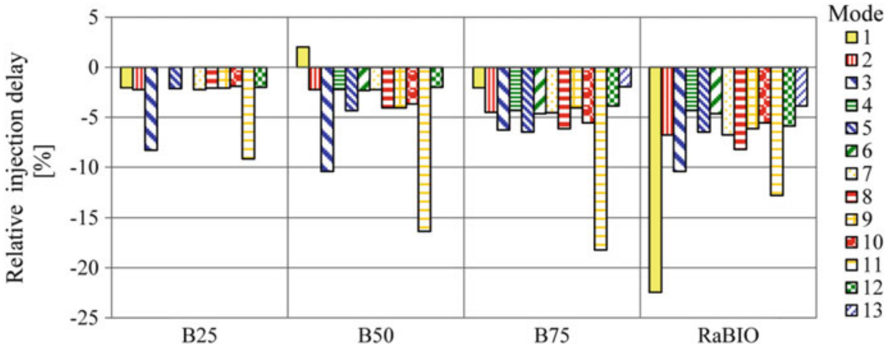

Fig. 5.11 Injection delay at 13 ESC test mode for blends of RaBIO and D100 with respect to D100

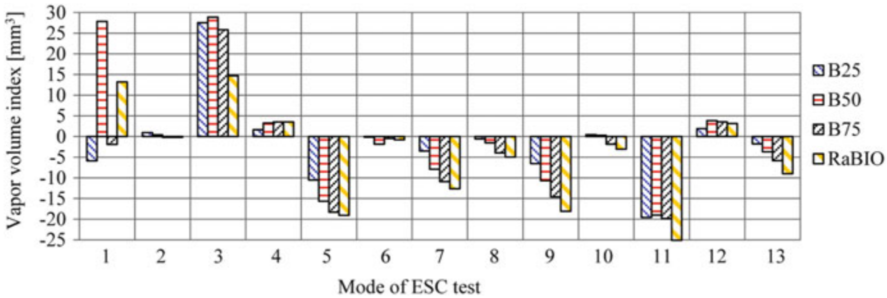

Fig. 5.12 Vapor volume indexes at 13 ESC test modes for blends of RaBIO and D100 with respect to D100

In ECFIS the influence of fuel properties on injection timing is rather minor. Especially for the single injection strategy it can practically be neglected (Boudy and Seers 2009). In the multiple injection strategy, however, variation in the friction coefficient and pressure wave velocity may alter the phasing of the pressure wave arrival and injector opening. For this reason the post injection of biodiesel typically starts earlier.

Experimental and numerical investigation performed on a mechanically controlled M injection system, Table 5.1, confirmed that a replacement of D100 by RaBIO results in advanced injection timing (Kegl 2006a). For the blends, the injection delay decreased practically linearly with the increasing part of RaBIO in the blend (Fig. 5.11). This observation was confirmed for practically all operating modes.

Further numerical simulation also revealed that the injection delay is also influenced by the vapor volume (Kegl 2006a). The vapor contents for various blends of RaBIO and mineral diesel at fuel temperature of 40 °C are shown in Fig. 5.12. Here, the vapor volume index is defined as the vapor volume of the actually tested fuel, multiplied by the fuelling ratio (fuelling of neat mineral diesel divided by the fuelling of actually tested fuel). By increasing the part of RaBIO, the

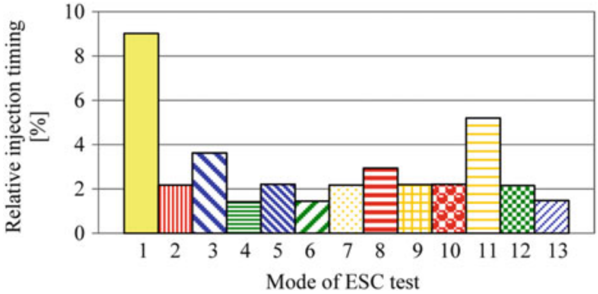

Fig. 5.13 Injection timing at 13 ESC test modes for RaBIO with respect to D100

vapor content decreases, especially at lower loads. At full and 75 % loads, the vapor volume indexes are practically the same for all tested fuels.

5.2.2 *Influence of Engine-Operating Regime*

Biodiesel usage typically advances the injection timing. However, the actual situation depends also on the operating regime, i.e., on engine load and speed.

Experimental and numerical investigation performed on a mechanically controlled M injection system, Table 5.1, confirmed that a replacement of D100 by RaBIO results in lower injection delay at all 13 modes of the ECS test (Kegl 2006a). However, the magnitude of this variation depends on the engine-operating regime. At the idle condition the injection delay for biodiesel is more than 20 % lower than the one obtained with mineral diesel, which results in advanced injection timing by about 9 % (Fig. 5.13). On the other side, the smallest injection timing advancements of less than 2 % were obtained at partial loads and higher engine speeds (modes 4, 6, 13).

5.2.3 *Influence of Temperature*

The influences of fuel temperature on injection timing can be illustrated by experimental and numerical investigation performed on a mechanically controlled M injection system, Table 5.1 (Kegl and Hribernik 2006). Injection timing was obtained from the needle lift h_n, which was determined at various operating regimes when using RaBIO. The results show that at full load lower fuel temperatures lead to advanced injection timing at 500 rpm (Fig. 5.14) at 850 rpm (Fig. 5.15) and 1,100 rpm (Fig. 5.16). At low load regimes, the influence of fuel temperature on the measured injection timing is quite similar to that at full load.

For the same system, the injection delay and injection timing were investigated at various temperatures and related to the injection delay at fuel temperature of 40 °C. Both, neat D100 and neat RaBIO were investigated. For both fuels, the relative injection delay decreased with decreasing fuel temperatures. This is mostly due to the higher sound velocity and can be observed at practically all operating

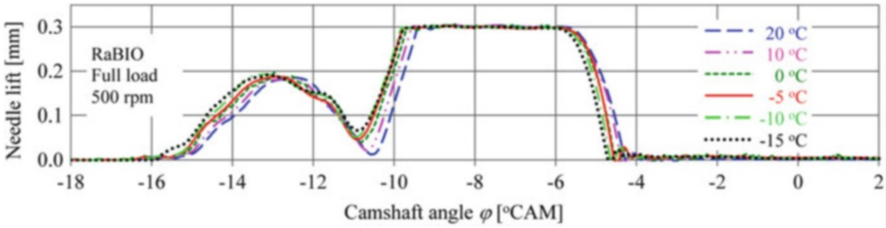

Fig. 5.14 Fuel temperature influence on injection timing at full load and 500 rpm

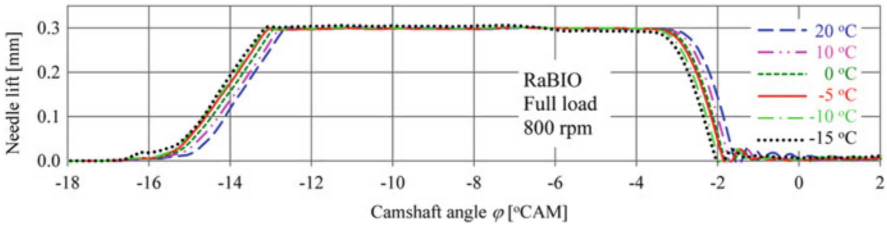

Fig. 5.15 Fuel temperature influence on injection timing at full load and 800 rpm

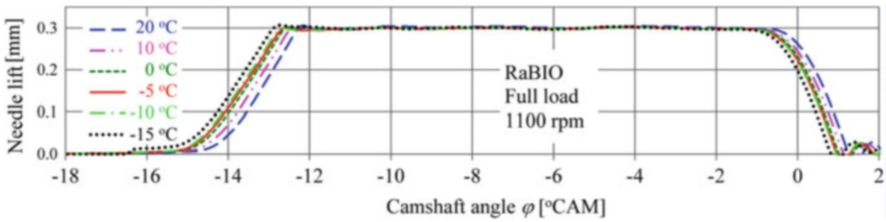

Fig. 5.16 Fuel temperature influence on injection timing at full load and 1,100 rpm

regimes (Kegl 2008). The relative injection timing of RaBIO with respect to D100 at several fuel temperatures is given in Fig. 5.17.

Reduced injection delay means that the injection timing at lower fuel temperatures is advanced. It is known that advanced timing causes the pressure and temperature in the cylinder to rise, leading to increased NO_x emissions. As shown in Fig. 5.18, advanced injection happens with both fuels at all ESC modes.

5.3 Injection Rate

Injection rate history, fuelling at various phases of injection, and the total fuelling depend directly on fuel properties, especially on the viscosity and density. Since viscosity and density of biodiesels may vary substantially; this may lead to

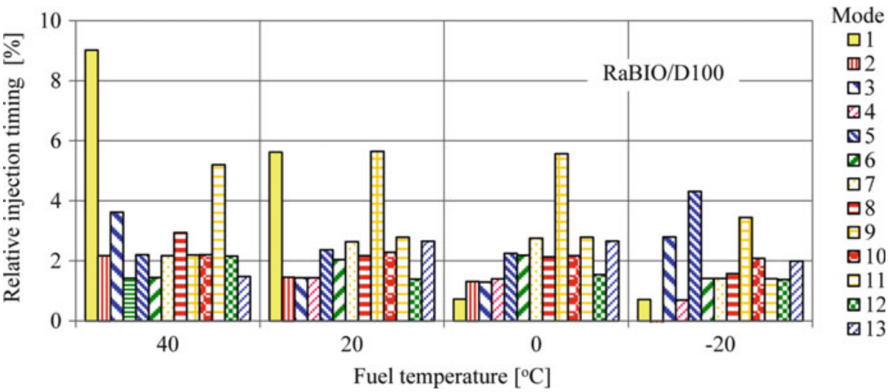

Fig. 5.17 Relative injection timing of RaBIO with respect to D100

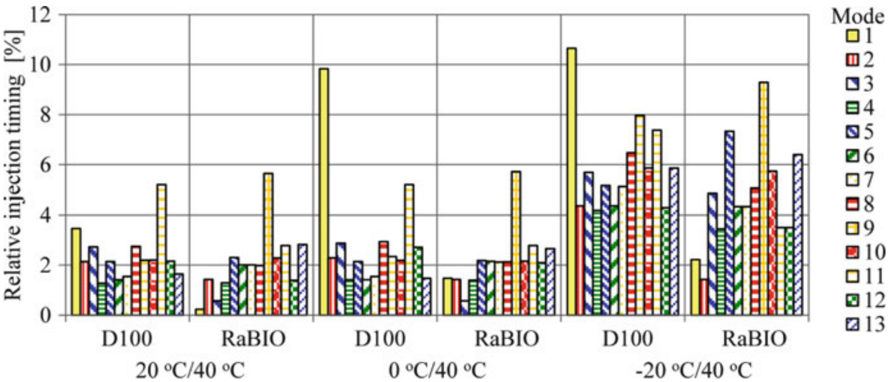

Fig. 5.18 Relative injection timing at various temperatures

significant effects on the injection rate. Furthermore, the density and viscosity of the fuel depend significantly on its temperature. Therefore, fuel temperature also represents a very important parameter.

As with other injection characteristics, biodiesel influence on injection rate is not equally exposed at all fuel injection systems. In MCFIS this influence is rather significant due to transport-related effects and lower injection pressures (Boudy and Seers 2009; Kegl 2008, 2006a). In ECFIS, however, this influence is rather minor. At a first glance, this comes as a surprise since biodiesels typically have higher viscosity than mineral diesel, which tends to retard the fuel flow into the combustion chamber and lower the volume of injected fuel. However, biodiesel fuels have higher density than mineral diesel, which implies that the mass of the injected fuel remains rather constant. These two counteracting effects can explain why there are no significant differences between both fuel injection rates in a high pressure common rail system (Luján et al. 2009a, b; Yoon et al. 2009).

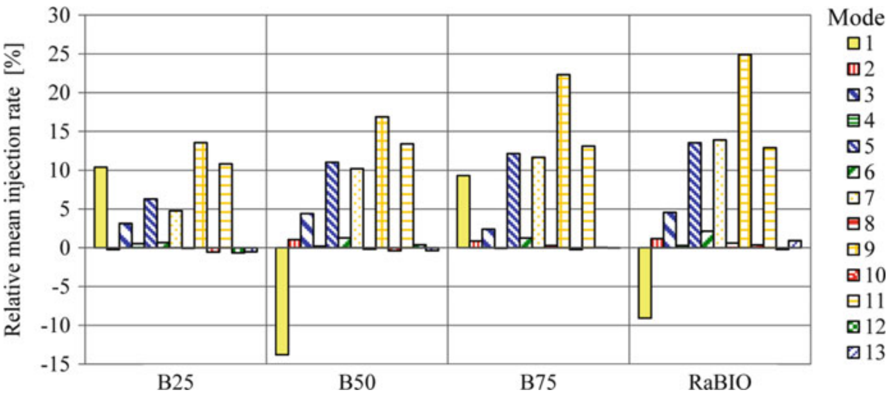

Fig. 5.19 Mean injection rates at 13 ESC test modes for blends of RaBIO and D100 with respect to D100

5.3.1 Influence of Biodiesel Properties

In MCFIS, a general observation is that higher values of fuel density, viscosity, and bulk modulus result in an increased fueling (Boudy and Seers 2009; Kegl 2006a). In ECFIS a higher fuel density may also lead to somewhat higher fueling, but only under special circumstances. In the case of single injection, the fuelling of various biodiesels is practically unchanged with respect to mineral diesel. Fuel density has also a negligible impact during pilot and main injections in the case of triple injection. However, during post-injection the higher density of biodiesel fuels may result in higher injected fuel mass. This effect may be even more emphasized, if the value of the bulk modulus decreases (Boudy and Seers 2009), i.e., if one type of biodiesel is replaced by another one with higher density and lower bulk modulus.

Investigations on a mechanically controlled M fuel injection system, Table 5.1, show that, in general, the mean injection rate increases when D100 is replaced by RaBIO or its blends. This can be observed at all ESC modes, except for neat RaBIO and B50 at idle (Fig. 5.19) (Kegl 2006a).

By taking into account the weighting factors of the 13 modes of the ESC test, the partial fuellings of various injection phases are presented in Fig. 5.20 (Kegl 2006a). The total fuelling consist of the partial fuelling during needle opening phase (A), which is subdivided into A1 (first 10 % of injection) and A2 (from end of A1 till the end of A), open needle phase (B) and needle closing phase (C), which is subdivided into C1 (from start of C till the beginning of C2) and C2 (last 10 % of injection).

The results presented in Fig. 5.20 show that the fuelling during the first 10 % of injection duration (A1) is the highest when using D100; meanwhile the fuelling during the last 10 % of injection duration (C2) is the smallest with B25 and B75. The fuelling during the needle lifting as well as needle closing decreases with increasing content of RaBIO in the blend with D100.

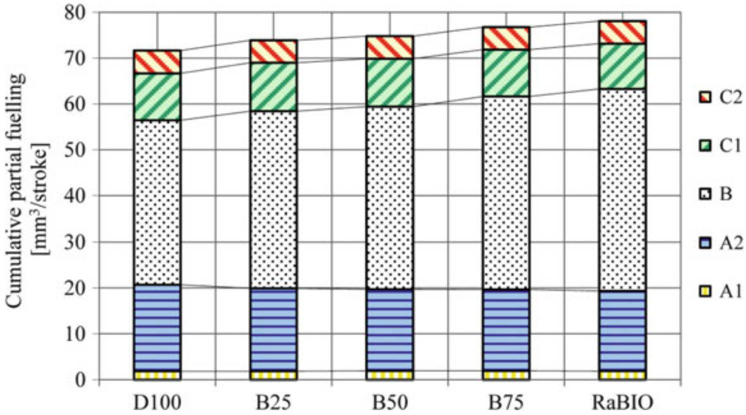

Fig. 5.20 Fuelling in various phases of injection, summed over 13 ESC modes, for various fuels

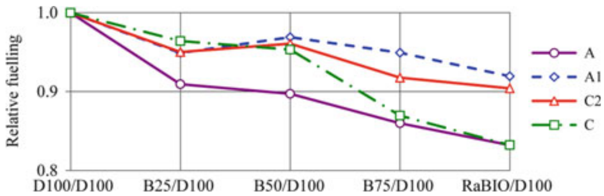

Fig. 5.21 Relative partial fuellings summed over all 13 ESC modes for various blends of RaBIO and D100

In order to enable a comparison between various fuels, the relative partial fuellings, summed over all 13 ESC modes, can be calculated (Kegl 2006a). The most interesting phases (A, A1, C, and C2) are compared in Fig. 5.21. One can see that by increasing the RaBIO content, all of the compared quantities decrease. This offers a good opportunity to reduce NO_x as well as smoke and PM emissions.

5.3.2 Influence of Engine-Operating Regime

In general, the mean injection rate is higher at higher engine loads and speeds. However, this may not always be the case. Investigations have shown that this situation may change in a particular operating regime.

In Kegl (2006a) RaBIO blends with D100 were tested in a mechanically controlled M fuel injection system, Table 5.1. It turned out that, in general, the fuelling increases by increasing the part of RaBIO in the blend (Fig. 5.22). Only at idle this was not the case.

The relative mean injection rates of RaBIO with respect to D100 are presented in Fig. 5.23 (Kegl 2006a). One can see that the injection rates increased the most at

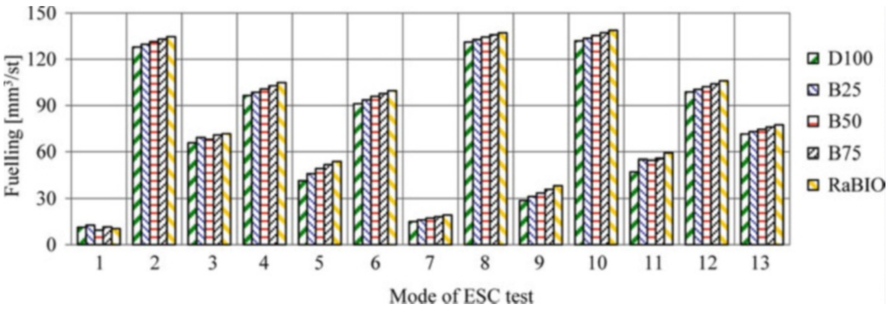

Fig. 5.22 Fuelling of RaBIO blends with D100

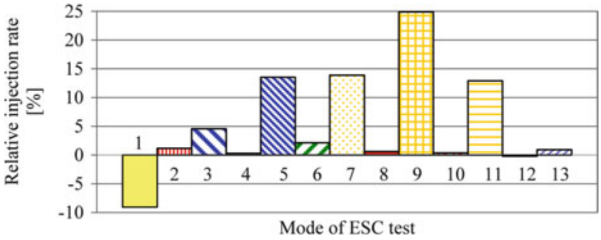

Fig. 5.23 Relative mean injection rate for RaBIO

lower loads (modes 7, 9, 11—25 % load and mode 5—50 % load). On the other side, at idle the mean injection rate is the lowest.

5.3.3 Influence of Temperature

In Kegl (2008) the influence of fuel temperature on fuelling per stroke was investigated on the mechanically controlled M fuel injection system, Table 5.1, by using D100 and RaBIO. In general, the fuelling of RaBIO is somewhat higher than that of D100, but the results depend significantly on fuel temperature (Fig. 5.24). The maximum difference (over 20 %) is obtained at lower loads (modes 5, 7, 9, and 11), especially at higher fuel temperatures.

In the mechanically controlled M injection system the fuellings during the initial and final injection phases are closely related to NO_x and smoke emissions. Therefore, it is worth to compare the partial fuellings for D100 and RaBIO at various operating regimes and various fuel temperatures (Kegl 2008). In order to estimate the NO_x emission, the partial fuelling A at various temperatures is shown in Fig. 5.25. One can see that the variations of relative partial fuelling A increase as the temperature becomes lower. For both fuels, D100 and RaBIO, this is especially evident below 0 °C. Both fuels behave similarly, except at three operating regimes (modes 1, 7 and 9) at the temperature of 0 °C. This means that at low load regimes, RaBIO is somewhat more sensitive to temperature. Thus, the relative increase of

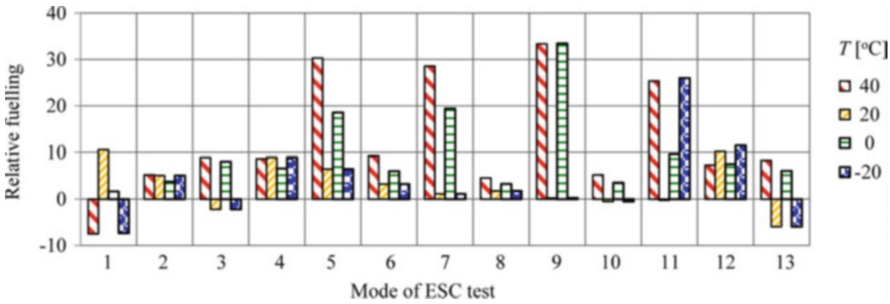

Fig. 5.24 Relative fuelling of RaBIO compared to that of D100 at various fuel temperatures

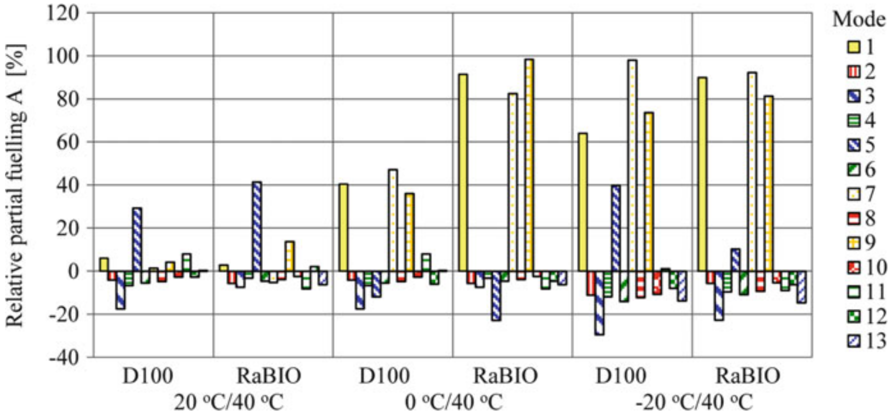

Fig. 5.25 Relative partial fuelling A

NO_x emission of RaBIO may be somewhat higher at these modes. At almost all other modes of the ESC test, the partial fuelling A decreases with lower temperatures.

By analyzing the partial fuelling A1 (Fig. 5.26) one can conclude that the differences between both fuels are relatively small. One can see, however, that the partial fuelling A1 practically always increases as the temperature is reduced. This means that at lower temperatures, higher NO_x emission can be expected for both fuels (Kegl 2008).

To estimate the influence of temperature on smoke emission, the partial fuellings C2 and C are shown in Figs. 5.27 and 5.28 (Kegl 2008). One can see that the relative partial fuelling C2 increases practically at all modes. The increase is relatively large; at some modes it almost reaches 100 %. The differences between RaBIO and D100 are rather small. A similar observation can be made for the relative partial fuelling C. According to the observations in the final phases of injection, one can expect that the influence of fuel temperature on smoke is similar for D100 and RaBIO.

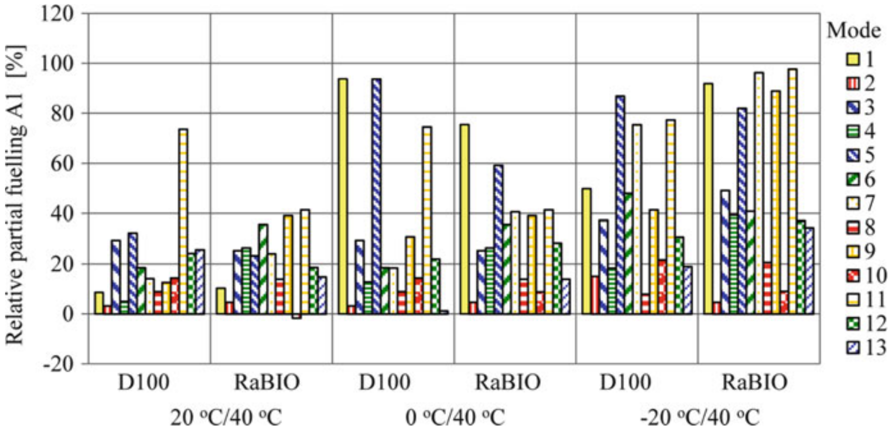

Fig. 5.26 Relative partial fuelling A1

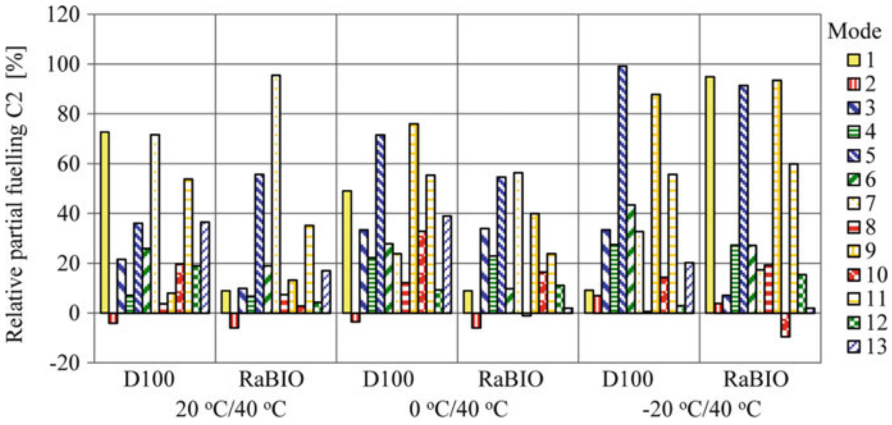

Fig. 5.27 Relative partial fuelling C2

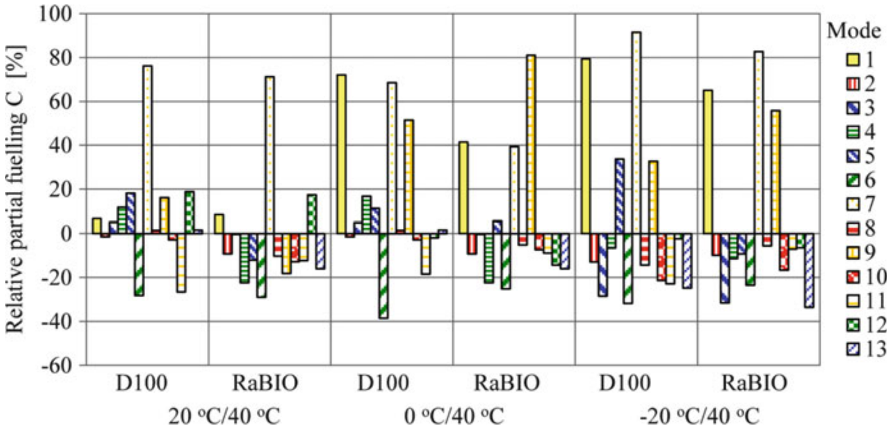

Fig. 5.28 Relative partial fuelling C

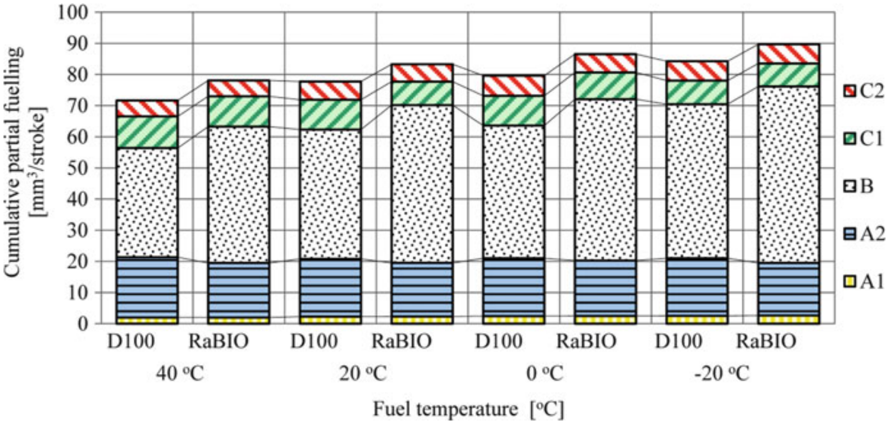

Fig. 5.29 Cumulative partial fuellings

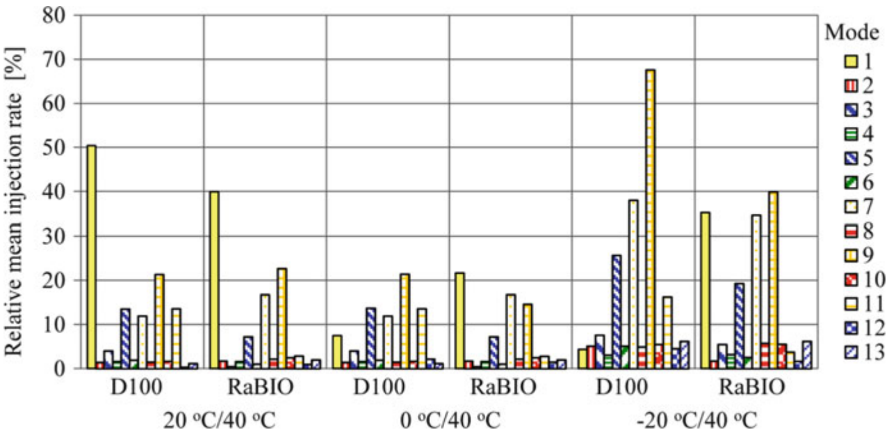

Fig. 5.30 Relative mean injection rate

The cumulative partial fuellings of both fuels (Fig. 5.29) reflect to a great extent the situation observed with the partial fuellings A1 and C2 (Figs. 5.26 and 5.27). Furthermore, as shown in Fig. 5.29, the cumulative partial fuellings A2 and C1 decrease with lower fuel temperatures (Kegl 2008). It is also evident that by lower temperatures the partial fuelling B increases, both in absolute and relative sense (partial fuelling B divided by the total fueling). The cumulative relative partial fuellings A1 and C2 increase with lower temperatures. Regarding the harmful emissions, this is not very encouraging. However, the cumulative relative partial fuellings A and C remain practically constant. Thus, the negative impact on harmful emissions might not be so problematic.

For both fuels, the relative mean injection rate increases with lower fuel temperatures (Fig. 5.30). Except at the idle regime, the increase of relative injection rate is somewhat lower for RaBIO, compared to that of D100. Since lower mean

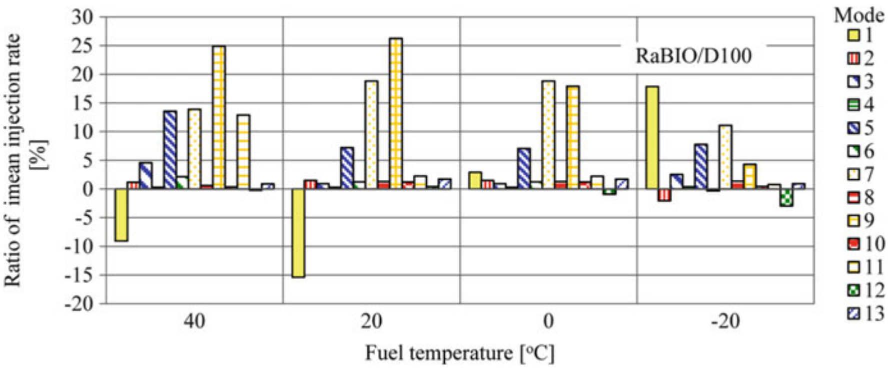

Fig. 5.31 Ratio of mean injection rate

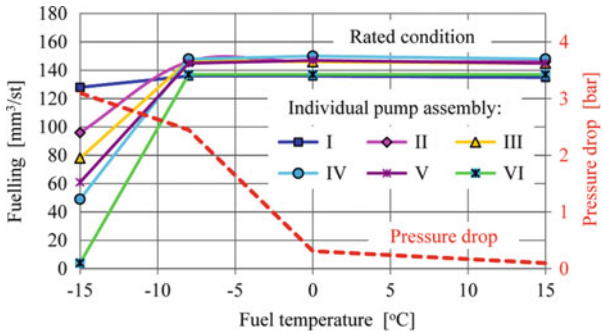

Fig. 5.32 Pressure drop and fuelling at rated condition for RaBIO

injection rate leads to higher smoke emission, it looks like RaBIO would give higher smoke emission, especially at the lowest temperature (Fig. 5.30). To clarify the situation, the ratio of mean injection rate of RaBIO and D100 is shown in Fig. 5.31. As shown, RaBIO offers higher mean injection rates at almost all ESC modes and at all temperatures (Kegl 2008).

Experimental investigations also show that low temperature can have a significant influence on unequal fuelling with respect to individual assemblies in the injection pump of a multi cylinder engine. This influence was investigated experimentally for the whole M fuel injection system of a 6-cylinder engine with injection assemblies I through VI (Kegl 2008). Experiments were done at two engine operating regimes (rated and peak torque conditions). The tested fuels were neat RaBIO and D100.

At rated condition, the fuellings of RaBIO for individual assemblies (I through VI) are presented in Fig. 5.32. One can see that above −7 °C the differences of fuellings through individual assemblies are within acceptable limits. However, at temperatures lower than −7 °C, these differences raise unacceptably. Only for the injection assembly I, being located the closest to the fuel inlet into the low pressure pump's gallery, the fuelling remains acceptable. For other assemblies, the situation becomes worse, as the distance between the gallery inlet and assembly inlet

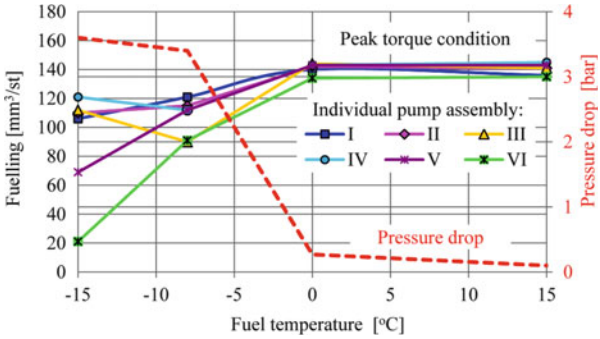

Fig. 5.33 Pressure drop and fuelling at peak torque condition for RaBIO

becomes larger. This observation can probably be explained by the increased pressure drop through the fuel filter (Fig. 5.32). This may result in insufficient fuel supply into the low pressure pump's gallery. The increased pressure drop through the filter is a consequence of high viscosity and density of RaBIO at lower temperatures.

Figure 5.33 presents the pressure drop and fuellings for RaBIO through injection assemblies I through VI at peak torque condition. The situation is somewhat similar to that of RaBIO at rated condition. The critical temperature is here about −3 °C.

The fuelling through all injection assemblies has also been measured for D100. The pressure drop through the fuel filter was practically unaffected by temperature changes, i.e., it remained low and constant. Thus, for D100 the temperature had no influence on the fuelling, both, at rated and peak torque conditions.

The analysis of experimental results, obtained on the M fuel injection system, shows that the distribution of RaBIO fuellings becomes very unequal among individual injection assemblies as the fuel temperature falls below the critical one (−7 °C at rated and −3 °C at peak torque regime). Obviously, the viscosity and the density of RaBIO increase to such extent that the fuel supply to the individual injection assemblies becomes critical. This is caused by the pressure drop through fuel filter and by increased flow resistance through the low pressure pump's gallery. The heating of RaBIO would be necessary to avoid these negative effects.

5.4 Discussion

The analysis of injection characteristics reveals that, in general, the fuelling, injection duration, injection timing, mean injection rate, and injection pressure increase under most considered operating regimes when mineral diesel is replaced by biodiesel. The higher sound velocity and bulk modulus of biodiesels lead to reduced injection delay and advanced injection timing. Regarding the partial fuellings at various phases of the injection process, the numerical results depend significantly on the operating regime. However, summing the results over all 13 modes of the ESC test (and taking into account the corresponding weighting factors) the fuelling at the beginning of injections (fuelling during needle lifting and

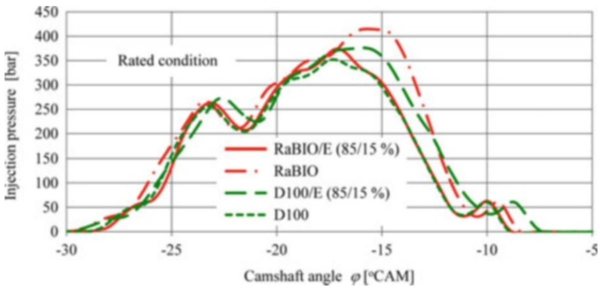

Fig. 5.34 Injection pressure history at rated condition

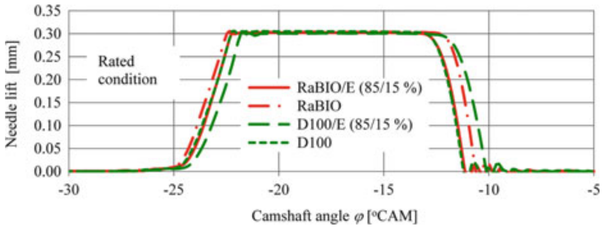

Fig. 5.35 Needle lift history at rated condition

during first 10 % of injection period) as well as the fuelling at the end of injections (fuelling during needle closing and during last 10 % of injection period) are lower when biodiesel (RaBIO) replaces mineral diesel.

In a mechanically controlled injection system the high mean injection pressure and mean injection rate of biodiesels offer a potential to reduce harmful smoke and NO_x emissions. This can be achieved by retarding the injection pump timing accordingly. It has to be pointed out that by proper modification of the injection pump timing most harmful engine emissions can be reduced, while the specific fuel consumption and other engine performances remain within acceptable limits.

Biodiesels obviously offer an interesting and potentially quite beneficial fuel alternative. Therefore, it may also be worth to investigate if it is possible to improve the injection characteristics by blending biodiesels with appropriate additives, like bioethanol.

First of all, it has to be pointed out that the injection characteristics obtained with the blends of RaBIO and bioethanol can be matched close to those obtained with mineral diesel (Torres et al. 2011). The experimental results, obtained at rated conditions in a bus MAN diesel engine with mechanically controlled M injection system, are shown in Fig. 5.34.

It can be seen that the addition of bioethanol decreases the maximal injection pressure. It may be worth noting that the maximal pressure decreases more, when bioethanol is added to biodiesel than to mineral diesel. Furthermore, one can see that the injection pressure history of the blend of 15 % bioethanol and 85 % RaBIO (RaBIO/E 85/15 %) is very close to that of neat mineral diesel.

From Fig. 5.35, where the needle lift history is shown, it can be observed that biodiesel injection timing is advanced with respect to that of mineral diesel and that

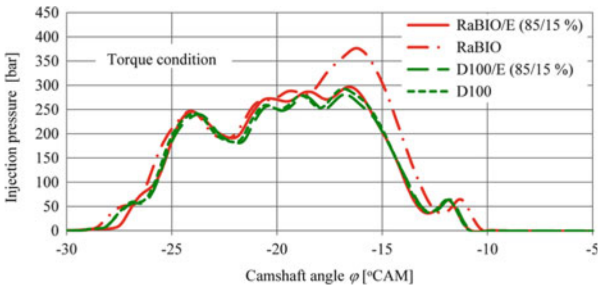

Fig. 5.36 Injection pressure history at peak torque condition

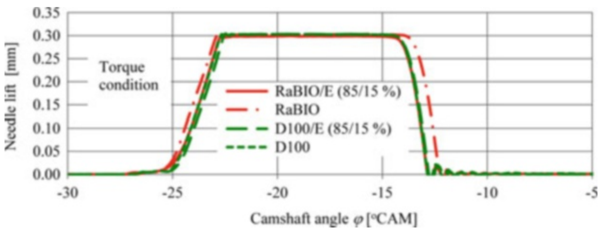

Fig. 5.37 Needle lift history at peak torque condition

biodiesel injection duration is longer. The addition of bioethanol retards the injection timing of diesel and biodiesel fuel. It has to be pointed out that this influence is more significant in biodiesel. Furthermore, the needle lift history of RaBIO/E (85/15 %) is practically the same as that of mineral diesel. This means that the injection timing, injection duration, and injection delay of RaBIO/E (85/15 %) are very close to those of D100.

The influence of bioethanol in biodiesel and diesel fuels at peak torque condition is similar to that obtained at rated condition. From Figs. 5.36 and 5.37, the injection characteristics comparison confirms that the RaBIO/E (85/15 %) blend delivers the injection pressure and needle lift histories very close to those of D100.

On the basis of experimental investigations, it can be summarized that for all injection characteristics, the influence of bioethanol in biodiesel is much more significant that in mineral diesel. Furthermore, bioethanol addition to biodiesel has a beneficial effect on the injection characteristics because it can bring them close to those of mineral diesel (Torres et al. 2011). It seems that the RaBIO/E (85/15 %) blend gives the best results. Namely, at most operating regimes the injection characteristics of this blend are the closest to those of mineral diesel or even seem to be better.

It is known that, compared to mineral diesel, RaBIO exhibits higher fuelling at most engine operating conditions. Bioethanol addition to biodiesel decreases the fuelling and can bring it close to that of mineral diesel. On the other hand, bioethanol addition doesn't modify substantially mineral diesel fuelling or increases it just slightly.

Injection timing and consequently injection delay are significantly influenced by the type of injection system (e.g., in-line or common rail injection system). When using a low pressure injection system, injection timing of biodiesel is retarded by bioethanol addition and injection delay increases due to lower density of bioethanol. The variation in injection timing caused by bioethanol addition is thus expected to decrease biodiesel's NO_x emissions. Injection timing is advanced slightly when increasing bioethanol content in mineral diesel and injection delay decreases due to bioethanol's lower viscosity.

An increment of bioethanol concentration in biodiesel leads to a decrement in injection duration. Meanwhile, the duration doesn't change or increases slightly when bioethanol is added to mineral diesel.

In general, mean injection rate varies almost negligible when bioethanol is added to diesel fuel because higher fuelling is compensated by longer injection duration. For biodiesel blends, the lower fuelling has more influence than the shorter injection duration, caused by bioethanol addition, which leads to a decrease in mean injection rate.

In most cases studied, bioethanol addition to biodiesel decreases the maximum injection pressure more than bioethanol addition to mineral diesel. In case of bioethanol–biodiesel blends it is expected that bioethanol offers a possibility to reduce NO_x emissions with respect to neat biodiesel.

References

Boehman, A. L., Morris, D., Szybist, J., & Esen, E. (2004). The impact of bulk modulus of diesel fuels on fuel injection timing. *Energy & Fuels, 18*, 1877–1882.

Boudy, F., & Seers, P. (2009). Impact of physical properties of biodiesel on the injection process in a common-rail direct injection system. *Energy Conversion and Management, 50*, 2905–2912.

Caresana, F. (2011). Impact of biodiesel bulk modulus on injection pressure and injection timing. The effect of residual pressure. *Fuel, 90*, 477–485.

Kegl, B. (2006a). Numerical analysis of injection characteristics using biodiesel fuel. *Fuel, 85*, 2377–2387.

Kegl, B. (2006b). Experimental investigation of optimal timing of the diesel engine injection pump using biodiesel fuel. *Energy & Fuels, 20*, 1460–1470.

Kegl, B. (2008). Biodiesel usage at low temperature. *Fuel, 87*, 1306–1317.

Kegl, B., & Hribernik, A. (2006). Experimental analysis of injection characteristics using biodiesel fuel. *Energy & Fuels, 20*, 2239–2248.

Kousoulidou, M., Ntziachristos, L., Fontaras, G., Martini, G., Dilara, P., & Samaras, Z. (2012). Impact of biodiesel application at various blending ratios on passenger cars of different fueling technologies. *Fuel, 98*, 88–94.

Luján, J. M., Bermúdez, V., Tormos, B., & Pla, B. (2009a). Comparative analysis of a DI diesel engine fuelled with biodiesel blends during the European MVEG-A cycle: Performance and emissions (II). *Biomass and Bioenergy, 33*, 948–956.

Luján, J. M., Tormos, B., Salvador, F. J., & Gargar, K. (2009b). Comparative analysis of a DI diesel engine fuelled with biodiesel blends during the European MVEG-A cycle: Preliminary study (I). *Biomass and Bioenergy, 33*, 941–947.

Ozsezen, A. N., & Canakci, M. (2010). The emission analysis of an IDI diesel engine fueled with methyl ester of waste frying palm oil and its blends. *Biomass and Bioenergy, 34*, 1870–1878.

Ozsezen, A. N., Canakci, M., & Sayin, C. (2008). Effect of biodiesel from used frying palm oil on the performance, injection, and combustion characteristics of an indirect injection diesel engine. *Energy & Fuels, 22*, 1297–1305.

Pandey, R. K., & Sarviya, R. M. (2012). Impact of alternative fuel properties on fuel spray behavior and atomization. *Renewable and Sustainable Energy Reviews, 16*, 1762–1778.

Payri, R., Salvador, F. J., Martí-Aldaraví, P., & Martínez-López, J. (2012). Using one-dimensional modeling to analyse the influence of the use of biodiesels on the dynamic behavior of solenoid-operated injectors in common rail systems: Detailed injection system model. *Energy Conversion and Management, 54*, 90–99.

Postrioti, L., Grimaldi, C.N., Ceccobello, M., Gioia, R.D. (2004). Diesel common rail injection system behavior with different fuels. *SAE Technical Paper Series* 2004-01-0029

Song, H., Tompkins, B. T., Bittle, J. A., & Jacobs, T. J. (2012). Comparisons of NO emissions and soot concentrations from biodiesel-fuelled diesel engine. *Fuel, 96*, 446–453.

Torres-Jimenez, E., Dorado, M. P., & Kegl, B. (2011). Experimental investigation on injection characteristics of bioethanol–diesel fuel and bioethanol–biodiesel blends. *Fuel, 90*, 1968–1979.

Tziourtzioumis, D., & Stamatelos, A. (2012). Effects of a 70 % biodiesel blend on the fuel injection system operation during steady-state and transient performance of a common rail diesel engine. *Energy Conversion and Management, 60*, 56–67.

Usta, N. (2005). Use of tobacco seed oil methyl ester in a turbocharged indirect injection diesel engine. *Biomass and Bioenergy, 28*, 77–86.

Yamane, K., Ueta, A., & Shimamoto, Y. (2001). Influence of physical and chemical properties of biodiesel fuels on injection, combustion and exhaust emission characteristics in a direct injection compression ignition engine. *International Journal of Engine Research, 2*, 249–261.

Ye, P., & Boehman, L. (2010). Investigation of the impact of engine injection strategy on the biodiesel NO_x effect with a common-rail turbocharged direct injection diesel engine. *Energy & Fuels, 24*, 4215–4225.

Ye, P., & Boehman, A. L. (2012). An investigation of the impact of injection strategy and biodiesel on engine NOx and particulate matter emissions with a common-rail turbocharged DI diesel engine. *Fuel, 97*, 476–488.

Yoon, S. H., Suh, H. K., & Lee, C. S. (2009). Effect of spray and EGR rate on the combustion and emission characteristics of biodiesel fuel in a compression ignition engine. *Energy & Fuels, 23*, 1486–1493.

Zhang, Y., & Boehman, A. L. (2007). Impact of biodiesel on NO_x emissions in a common rail direct injection diesel engine. *Energy & Fuels, 21*, 2003–2012.