Investigation of the Fuel Influence on the Injection and Mixture Process for Short Injection Periods under Different Diesel Engine Conditions

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Abstract

New diesel engine combustion systems for reduced emissions and lowered fuel consumption bear the risk of promoting combustion instabilities. Therefore, a multiple-injection strategy is employed. In this paper specifically, sprays generated by short injection timings at low ambient temperature conditions have been investigated using a visualization technique. In addition to the variation in operating conditions (injection pressure, injected amount, chamber pressure and chamber temperature), 3 different fuels (n-decane, IDEA, diesel) were investigated. The intention of the fuel variation was to identify a Diesel substitute for Computational Fluid Dynamics simulations.
Despite the short injection timing, the visualization measurements show comparable results to the literature reporting experiments at long injection conditions. The main difference between the results of short and long injection timings can be observed in a rapid decrease in liquid penetration length. No stationary penetration length has been observed for short injection timings.
The fuel variation reveals a quite similar behavior for the 3 fuels, with a faster evaporation time for IDEA fuel and n-decane compared to diesel. Since the penetration curve for IDEA is very close to the one of diesel and no stationary penetration length can be observed that may intensify the influence of the faster evaporation of IDEA, the replacement of diesel by the IDEA fuel, in order to simplify the numerical simulation of the multi-component diesel engine sprays, seems reasonable.

Introduction

New diesel engine combustion systems like HCCI (Homogenous Charge Compression Ignition) satisfy the demand of lower emissions and reduced fuel consumption but come along with combustion instabilities and the risk of misfiring. Therefore, in the Collaborative Research Centre (SFB 686), model-based control is used as a countermeasure to prevent the instabilities. One possible option for this is a splitting of the injection into multiple small injections. This paper concentrates on the injection process in diesel engines applying short injection periods for multiple injections and engine conditions at early fuel injection timings, as employed in HCCI-engines. In order to develop a model for the injection and mixture process, the experiments have to be supplemented with numerical simulations: consequently, a model fuel had to be tested for applicability at the short injection periods and low temperature conditions of the HCCI-engine. The model fuel investigated in this paper is the IDEA-fuel. Replacing diesel by a model fuel like IDEA will simplify the description of the multi-component evaporation in the numerical simulations.

In the past, a mixture of 70 vol % n-decane and 30 vol % 1-methylnaphthaline called IDEA has been used as model fuel for diesel in order to obtain the ignition delay of diesel. The same flow behavior at the nozzle exit was observed for IDEA fuel and diesel [1]. For long injection timings, similar evaporation and mixture characteristics were measured injecting IDEA and diesel [2]. Nevertheless, the applicability of IDEA for short injection timings or multiple injection strategies applied to control the combustion process has not been shown so far.

Also the injection of other fuels applying short injection timings has not been investigated in detail in the past. The evaporation and mixture process for long injection timings is already well described by different authors [3], [4], [5] and [6], who derived different correlations for the penetration length.

Therefore, this paper investigates the penetration length of n-decane, IDEA and diesel for short injection timings applied for multiple small injections and under low temperature conditions occurring in HCCI-engines, since the control of the combustion instabilities by multiple injection is the main aspect of the Collaborative Research Centre (SFB 686). The results for short injection timings are compared to the existing correlations. In addition, the applicability of IDEA as model fuel for short injection timings and low temperature conditions has to be examined.

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Experimental Setup

The measurements have been performed in a pressurized chamber, see Figure 1. The chamber is supplied with a continuous air stream of 25 kg/h having a temperature of up to 900 K and a pressure up to 5 MPa in order to remove the combustion residue and unburned fuel shortly after an injection event. The chamber is equipped with 4 side openings, which can be used either for optical access, illumination or for mounting of the injector. In the setup of Figure 1, the injector holder is mounted in one side opening and is equipped with one quartz glass window. On the opposite side, a CCD camera is placed. The investigated 7 hole solenoid injector has a spray elevation angle of 148° and a hole diameter of 0.140 mm. The ks-factor of the nozzle is 1.3. Comparing the nozzle geometry and the experimental conditions with the results of Schugger [8] cavitation has to expected for this nozzle. However cavitation will not be investigated explicitly here. The injector equipped with a sac-hole nozzle is mounted in a way that one spray cone is directed upwards. Since the nozzle holes are identically and symmetrically arranged, it is assumed that the sprays are identical, Therefore, only the upward directed spray cone is investigated. The window in the injector holder is used to illuminate the spray with a nanolite, applying a Schlieren technique for determination of the penetration length of the vapor phase. The liquid phase is illuminated via a window mounted in the chamber head, using a defocused Nd:YAG laser sheet.

The CCD camera is operated in double frame mode. The first frame is grabbing the laser light scattered by the liquid phase whereas the vapor phase using the Schlieren technique is recorded on the second frame. The time difference between both frames is 10 µs.

The timing of the injection, the illumination and the camera are triggered by a Programmable Timing Unit. The injection is activated every 2 s, while the offset between the triggering of injection and camera is increased continuously from 300 µs to 4000 µs. For every offset, 20 pictures are taken.

The experiments investigate the influence of the injection parameters, the chamber conditions as well as the fuel influence. The chamber conditions C1 to C4 (see Table 2) are chosen based on diesel engine conditions. In addition the chamber pressure and the chamber temperature are varied (C5 to C8). The injection pressure and the amount of fuel injected are altered as well (see Table 3). The fuels investigated are n-decane, diesel and IDEA. Some selected properties of the different fuels are listed in Table 1.

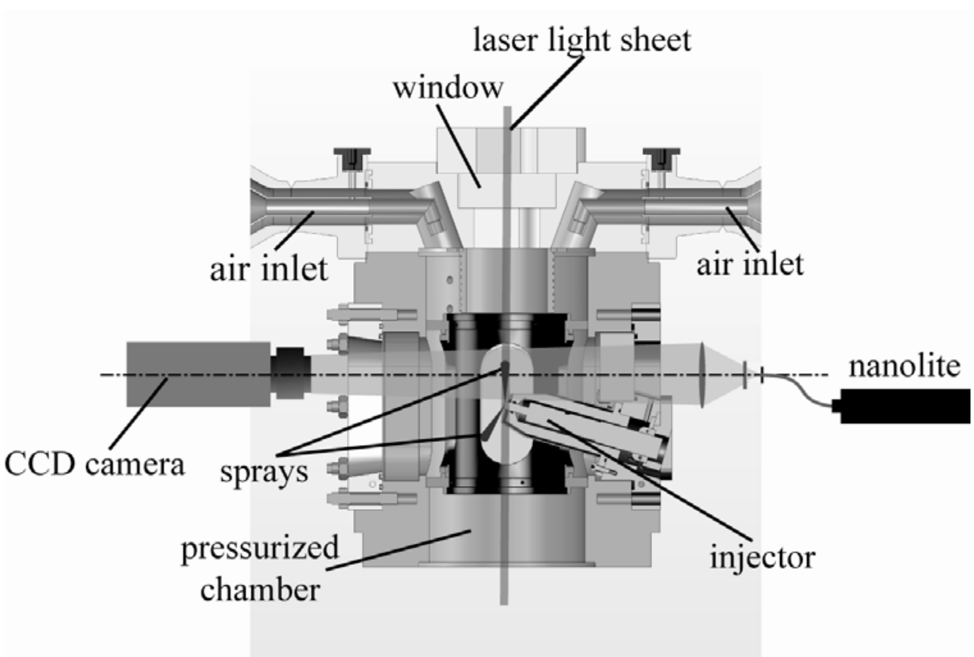

Figure 1. Pressurized Chamber

	diesel	n-decane	IDEA
Liquid Density [kg/m^3]	830	741	825
Surface Tension [N/m]	0.029	0.0239	0.0292
Boiling Temperature [K]	453 - 633	447,5	447,5 - 517,85

Table 1. Selected Properties of diesel, n-decane and IDEA

	C1	C2	C3	C4	C5	C6	C7	C8
Pressure [MPa]	1.3	2.1	3.5	5	1.5	3	2.1	2.1
Temperature [K]	520	590	670	730	590	590	550	650

Table 2. Investigated conditions of the pressurized chamber

	F1	F2	F3
Pressure [MPa]	70	70	125
Injected Volume [mm^3]	10	15	15
End of injection [µs]	750	1000	800

Table 3. Investigated conditions of injection

Experimental Results

Figure 2 shows the examined quantities, maximum penetration, maximum spray width and axial position of maximum spray width labeled in an image of the laser light scattered by the liquid spray. These three quantities are investigated for the liquid phase. Investigating the vapor phase, just the maximum penetration length is evaluated. The mean value of the examined quantities are plotted over time after triggering the injector. The cycle to cycle variations are shown by plotting the standard deviation for each mean value. In addition the time of injection is highlighted with a grey background according to the values for the end of injection listed in Table 3. Based on the size of the windows in the pressure chamber, the visual range of the measurements is limited to 60 mm. For some conditions the penetration length of the vapor phase exceeds the optical range. In these cases the vapor phase behavior is not evaluated.

Investigating the influence of the operating conditions both, the impact of the injection conditions (injection pressure and amount of fuel injected) and the chamber conditions (chamber pressure and temperature) have to be examined.

The impact of the injected fuel mass is shown in Figure 3, 4 and 5. Its influence on liquid phase penetration becomes visible only after 0.8 to 1.2 ms, depending on the fuel utilized. While the charts show a further increase with time for condition F2, the F1-curves decrease at larger times. This influence is independent of the fuel injected.

The injection pressure has a clear impact on the gradient of all charts. The liquid penetration length as well as the axial position of maximum spray width and the maximum spray width increase faster. A higher pressure difference between atmosphere and spray orifice raises the internal energy of the fluid in the nozzle. If the fluid leaves the nozzle the internal energy will be converted into kinetic energy, resulting in a higher spray velocity for increased injection pressures and therefore longer penetration lengths. Caused by the shorter injection time for the same amount of fuel, the curves reach their maximum position earlier (see Figures 3, 4 and 5). In general, a decrease of maximum liquid penetration always goes along with a decrease in maximum spray width and related axial position. Therefore, the following paragraphs only mention the influence of the parameter variations on the maximum liquid penetration. The impact of the parameter variations on the liquid penetration length can be transferred to the maximum spray width and the axial position of maximum spray width.

The impact of chamber pressure, however, can be observed from 600 µs after triggering onwards (see Figure 6). The gradient of the curves for liquid penetration length and the position of maximum spray width decreases with increasing chamber pressure as expected considering previous described relation between the pressure difference and the Bernoulli spray velocity. In addition, an increase in chamber pressure results in an increase in ambient density decelerating the injected spray further on [5].

The variation of chamber temperature influences only the point of time at which the spray is totally evaporated. At this time the plotting of the curves of liquid penetration length terminates and the time is referred to as evaporation time. First the charts show the same behavior for all curves, whereas the enhanced vaporization at elevated temperatures causes a deviation of the different curves for larger times, e.g. Figure 7 for the liquid penetration length. This drop in liquid penetration length is due to the spray evaporation which can be first investigated at the spray tip when the fuel supply to the spray stops (end of injection). The temperature influence on ambient density and thus on the spray droplet drag, however, is rather small, which has also been indicated by [7]. But in contrast to the mentioned literature, the results shown in this paper do not show a stationary penetration length at the end of the penetration process. The reasons for this may be the shorter injection timing being influenced by throttling (also mentioned by [7]) or the smaller amount of fuel injected, which evaporates faster since the concentration of fuel in the surrounding air is lower than for long injection durations.

The influence of the fuel injected is investigated for four different chamber conditions (C1 to C4) representing different timings of injections in an engine cycle and for a chamber pressure and chamber temperature variation. In addition, also the injection pressure and the amount of fuel injected are changed (see Figures 8 to 12).

Independent of the chamber and injection conditions investigated, the liquid penetration lengths of the different fuels are at first identical, even though the change in density affecting the Bernoulli velocity is up to 12 per cent and the change in surface tension affecting the Weber number is up to 22 per cent (see Table 1). Only the evaporation times vary for the different fuels. The liquid penetration length of the fuels having a lower boiling temperature (see Table 1) drops first. As already mentioned for the investigation of the temperature variation, the drop in penetration length is caused by the spray tip evaporation when no new fuel is supplied to the spray tip at the end of the injection. The penetration length of n-decane declines first, about 0.1 to 0.2 ms later the penetration length of IDEA also drops, while the penetration length of diesel increases further. The dependency of the evaporation time on the chamber and injection conditions is already described above. The Figures 8 to 12 prove the identical initial evaporation behavior of the different fuels showing the results for different chamber conditions measured in a combustion cycle for early injections timings (see Figure 8) and late injection timings (see Figure 9). A variation in either chamber pressure or chamber temperature is illustrated in Figure 10 to 12.

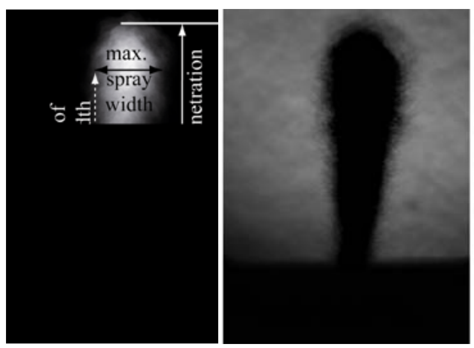

Figure 2. Quantities to be measured for liquid phase labeled in an image of the laser light scattered by the liquid spray (left), schlieren image of the spray (right)

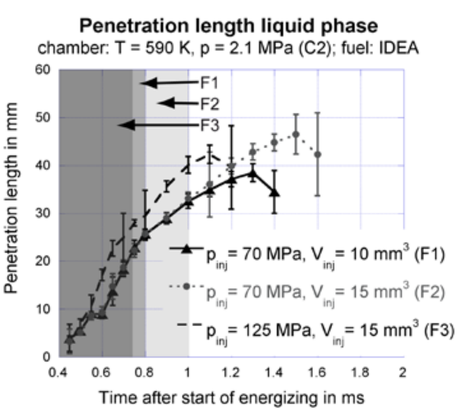

Figure 3. Influence of injection conditions on penetration length (C2 for F1, F2 and F3, grey background representing time of injection, see Table 3)

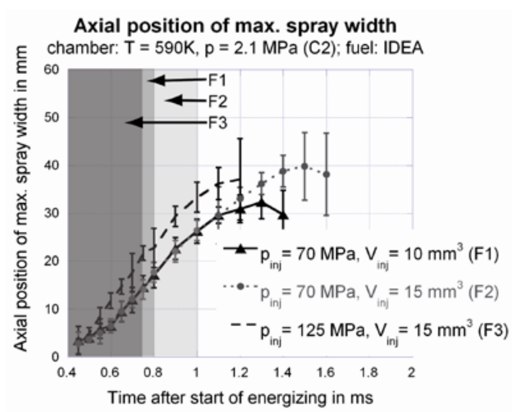

Figure 4. Influence of injection conditions on axial position of max. spray width (C2 for F1, F2 and F3, grey background representing time of injection, see Table 3)

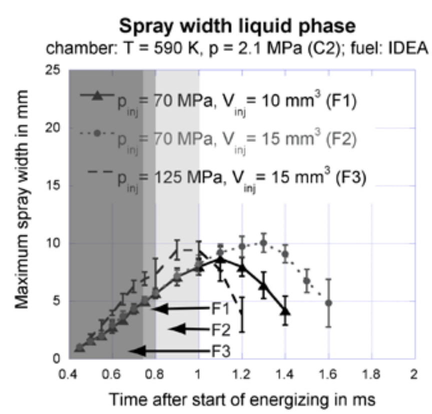

Figure 5. Influence of injection conditions on max. spray width (C2 for F1, F2 and F3, grey background representing time of injection, see Ta-

ble 3)

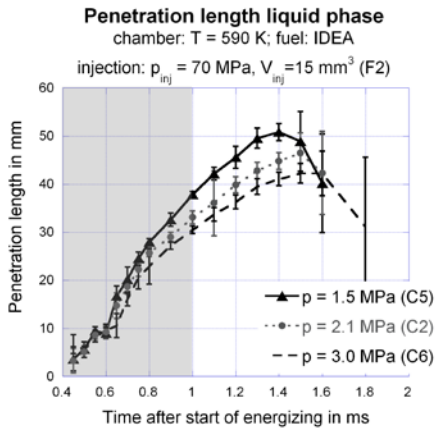

Figure 6. Influence of chamber pressure on penetration length (F2 for C5, C2 and C6)

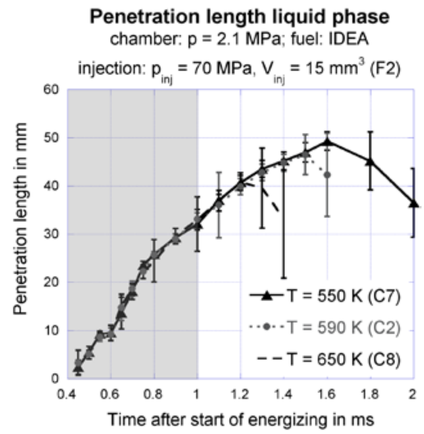

Figure 7. Influence of chamber temperature on penetration length (F2 for C7, C2 and C8)

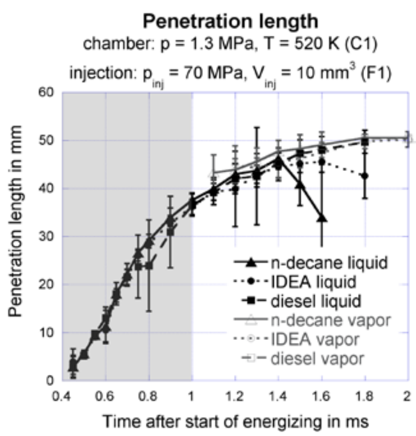

Figure 8. Investigation of fuel influence at chamber conditions C1 and injection conditions F1

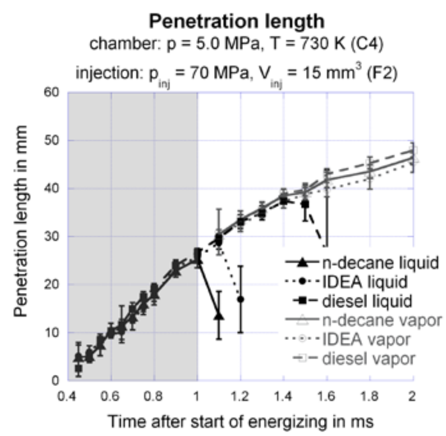

Figure 9. Investigation of fuel influence at chamber conditions C4 and injection conditions F2

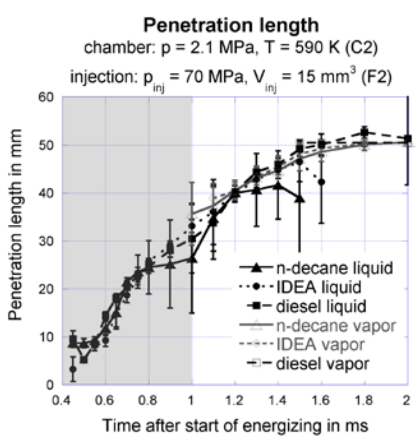

Figure 10. Investigation of fuel influence at chamber conditions C2 and injection conditions F2

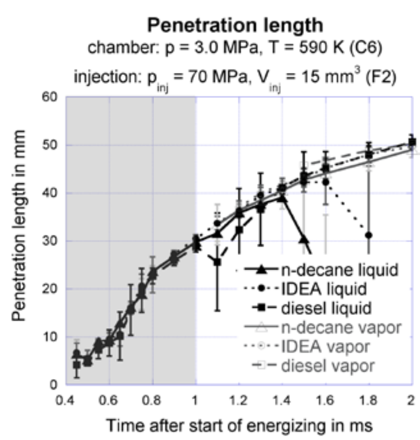

Figure 11. Investigation of fuel influence at increased chamber pressure C6 and injection conditions F2

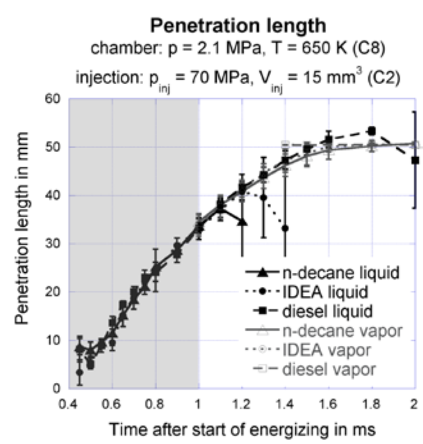

Figure 12. Investigation of fuel influence at increased chamber temperature C8 and injection conditions F2

Conclusion

Using a solenoid diesel injector in a preheated, pressurized chamber, the influence of the injection and chamber conditions as well as fuel variations have been investigated.

Examining the impact of the injection conditions, an increase in injected fuel mass does not change the penetration behavior, as long as new fuel is supplied to the spray tip. At the end of the injection the evaporation causes a drop of the curve of the liquid penetration length. Therefore, using the same injection pressure an increase in injected fuel, which is connected with a longer injection time, will increase the maximum liquid penetration length and the evaporation time. In the engine this may result in fuel wall impingement. An increase in injection pressure while keeping the injected fuel mass constant, results in shorter injection events, which in turn leads to faster evaporation times. The increase in chamber pressure results in a decrease of penetration length. These results go along with different correlations considering the impact of chamber pressure on gas density. An impact of chamber temperature on penetration can only be observed examining the evaporation time, which decreases with increasing chamber temperature. Since the variation in temperature is small, its effect on gas density can be ignored.

The 3 fuels used (n-decane, IDEA and diesel) show a quite similar behavior for the macroscopic spray behavior. Only the evaporation time differs when changing the fuel.

The investigation of the short injection timing does not show the stationary penetration length typically observed for longer energizing times. The reasons for this may be the faster evaporation injecting smaller fuel amounts and the effect of throttling, which may occur since the time of full needle lift is very small. Hence, most of time during the injection period the needle is either opening or closing. Nevertheless, the influences of the operating conditions support the statements of the correlations mentioned earlier.

Comparing the experimental results for the different fuels the conclusion can be made that IDEA can be used as a model fuel replacing diesel also for short injecting times and at HCCI conditions. There is only a difference in evaporation time compared to diesel. In order to state further conclusions about the applicability of IDEA as a model fuel simplifying the numerical simulation of diesel sprays, other measurement techniques like the Phase-Doppler Anemometry will be applied and in addition also the combustion process should be investigated.

Acknowledgements

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