Investigation of the Diesel spray atomization process with use of Phase Doppler Anemometry at high injection pressures and at engine-like gas density

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Abstract A series of experimental studies on the microscopic Diesel fuel spray characteristics were carried out in a constant volume bomb (CVB) to investigate the atomization and mixing process by applying the Phase Doppler Anemometry (PDA). The time-resolved velocity and diameter of droplets in Diesel spray injected into ambient and pressurized air were measured. The fuel was injected through an eight-hole injector, with fuel pressure ranging from 30 to 160 MPa.

It was shown that an increase of the injection pressure lead to an increase of the droplet velocities and diameters along and near the spray axis, which at ambient conditions can be explained by the reduced aerodynamic forces due to the increased velocity of the entrained gas. At pressurized conditions the increase of the droplets can be attributed to the increase of droplet coalescence. Towards the spray periphery the influence of aerodynamic forces becomes dominant, resulting in slightly smaller droplets at higher injection pressure. The droplet diameter and velocity show strong dependence on the density of the surrounding gas. By increasing the back-pressure from ambient to 2.5 MPa an increase of the droplet size by on average 30 % was observed. Thereby the droplet velocity decreased dramatically. It was furthermore found that the energizing time strongly affects the droplet velocity and diameter, which means that if the needle does not open completely, the droplet velocities are significantly lower and the diameters are smaller due to the induced turbulence of the restricted flow.

1. Introduction

The emissions standards for heavy-duty diesel engines are getting more and more stringent. Especially particulates, which mainly consist of soot and NOx emissions, have to be limited in order to meet future regulations. An improvement of the fuel air mixing and the subsequent combustion process is crucial to reduce raw emissions. The single processes, which are still not sufficiently understood, are significantly influenced by the capability of the injection system as well as the conditions of the surrounding gas in the combustion chamber.

In order to better understand the fuel atomization and fuel air mixing process, comprehensive experimental studies have been undertaken by means of optical measurement techniques. One of the most widely used optical techniques, which has been applied to Diesel spray investigation is the Phase Doppler Anemometry (PDA). This method allows time-dependent velocity and size measurements of spherical droplets at single locations in the fuel spray. Despite those advantages the application of the Phase Doppler Anemometry to Diesel sprays has become increasingly challenging due to the engine designer's requests for increasingly higher injection pressures, corresponding to high injection velocities as well as the demand of getting a deeper insight into the process of mixture formation at engine-like gas density.

As far as the effect of the injection pressure on the microscopic atomization characteristics is concerned many studies proved that an increase of the injection pressure leads to higher droplet velocities and therefore to a better spray atomization (Hung et al. 1997; Ofner and Mayinger 1998; Lacoste et al. 2003). Lacoste et al. (2003), for example, investigated on a rapid compression machine the influence of the injection pressure on droplet diameter. They found that the droplet mean diameter decreases as the injection pressure is increased. Similar trends were observed by
Payri et al. (2008) at high gas density at three axial distances from the nozzle. Hung et al. (1997) in their studies applied two injection pressures. They observed smaller droplets far downstream from the nozzle with the higher injection pressure, as the spray in both cases was well atomized. On the contrary to that, further upstream larger droplets were measured with the higher injection pressure, which in their opinion was due to the fact that only in the lower injection pressure case the spray had enough time to complete the droplet break-up.

Comprehensive work has been done in order to study the fuel atomization process in an atmospheric environment by use of the PDA technique (Hung et al. 1997; Ofner and Mayinger 1998; Kim and Lee 2007; Suh et al. 2007). However, the necessity of studying the atomization process under engine-like in-cylinder air density has been emphasized in several publications (Hiroyasu and Arai 1990; Araneo et al. 1999, Doudou and Maslouhi 2007), as the atomization behavior is known to be different at higher density. Doudou and Maslouhi (2007), for example, observed a strong dependence of the droplet size on the gas density in a non-evaporating and pressurized environment. They found that increasing the back-pressure results in an increase of the mean diameter due to increased coalescence effects. Investigations by Hiroyasu and Arai (1990) show that an increase of the ambient gas density leads to an increased droplet concentration, which results in an increased mean droplet diameter. In contrast, the investigations of Lacoste et al. (2003) showed the opposite trend. They assumed that increased shear and aerodynamic forces at higher back-pressures are responsible for their observations. Schneider (2003) investigated the droplet distribution at high gas densities at different radial distances from 2.4 to 3.3 mm from the spray axis. He could not find any effect of the gas density on the mean droplet diameter when increasing the back-pressure from 4.0 to 8.0 MPa.

Most of the investigations on Diesel spray characteristics by means of PDA were carried out at relatively low injection pressures and at atmospheric conditions. Also, the spray is often injected through a single-hole injector. Therefore, further studies are still necessary to assess the atomization process of a Diesel spray from a multi-hole injector by applying high injection pressures and under engine-like gas density. For this purpose measurements were conducted for injection pressures ranging from 30 to 160 MPa at back-pressures of ambient conditions and 2.5 MPa, respectively. The energizing time, which has a dramatic influence on the droplet velocity, was set to 0.7, 1.2 and 2.0 ms, respectively, in order to study, both, the transient as well as the quasi stationary injection phases. The measurements were carried out along the spray axis as well as at different radial positions at an axial distance of 40 mm from the nozzle exit.

2. Test facility

2.1 Injection system and test chamber

The test rig consists of a constant volume bomb (CVB) equipped with quartz glass windows and a common rail injection system. Experiments were undertaken at back-pressures of ambient conditions and 2.5 MPa, respectively. In case of pressurized conditions the bomb was charged with nitrogen gas. The applied injection pressures ranging from 30 to 160 MPa were provided by a commercial air driven high pressure pump. The fuel was injected into the chamber by a mini-sac eight-hole injector. In order to examine the droplets of only one spray jet, a specially designed spray separation was applied to avoid other jets entering the chamber. Two nozzles were tested, namely D200 with a diameter of 200 mm and D175 with a diameter of 175 mm. The nozzles were not compared as they also differ in the degree of conicity and the rounding at the nozzle inlet.
2.2 PDA set-up

The light source was an Argon-Ion laser (Spectra Physics) with an output power of up to 2 W in the green line. The laser beam enters the Bragg cell and color separator unit, where the beam is splitted into two beams. The Bragg cell shifts the frequency of one of the beams by 40 MHz in order to avoid directional ambiguity. A lens on the transmitting optics focuses the two beams, which form the measurement volume at a focal length of 310 mm. The transmitting probe was mounted on a traverse, which allows measurements at any point in the Diesel spray. The measurement volume was set to the smallest possible size in order to minimize the risk of burst splitting and other multiple particle events (Strakey et al. 1998; Payri et al. 2008). A front lens with a focal length of 310 mm was mounted on the receiving optics to focus the scattered light from the measuring volume onto the detectors. The receiving probe was placed at 310 mm from the measuring volume at an angle of 70 %. The detected light signals pass through optical fibers and reach the signal processing unit where photomultipliers transform the light signals into voltage signals, which can be processed.

Fig. 1 Set-up of the PDA system.

The injection control unit and the PDA processor were synchronized by a TTL command trigger signal. The time from the trigger signal to the first burst of droplets entering the measurement volume is due to the required delay time set in the signal control unit, the mechanical delay the needle needs to be lifted and the time the first droplets require to reach the measurement volume. The experimental set-up of the PDA system is shown in Fig. 1. Preliminary tests were performed in order to obtain sufficiently high data acquisition rate. This means that a compromise of the detection of smaller droplets with weaker signals and the reduction of noise signals had to be found. In this investigation a beam power of each beam of 150 mW and an amplification level of the photomultipliers (PM) of 1000 V were found to be the best settings. At pure velocity measurements in the LDA application the signal-to-noise (SN) ratio was set to -3. In order to get a sufficiently high validation rate in the PDA mode the SN ratio had to be set to -6dB.
3. Experimental results

3.1 Time-resolved droplet velocities and droplet diameters and effect of injection pressure

Fig. 2 shows a typical time-resolved evolution of the axial velocity and droplet diameter over time after start of pulse. The measurements were performed on the spray axis at an axial distance of 40 mm from the nozzle exit. The energizing time was set to 2.0 ms. As can be seen, the evolution can be divided into four phases:

- the spray head, which corresponds to the needle opening phase (I)
- the quasi stationary phase at fully open nozzle (II)
- the quasi stationary phase at fully open nozzle with an increase of the droplet sizes (III)
- the spray tail, which describes the needle closing phase (IV).

In the first phase of the Diesel spray injection, the spray head, slower droplets in the spray tip are detected. This is on the one hand caused by throttling effects in the needle seat (Delebinski et al. 2005) and on the other hand due to the drag force, produced by the surrounding gas (Araneo et al. 1999), both resulting in a deceleration of the droplets in the spray tip. The subsequent droplets just after those in the spray tip have higher velocities because of less aerodynamic interaction with the gas. As a consequence the faster droplets overtake and accelerate those in the spray head, whereas the fastest again lose momentum and become slower (Araneo et al. 1999; Schneider 2003; Doudou and Maslouhi 2007). In addition, it comes to collision and coalescence effects especially in the spray tip, which lead to an increase of non spherical droplets and explains the low detection rate of the droplets towards the end of the opening phase (Hung et al. 1997; Ofner and Mayinger 1998; Doudou and Maslouhi 2007). The surrounding gas is accelerated and entrained into the spray and in combination with the further opening nozzle the droplet velocity continuously increases during the needle opening phase. The plateau corresponds to the quasi stationary phase at fully open injector needle where the fastest droplets at a certain injection pressure can be detected.

![Fig. 2](image-url) *Droplet velocity and diameter distribution at an injection pressure of 80 MPa, energizing duration 2.0 ms and atmospheric back-pressure; measured on the spray axis at 40 mm from the nozzle exit; nozzle D200.*

In the second phase of the quasi steady period an increase of the droplet sizes can be observed, which cannot be due to coalescence effects as the data rate in this period of injection is relatively high. Another explanation seems more reasonable. The highest droplet sizes were measured behind
the spray tip. The droplets at the front of the spray were decelerated due to the momentum exchange with the surrounding gas, resulting in an acceleration of the gas. Hence, the relative velocity of the subsequent droplets and the accelerated gas decreases. As a result the droplet break-up is reduced due to aerodynamic forces.

At the spray tail the throttling effects within the nozzle increase again resulting in a reduction of the droplet velocities and droplet sizes.

The above mentioned coalescence effects in the spray tip lead to a low sample number in the spray head, which is indicated in Fig. 2 and more obvious in Fig. 3. In this present study it was found that, by increasing the injection pressure the validation rate decreases, mainly in the spray tip but also during the entire injection event. This phenomenon can be explained by an increase of non spherical droplets (Ofner and Mayinger 1998). Lacoste et al. (2003) assume that the enhanced spray atomization results in higher droplet concentration and increases the probability of multiple particle events.

Fig. 3 Droplet velocity and diameter distribution at an injection pressure of 120 MPa, energizing duration 2.0 ms and atmospheric back-pressure; measured on the spray axis at 40 mm from the nozzle exit; nozzle D200.

The left hand side diagram of Fig. 4 shows the mean axial velocity for fuel pressures ranging from 30 to 160 MPa. As expected, the peak velocities increase as the injection pressure is increased, which is consistent with other publications reported in the literature (Hung et al. 1997; Ofner and Mayinger 1998; Lacoste et al. 2003). This is due to the fact that the higher pressure is transferred into higher kinetic energy.

It can furthermore be seen that the time from the first measured droplets to the start of the quasi steady period decreases as the fuel pressure is increased. This indicates that a higher pressure of the fuel leads to a shorter opening time of the needle.

For the applied injection pressures the trends of the curves are all similar. During the quasi stationary period of the injection the velocity remains nearly constant at a maximum value, indicating that the throttling effects inside the nozzle are comparatively low. Only the plot at 30 MPa injection pressure does not show a clear plateau as can be seen at the other plots. Hence, it can be concluded that even an energizing time of 2.0 ms is not enough time for the needle to reach the maximum lift.

The plots for the corresponding droplet diameters are presented on the right hand side in Fig. 4 and perhaps do not show the intuitively expected results. It is clearly shown that for all injection pressures at the second phase of the quasi stationary period the mean diameter increases, as
discussed above. Furthermore, it can be seen that the mean droplet size increases as the injection pressure is increased. A possible explanation for this phenomenon is that the increased acceleration of the entrained gas leads to less aerodynamic forces acting on the subsequent droplets behind the spray tip. Hence, it can be assumed that a reduced droplet break-up takes place.

Again, the result of the measurements with 30 MPa injection pressure differs from the others as no increase of the droplet sizes during the quasi steady phase can be noticed. Turbulence inside the nozzle leads to a higher droplet break-up. This effect is discussed in more detail in the following chapter.

It was observed that with an increased injection pressure the validation rate decreases. Especially at the 160 MPa plot the erratic profile during the time period 1.4 to 2.0 ms indicates a low sample number. As a result of that droplet size measurements were not successful for high pressure.

**Fig. 4** Mean droplet velocity and diameter profiles at an energizing duration of 2.0 ms and atmospheric back-pressure; measured on the spray axis at 40 mm from the nozzle exit; nozzle D200.

### 3.2 Effect of injection duration

Fig. 5 depicts the distributions of mean velocities under energizing durations of 0.7 ms, 1.2 ms and 2.0 ms. The results clearly show that with 0.7 ms the peak velocity is significantly lower than that with the two other energizing durations. This indicates that due to the short duration of 0.7 ms the needle is solely in the ballistic phase. The throttling effects at the needle seat lead to a lower momentum and therefore to lower droplet velocities. On the contrary to that, by increasing the energizing duration (here: 1.2 ms and 2.0 ms), the needle reaches its maximum possible lift so that possible cavitation effects and turbulence within the needle seat region are reduced. Hence, there are less pressure losses within the nozzle, resulting in increased peak velocities (Ofner 2001). Seebode (2004) demonstrated in his studies that at short injection durations the pressure in the sac hole is significantly lower than the applied rail pressure.

Despite the large difference in maximum mean velocity the measurement location is reached by the spray tip at the same time for all employed injection durations. The plots reveal that the first droplets pass through the measurement volume (about 0.9 ms after start of recording) during the needle opening phase when the flow is restricted, which applies for all three energizing durations. About 0.2 ms later with the short duration of 0.7 ms the needle begins to close again, whereas for the two longer injection durations the needle opening phase is still ongoing until the needle reaches
its maximum position. Those findings clearly demonstrate the importance of the needle opening and closing phase. Especially a shorter needle opening increases the transfer from pressure to kinetic energy. In the present project solenoid-driven injectors were used; piezo-driven injectors offer a shorter injection delay resulting in higher droplet velocities and smaller droplet sizes literature (Ofner and Mayinger 1998; Park et al. 2006).

**Fig. 5** Mean droplet axial velocity profiles at an injection pressure of 120 MPa, energizing duration of 0.7 ms, 1.2 ms and 2.0 ms and atmospheric back-pressure; measured on the spray axis at 40 mm from the nozzle exit; nozzle D200.

As can be seen in Fig. 5 that with an energizing duration of 2.0 ms significantly larger droplets were measured over the whole injection period than with 0.7 ms. It is thought that the induced turbulences in the sac hole, which are dominant at 0.7 ms over the whole injection event, are responsible for the enhanced droplet break-up.

The trend observed differs from those obtained by Suh et al. (2007) who did not find any effect of the energizing duration on the droplet sizes. However, they applied energizing durations of 0.3, 0.5 and 0.7 ms. Due to those short durations it can be assumed that the quasi steady phase was not reached in any case and hence a high level of turbulence occur at all applied injection durations.

Furthermore it can be seen that no increase of droplet sizes at any time of the injection period can be noticed with 0.7 ms as it is with 2.0 ms during the quasi steady period. The droplet distribution at 0.7 ms is in good agreement with those found in literature (Ofner and Mayinger 1998; Ofner 2001; Suh et al. 2007). The largest droplets are found in the spray tip, where maximum droplet coalescence exists. The plot at 1.2 ms shows a slight increase towards the end of the quasi steady phase but is, however, not as distinctive as at 2.0 ms.

3.3 Droplet velocities and diameters under Diesel engine-like air density

The density of the surrounding gas mainly dominates the spray atomization and the air entrainment into the spray jet. The influence of the gas density on the spray characteristics is discussed in the following. Fig. 6 compares the droplet velocities and mean diameters at two radial distances and at back-pressures of 0.1 MPa and 2.5 MPa, respectively. The measurements were performed with nozzle D175 and the injection pressure was 80 MPa. For all measurements under pressurized conditions the energizing time was set to 0.7 ms.
The results presented in Fig. 6 clearly demonstrate the dramatic effect of the in-cylinder pressure on the droplet velocity, which is similar to previous studies (Lacoste et al. 2003). As can be seen from the results of the measurements on the spray axis at atmospheric conditions many droplets with velocities well over 200 m/s were detected whereas the fastest droplets at 2.5 MPa are considerably slower than 100 m/s. Another indicator of that fact is the time at which the first droplets appear in the measurement volume. At 0.1 MPa the first droplets were detected at about 0.8 ms after trigger signal, whereas at 2.5 MPa the first burst of droplets appeared at about 1.4 ms after trigger signal. Furthermore a steep velocity gradient at 0.1 MPa can be observed. As shown by the plots on the left hand side the range of velocities is between 50 and about 270 m/s along the spray axis and decreases at a radial distance of 2 mm to a range of 0 to about 160 m/s. By contrast, the droplet velocity plots at 2.5 MPa air pressure indicate a small decrease with increasing radial distance from the spray axis. From those results it can be concluded that with an increased chamber pressure the spray shape becomes wider and an increased spray cone angle can be expected. Similar trends were reported by Payri et al. (2008).

Also the effect of the in-cylinder pressure on the droplet sizes is illustrated in the figure. As can be deduced by comparing the plots on the left and on the right, the probability of interaction between droplets increases with an increased cell pressure, resulting in noticeably larger droplets. Especially along the spray axis it can be seen that the mean diameter at 2.5 MPa is on average 30 % higher.
than that at 0.1 MPa. This increase in droplet size can be attributed to the increase of droplet coalescence.

Another interesting difference between the high back-pressure case and the ambient back-pressure case reveals the temporal evolution of the diameter. At ambient conditions and at the spray centerline the highest values of about 14 µm were measured in the spray tip. Towards the end of injection the droplet diameters decrease to about 10 µm. The largest droplets seem to be the fastest. Similar results at atmospheric conditions were qualitatively found by (Ofner and Mayinger 1998; Ofner 2001). In contrast, the data obtained at 2.5 MPa back-pressure show a gradual increase of the mean diameter, which then shows a nearly constant value. The trend observed is consistent with other measurements reported in the literature (Quoc and Brun 1994; Schneider 2003; Doudou and Maslouhi 2007). It is assumed that the largest droplets in the spray tail are due to less interaction with the surrounding gas in combination with increased coalescence effects (Schneider 2003; Doudou and Maslouhi 2007), whereas strong aerodynamic interaction between those droplets in the spray tip and the ambient gas enhances the droplet break-up (Schneider 2003).

The velocity and diameter profiles for the injection pressures 80 and 160 MPa at a back-pressure of 2.5 MPa are displayed in Fig. 7. The results are presented from measurements carried out at radial
distances of 1 mm, 2 mm and 4 mm from the spray axis. Measurements for 160 MPa injection pressure on the spray axis could not be undertaken due to extreme droplet density and therefore no comparison with those for 80 MPa could be made. The diagrams reveal, as expected, that the droplet velocities for the injection pressure of 160 MPa are significantly higher than those of 80 MPa. As far as the droplet diameter is concerned the trend is not as obvious. At a radial distance of 1 mm and 2 mm, respectively, the droplets injected with 160 MPa are larger than those with 80 MPa. Conversely, at 4 mm from the spray axis slightly smaller mean droplet diameters are obtained at 160 MPa injection pressure. At 160 MPa and at a radial distance of 6 mm similar droplet sizes were measured to those of 4 mm (not shown the figure), whereas at 80 MPa no droplets were measured at all. Due to the fact that at a radial distance of 6 mm only at 160 MPa injection pressure droplets were measured it can be concluded that the spray angle at 160 MPa is wider than at 80 MPa. Near the spray axis (here: 0 - 2 mm) droplet coalescence seems to be the dominating effect, which leads to larger droplets at higher injection pressures. Towards the spray periphery the interaction with the surrounded gas increases, resulting in slightly smaller droplets at 160 MPa. From the present findings under non-evaporating conditions it can be assumed that, despite the larger droplets near the spray axis, better atomization characteristics at higher injection pressure can be expected due to the smaller droplets towards the outer region of the spray as well as due to the wider spray dispersion angle.

4. Conclusions

In order to understand the atomization characteristic of high pressure Diesel fuel spray, an experimental investigation was carried out applying Phase Doppler Anemometry (PDA). The results can be summarized as follows:

- Increasing the injection pressure leads to an increase of the droplet velocity and to a shorter needle opening phase.
- At ambient conditions during the quasi steady period the increase of the droplets can be explained by the reduced aerodynamic force due to the increased velocity of the entrained gas.
- In the second phase of the quasi stationary period the mean diameter increases as the injection pressure is increased.
- At short energizing durations (in this work 0.7 ms), where the needle does not open completely, significantly lower droplet velocities were observed due to the restricted flow over the entire injection. The induced turbulence leads to smaller droplet diameter.
- It was shown that the droplet velocity decreased dramatically when the back-pressure was increased from 0.1 MPa to 2.5 MPa.
- Larger droplets were measured at the higher gas pressure of 2.5 MPa. Along the spray axis the mean diameter increased by on average 30 % comparing to ambient conditions. This can be attributed to the increase of droplet coalescence.
- From the measurements at different radial positions it was found that with an increased chamber pressure the spray shape becomes wider.
- The temporal distribution of the droplet sizes at 0.1 MPa back-pressure is different compared to those measured at pressurized conditions.
- The droplet diameter and velocity were shown to be dependent on the radial position within the spray. At both, ambient and pressurized conditions the fastest and largest droplets can be found along the spray axis.
- Measurements at pressurized conditions showed that at higher injection pressure droplets are larger near the spray axis but tend to be smaller towards the spray periphery.
References


