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Experimental characterization of an MPDI gas injector for four-stroke applications

Fuel Injection & Gas Admission and Engine Components

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ABSTRACT

The dual-fuel combustion process, in which the combustion of a mixture of air and fuel gas is initiated by a pilot quantity of diesel fuel, offers great potential for low-emission operation of medium-speed marine engines. The 1/34DF single-cylinder research engine located at the University of Rostock currently offers excellent conditions for investigating the aforementioned combustion process in detail. In projects that have already been completed, the introduction of the fuel gas through external mixture formation was investigated. A mobile injection rate analyzer (IRA) was developed to characterize the gas valve responsible for this, using the Zeuch principle to determine the time-resolved injection of the combustion gas and the resulting gas masses introduced per shot. This allows properties such as volume maps, shot-to-shot deviations and leakage rates to be determined.

A decisive approach to optimizing dual-fuel engines was investigated in the ongoing TEME2030+ research project: The direct injection of fuel gas (e.g., LNG, hydrogen and LPG) into the engine combustion chamber offers the advantage that the fuel slip caused by valve overlap is no longer included in the emissions balance. The focus of the investigations is on medium-pressure gas injection, in which a quasi-homogeneous premixed combustion process can be implemented. The high-pressure variant with a diffusive combustion process will be investigated in the further course of the project. Both variants are based on an injector developed for their respective pressure level. Due to the resulting inhomogeneity of the direct injection of the combustion gas into the combustion chamber in combination with the pre-injection of the diesel, the characterization of the injector and the amount of gas injected per time gains additional importance for the systemic understanding of the combustion process in a simulation and test bench environment.

The paper describes the evaluation work carried out to characterize the middle pressure DI gas injector in detail. The expertise already available from the low-pressure injection analysis was used to further develop the IRA for higher pressure applications. The results and phenomena presented enable precise control of the injectors in engine operation on the test bench. In addition, the in-house high-pressure, high-temperature injection chamber test bench was modified and expanded in order to visually display jet propagation phenomena. The results presented here are intended to provide a comprehensive understanding of mixture formation in the combustion chamber and form the boundary conditions for further simulation of the entire combustion process and optimization of injection strategies.

1 INTRODUCTION

The characterization of direct-injection gas injectors for large engines is a key focus in the development and optimization of modern propulsion technologies, particularly in sectors such as industrial, marine, and power generation applications. Large engines powered by gas are gaining increasing importance as they present a more environmentally friendly alternative to conventional diesel or heavy fuel oil powered engines. In this context, the precise control and metering of the injected gas play a crucial role in the efficiency and performance of the engine.

Direct-injection gas injectors (DI injectors) are responsible for introducing gas directly into the combustion chamber, where the shape, quantity, and timing of the injection significantly influence the combustion process. Suboptimal injection can lead to incomplete combustion, higher emissions, and inefficient fuel consumption. Therefore, it is essential to thoroughly understand the properties of the gas injectors to control the injection process accurately. This involves not only the physical characteristics of the injector, such as spray pattern and pressure range, but also its behavior under various operating conditions, which demand a high degree of flexibility and adaptability from the injectors.

This study, conducted as part of the BMWK-funded project TEME2030+, focuses on a detailed investigation of the various factors that must be considered when characterizing natural gas based DI gas injectors for large engines. It also highlights why this characterization is of central importance for the future development and operation of large engines.

A precise characterization of the injectors enables the optimization of not only the mechanical and thermodynamic properties of the injection system but also the overall engine control. Detailed analysis allows for maximizing engine performance, minimizing fuel consumption, and significantly reducing emissions – particularly nitrogen oxides (NO_x) and methane (CH_4). In light of increasing environmental requirements and tightening global regulations regarding emissions, the precise characterization of gas injectors for large engines represents a key technology on the path toward more sustainable and efficient propulsion solutions.

2 INJECTORS

The injectors developed as part of the TEME2030+ project for the direct injection of natural gas into the combustion chamber are installed on a medium-speed dual-fuel research engine configured as a single-cylinder variant (1/34DF). This engine is characterized by a bore of 340 mm, a stroke of 560 mm, and a cylinder output of 450 kW at 720 rpm. Two geometrically identical variants of direct-injection gas injectors are available for this application: one for medium-pressure operation (up to 100 bar gas pressure) and another for high-pressure operation (up to 500 bar gas pressure). The medium-pressure variant is used for premixed combustion processes, where gas is injected after the exhaust valves close, while the high-pressure variant is designed for diffusive combustion processes, where gas is injected around top dead center into the already micro-pilot-ignited diesel flame. To validate the combustion processes under investigation, identical operating points in the low-pressure combustion process are employed.

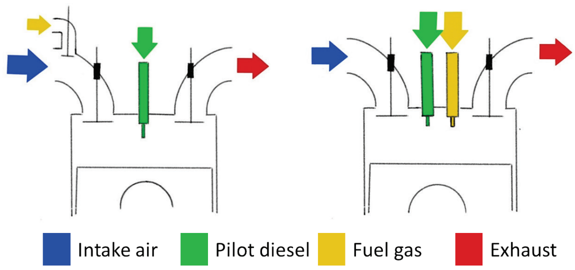

Figure 1. Schematic comparison of external and internal mixture formation of the dual fuel combustion process

The design of the injectors minimizes methane slip during the gas exchange process and prevents the accumulation of unburned fuel in quench zones and near-wall regions, enabling efficient combustion. The injectors can operate either with a vertical spray orientation or a wide cone angle, supporting various injection strategies. For hydrogen operation, the maximum full-load injection quantity is approximately 1750 mg, while for methane, it can reach up to 7000 mg. The injectors also achieve a minimum injection capability of 80 mg for CH_4 and 20 mg for hydrogen, allowing for precise metering even at low loads. Furthermore, the system supports the mixing of different fuel gases, with an annular spray pattern achieved through outward-opening nozzles. [1][2][3]

3 TEST BENCHES

3.1 Gas Injection Rate Analyzer (IRA)

The characterization of DI gas injectors is a central aspect of the development of modern drive technologies, particularly with regard to low-emission combustion processes and the use of alternative fuels. The focus here is on investigating the injection behavior under realistic conditions in order to analyze the jet geometry, mixture formation and dynamic behavior of the injectors. Various test benches and measuring methods, such as the High Pressure High Temperature Injection Chamber (HPHT) and the Gas Injection Rate Analyzer (IRA), provide valuable insights. For this purpose, the University of Rostock has developed a gas infrastructure in which the injector can be supplied with an inlet pressure of up to 600 bar.

The Gas Injection Rate Analyzer is a precise method for the quantitative characterization of gas injectors. It was developed to precisely analyze the injection behavior and enable a better understanding of the underlying physical processes. The measuring system is based on an adapted principle according to Zeuch, in which the pressure changes caused by the gas injection are recorded and evaluated in a quasi-closed measuring chamber. The data obtained here provides detailed information about the mass flow dynamics, the injection volume and the injection rate, which are of central importance for the optimization of modern gas drive systems.

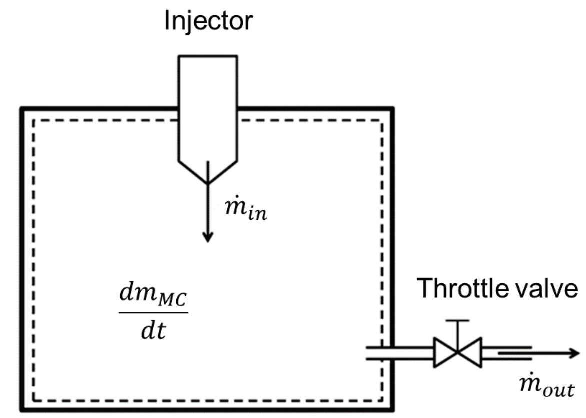

Figure 2. System limits of the measuring chamber volume of the IRA with corresponding mass fractions during the injection process

The functional principle of the IRA is based on the precise detection of pressure changes in the measuring chamber during the injection process. As soon as the injector is activated, the injection leads to an increase in chamber pressure. This increase in pressure is continuously measured by high-resolution sensors. An adjustable throttle valve is used to discharge the injected mass flow from the chamber and thus restore the initial conditions for the next measurement. The throttle valve allows the back pressure in the measuring chamber to be adjusted, making the system extremely flexible and adaptable to different operating scenarios. For the subsequent calculation of the injection rate based on the recorded pressure signal, the measuring chamber is assumed to be a constant volume.

The pressure data is analyzed assuming an adiabatic change of state of the gas in the chamber. Using the equation of state of ideal gases, the mass flow is calculated from the difference between the gas escaping through the throttle and the pressure change in the chamber (see formula 1-3).

$$\dot{m}_{in} = \frac{dm_{MC}}{dt} + \dot{m}_{out} \qquad (1)$$

$$\frac{dm_{MC}}{dt} = \frac{V_{MC}}{\kappa \cdot R_s \cdot T_{MC}} \cdot \frac{dp_{MC}}{dt} \qquad (2)$$

$$\dot{m}_{out} = \frac{A_{TV} \cdot c_{TV}}{\sqrt{R_s \cdot T_{MC}}} \cdot \sqrt{\kappa \cdot \left(\frac{2}{\kappa + 1}\right)^{\frac{\kappa+1}{\kappa-1}}} \cdot p_{MC} \qquad (3)$$

This method requires correct selection of sensors and precise knowledge of the geometry of the measuring chamber to ensure accurate results. A prerequisite for the calculation of the results is a supercritical flow from the measuring chamber to the environment, as the variable throttle cross-section cannot be defined. In the case of methane, this condition is met at a chamber pressure of ≥1.84 bar.

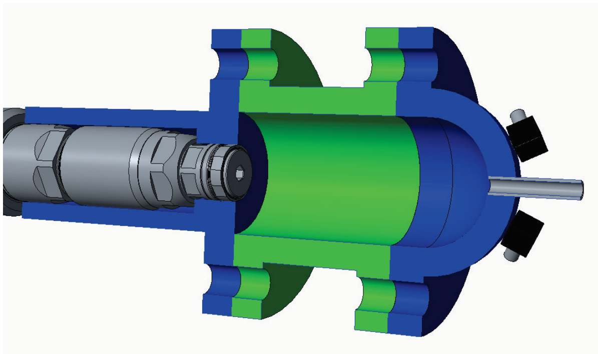

Figure 3. Half-section of the modular design of the IRA with the basic setup consisting of injector enclosure and measuring chamber volume (blue), as well as the measuring volume extension (green)

The design of the IRA system is modular so that it can be tailored to different requirements. The basic measuring volume can be expanded, which makes it possible to test geometrically different injectors with corresponding injection quantities. The pressure range is designed for 35 bar, which allows injection masses of up to 10 grams per shot to be tested. The system is also designed to be mobile, which means it can be used on different test benches and under different fuel infrastructures.

The technical equipment of the IRA includes high-resolution pressure and temperature sensors that enable precise measurements both before the gas enters the injector and in the measuring chamber itself. These sensors provide high-resolution data for calculating the injection rate and other parameters that characterize the injection process. By integrating several sensor positions in the chamber, the measurement accuracy can be further increased and validated.

The system has been specially developed to work with alternative fuels such as methane, hydrogen and ammonia. This versatility makes it a future-oriented tool for the characterization of injectors, especially in view of the increasing importance of low-emission and climate-friendly drive technologies. The precise data obtained with the IRA is not only crucial for the optimization of mixture formation and combustion in engines, but also for the development of advanced actuation strategies and the validation of numerical models. [4][5][6]

3.2 High Pressure High Temperature injection chamber (HPHT)

The visual characterization of DI gas injectors is an essential step in the development of modern, low-emission combustion engines. The aim of these investigations is to gain an in-depth understanding of the interactions between injection parameters, jet geometry, mixture formation and combustion quality. Specific parameters such as jet length, dispersion angle and jet penetration behavior are investigated in detail. The High Pressure High Temperature injection chamber (HPHT) is used to carry out these studies. Its technical properties create realistic test conditions for different injection strategies.

The data obtained from the HPHT injection chamber is a proven tool for the development of modern gas engines. They contribute to a better understanding of mixture formation in the combustion chamber and make it possible to increase combustion efficiency and reduce emissions. In addition, they provide valuable insights for the further development of injector concepts and their control strategies. The data collected will also serve as a basis for the modeling and simulation of dual fuel combustion processes with internal mixture formation, in which the precise addition of natural gas is crucial.

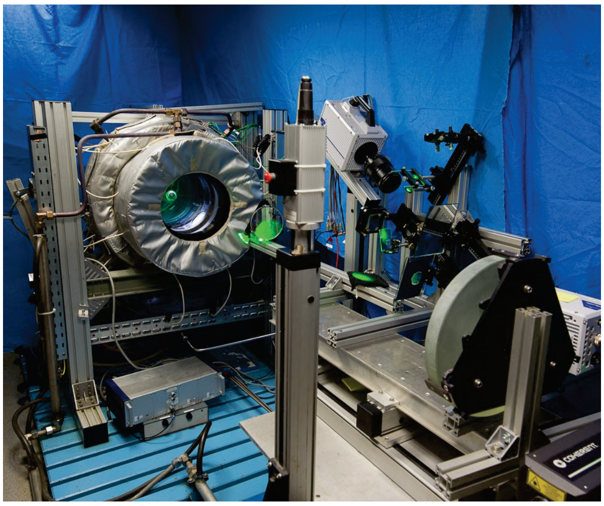

Figure 4. Test bench setup of the HPHT measuring chamber with the chamber volume (left) & the camera system (right)

The HPHT injection chamber at the University of Rostock, developed in collaboration with FVTR GmbH, allows tests to be carried out under gas pressures of up to 150 bar and temperatures of up to 900 K. This makes it possible to simulate conditions that occur in real engines. The chamber is equipped with several optical accesses, including a frontal access with a viewing distance of 300 mm and four side accesses of 80 mm each. This configuration allows flexible positioning of the injectors to be examined in relation to the high-speed camera, which captures the injected fuel at up to 25,000 images per second. This allows spray images to be captured and analyzed both frontally and laterally.

A decisive advantage of the chamber lies in the use of various optical analysis methods. In the case of gaseous fuels, the Schlieren method is used. This method makes density differences in the gas phase visible and enables precise examination of the jet characteristics. As a result, key parameters of the jet characteristics can be quantitatively evaluated. This is supplemented by adapted lighting systems and image processing algorithms that enable high-resolution analysis of the injection processes.

The DI gas injectors are characterized under various boundary conditions, such as varying injection pressures, actuation durations or defined simulations of the combustion chamber atmosphere at the time of injection in the research engine. The chamber allows injection processes to be analyzed both in an inert atmosphere and under combustible conditions. This allows the interactions between injection parameters and mixture formation to be investigated realistically.

The focus is on examining the spray patterns, which are analyzed in terms of jet geometry and width characteristics. The effects of injection parameters on mixture formation and subsequent combustion can be examined in detail with the help of precise pressure and temperature sensors and the exact control of the test bench. The optical measurements form the basis for the validation of simulation models, which in turn contribute to the optimization of injector control systems for test series on the research engine.

By combining experimental investigations and model-based approaches, comprehensive findings can be obtained for the optimization of future injection strategies. This flexibility enables targeted adaptation of the injector concepts to specific requirements and supports the development of low-emission, efficient gas drives for sustainable mobility. [7]

4 RESULTS

As part of this study, investigations were carried out on the medium-pressure variant of the gas injector (MPDI), while the high-pressure variant (HPDI) is currently still under development. Initial results for the high-pressure variant will be presented in the conference contribution. The analyses comprised two central scenarios that take different pneumatic conditions into account.

In the first scenario, the pneumatic conditions were investigated according to the conditions specified by the injector manufacturer in order to validate the measurement results and characterize the injector under idealized conditions. These investigations were carried out exclusively in the Injection Rate Analyzer (IRA). The second scenario focused on the pneumatic conditions prevailing within the project's research engine. The aim of these analyses was to transfer the measurement results to real operating conditions and to gain new insights into the combustion process. Both the IRA and an HPHT injection chamber were used for these investigations in order to ensure the transferability of the results.

One crucial aspect was the adaptation of the gas infrastructure. While the research engine is already designed for high-pressure operation, the medium-pressure process led to restrictions in the pressure supply due to the reduced gas supply. This illustrates the challenges involved in transferring measurement results from idealized scenarios to real operating conditions, particularly in the context of combustion process optimization.

The test results of the gas injectors concentrated on two key aspects in order to analyze both the dynamic properties of the injection and the differences between ideal and real conditions. A central focus was on the analysis of the time-resolved signal curves during injection, which provided in-depth insights into the dynamic processes of gas injection. These curves were examined in detail in order to characterize the reaction times, pressure fluctuations and the course of the injection rate. Particular attention was paid to the key moments of the injection cycle, including the initial phase, the stability phase and the decay phase. The time-resolved data provided valuable information to evaluate critical parameters such as injection time and the influence of system inertia.

In addition, quantitative comparisons of the measurement characteristics were carried out to identify differences and similarities between the investigated conditions. As part of this analysis, the injection quantities as well as the time delays between injector actuation and fuel injection were evaluated. This enabled a comprehensive investigation of the transferability of the results from idealized conditions in the Injection Rate Analyzer to real operating conditions in the HPHT injection chamber. The results illustrate how different pneumatic boundary conditions of the gas supply as well as thermodynamic boundary conditions on the part of the combustion chamber affect the injection characteristics. Furthermore, they lay the foundation for the optimization of simulation models also developed in the project under real operating conditions.

4.1 Mass-related analysis

This study deals with the detailed analysis of the injection rate of the injection rate analyzer, taking into account different piping configurations. The aim is to evaluate the influence of the system inertia and the infrastructure used on the injection characteristics and the resulting mass injection. Both experimental measurements and simulative approaches were used to provide a comprehensive understanding of the injection processes.

The measurements were carried out in a static measuring chamber in which only a pressure increase due to the injection takes place. Changes in the ambient pressure due to the movement of a piston - as would be the case in a real combustion engine - were not simulated. Only the pressure level at the start of injection was adjusted, while no temperature compensation was carried out.

Natural gas was used as the medium for the tests. Injection was carried out using the medium-pressure version of the injector with its jet guide installed. Due to the conditions acting globally in the measuring chamber, no significant differences were found between the measurement results with and without jet guidance.

The inertia of the overall system played a significant role in the measurement results recorded. In particular, delays between the electrical energization of the injector and the actual start of injection influenced the accuracy of the time-resolved injection rates. The duration of gas injection into the combustion chamber was also examined in order to identify systematic deviations.

Occasional deviations of individual measured values from the expected phenomena were observed. These resulted from the sensitive detection of the start and end parameters of the injection, which in turn depend on numerous variables. The challenge was to ensure that these parameters were recorded accurately while taking measurement uncertainties into account.

A central objective of the study was to analyze the effects of different piping systems on the injection characteristics. Two variants were compared:

1. Ideal gas infrastructure: inner pipe diameter of 19 mm
2. Test bench-compliant piping: internal pipe diameter of 7.9 mm

A model according to Prof. Borchsenius (OTH Regensburg) was used to capture the differences both experimentally and simulatively. Figure 5 shows an example of the simulation of pressure losses during injection for both variants. The simulation showed that there would be a drop in the injection rate due to the insufficient pipe cross-section of the test bench piping. The simulation results also agree very well with the experimental measured values.

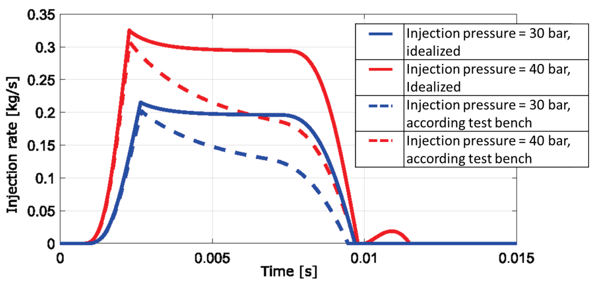

Figure 5. Simulation of pressure losses during injection (idealized vs. test bench-standard)

The test bench piping was designed for high-pressure applications with gas pressures of up to 600 bar. At lower pressures - which would be sufficient for premixed combustion processes - there was a significant drop in injection pressure during injection. Ideally, the injection rate should have a plateau, which corresponds to a constant flow of gas with the injector nozzle fully open (full stroke).

However, the tests carried out showed that the test bench piping exhibited a continuous pressure drop over the entire injection period. This led to a change in injection characteristics, particularly at low inlet pressures below 15 bar. Here, the injector nozzle exhibited partial needle lift behavior, which also resulted in deviating gas flow dynamics compared to higher inlet pressures.

The following time-resolved measurement results were created using optimised piping in order to illustrate the basic phenomenological relationships of the injection. A direct comparison with the test bench configuration was made in the mass-related comparisons in order to show the differences between idealized conditions and the actual processes on the research engine.

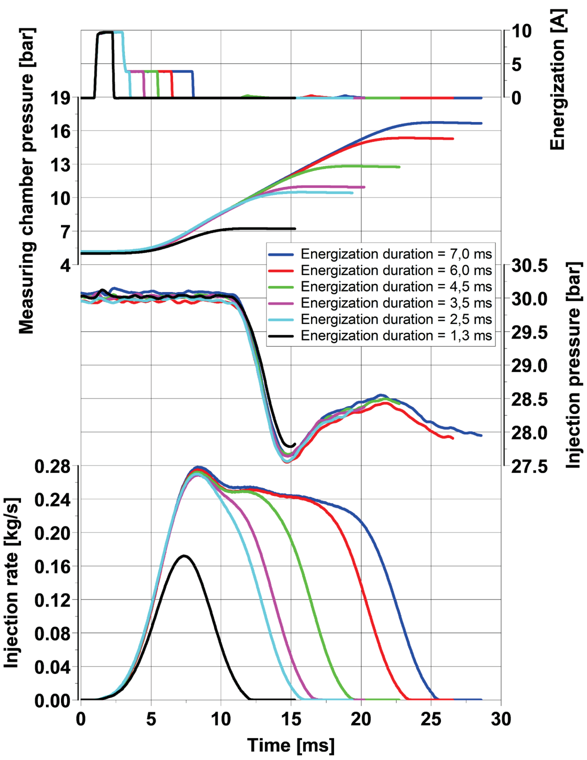

Figure 6. Energization duration variation with gas pressure = 30 bar, measuring chamber pressure = 5 bar (time-resolved)

The energization duration has a significant influence on the injected gas mass and the pressure behavior in the measuring chamber. Figure 6 shows that more gas is injected into the measuring chamber as the actuation time increases, which leads to a greater pressure difference. However, the pressure increase behavior remains constant. The inlet pressure does not collapse at the same time as the start of injection, but only during the injection process, which is due to the distance of approx. 2 m between the injector and the inlet pressure sensor as a result of the backflowing pressure wave from the open injector.

In the case shown here, the nozzle reaches full lift with an actuation time of 2.5 ms or greater, resulting in a typical plateau in the injection rate. With shorter actuation times, such as 1.5 ms, the nozzle is in the ballistic range and does not open fully, resulting in partial injection.

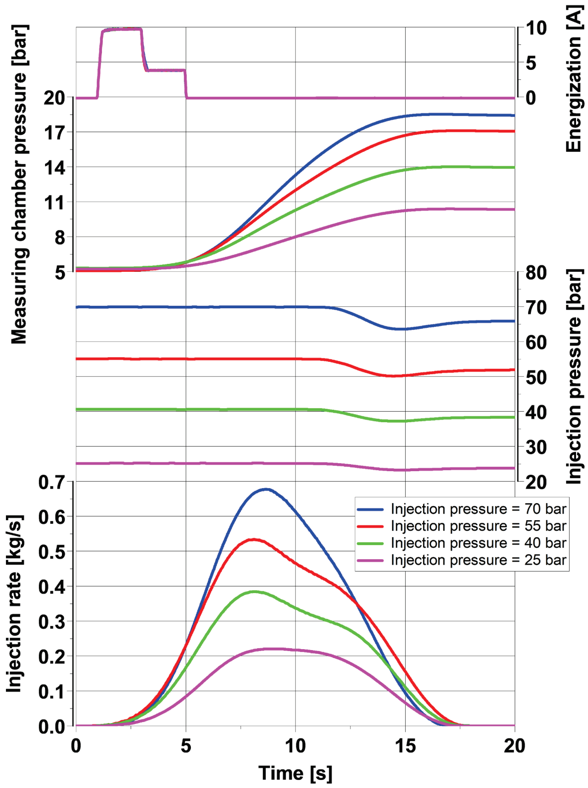

Figure 7. Gas pressure variation (full lift) with measuring chamber pressure = 5 bar, energization duration = 4 ms (time-resolved)

Figure 7 shows the gas pressure variation at full lift, in which the increasing inlet pressure leads to a greater increase in the measuring chamber pressure. This results in a higher peak pressure and an increased injection rate. In addition, the time span for plateau formation is shortened. Regardless of the inlet pressure level, the pressure value is constantly reduced by 10%.

The behavior at partial lift tends to be proportionally similar to that of the full lift (see Figure 8), but the injection durations remain constant and are significantly longer at lower inlet pressures. Here, the remanence of the control solenoid and the reduced counterforces due to the reduced gas pressure influence the closing behavior of the nozzle. The outstanding investigations already consider an optimized version of the injector, in which remanence has been further reduced significantly by 80%. The capability for precise small-quantity injection is already clearly visible.

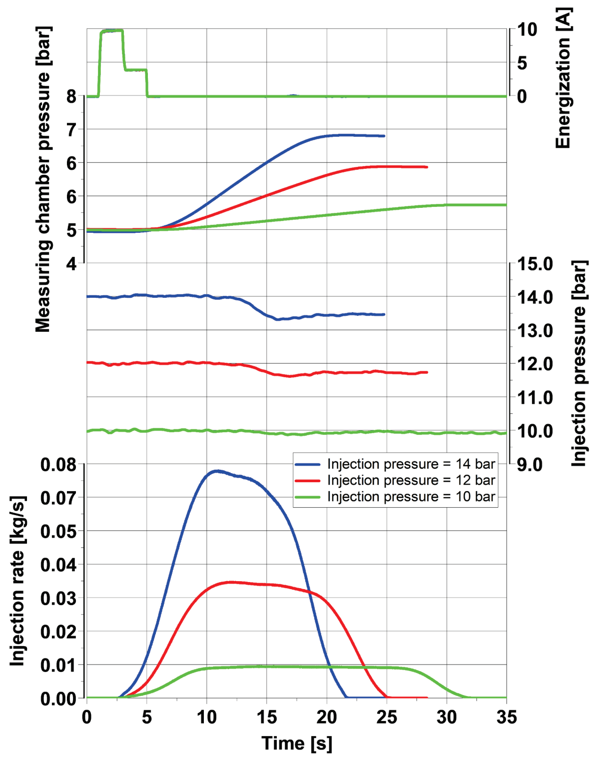

Figure 8. Gas pressure variation (partial lift) with measuring chamber pressure = 5 bar, energization duration = 4 ms (time-resolved)

As Figure 9 shows, the back pressure has hardly any influence on the injection behavior in this case, as all measurements were carried out under supercritical flow. This means that the gas pressure was at least twice as high as the back pressure at all times and the gas escaped at the speed of sound. With increasing back pressure, there is only a minimal influence on the nozzle behavior due to the increased forces acting on the nozzle.

A decisive factor for the injection characteristics is the gas infrastructure upstream of the injector, as can be seen in Figure 10. Depending on the level of upstream pressure, the piping cross-section plays a key role in terms of storage volume and throttling properties. As natural gas is a compressible medium, the requirements for fuel supply are more complex than for liquid fuels.

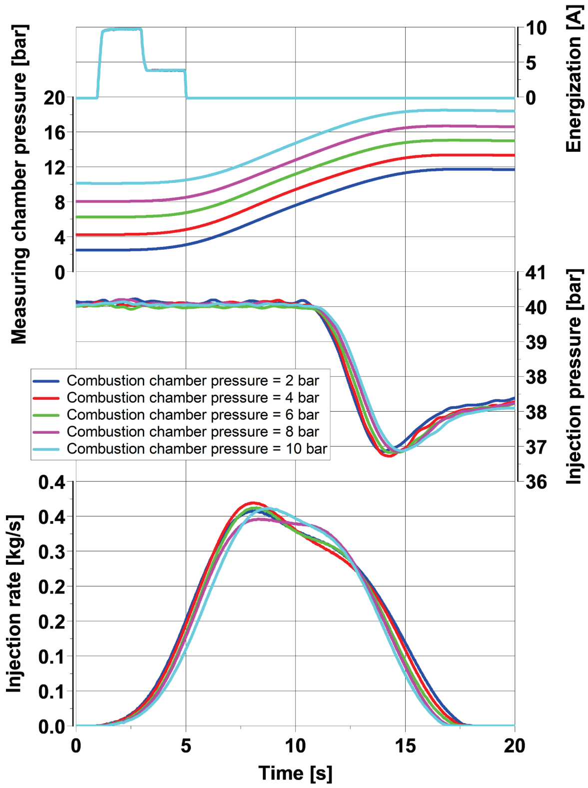

Figure 9. Measuring chamber pressure variation with gas pressure = 40 bar, energization duration = 4 ms (time-resolved)

The system of the research engine designed for high pressures is not optimal for low pressures. Despite an additional storage volume, not enough gas mass is stored upstream in the piping, and the cross-section prevents a constant downstream flow at the same pressure level. This is reflected in the measuring chamber pressure curve by the failure to reach the peak pressure, in the upstream pressure curve by a permanent drop in the gas pressure supply and in the injection rate by a continuous drop in the mass flow after the nozzle has reached full stroke. In general, the measurements with an ideal setup show the following findings compared to those of the research engine:

- Higher injected mass
- Lower shot-to-shot fluctuations
- Shorter opening delay
- Longer injection duration and higher closing delay

The analysis of the measuring chamber pressure variation (see Figure 11) shows that the injected mass decreases with increasing back pressure, as the nozzle has to perform more counter work when opening. This leads to an increase in the opening delay and a reduction in the injection time and closing delay. The high closing delay is due to the residual remanence of the solenoid of the injector nozzle.

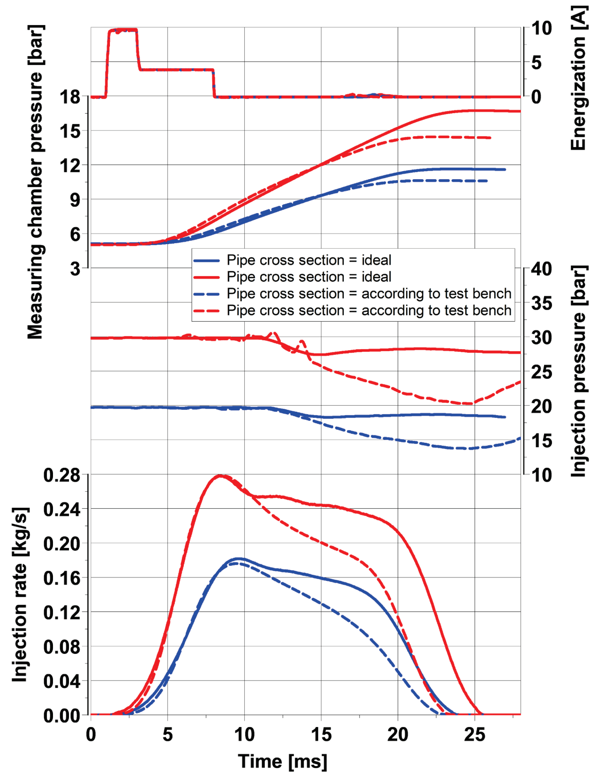

Figure 10. Comparison of experimentally determined injection rate curves (ideal vs. test bench-standard) (time-resolved)

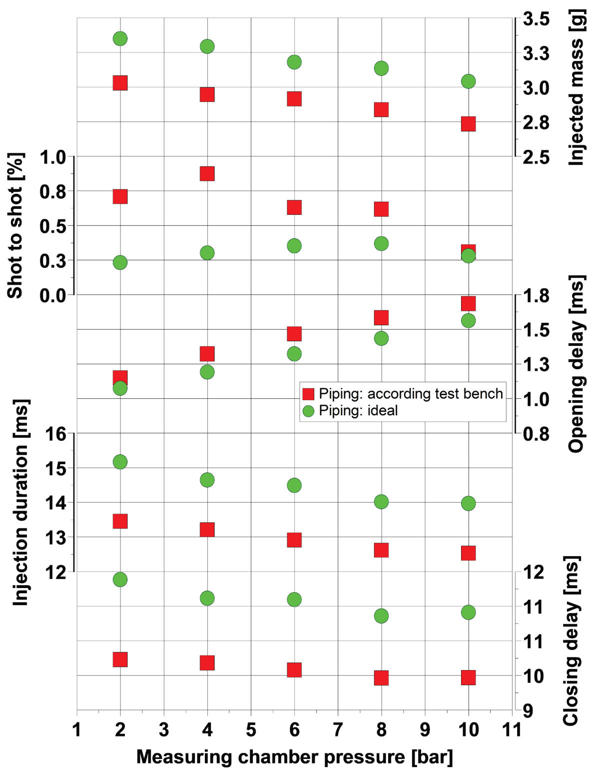

Figure 11. Measuring chamber pressure variation with gas pressure = 40 bar, energization duration = 4 ms (mass-related)

At the start of injection, the inlet pressure parameters are identical so that the opening delay remains relatively constant. Towards the end of injection, however, the inlet pressure decreases significantly, which leads to a fundamentally lower closing delay and a shorter injection duration in the test bench infrastructure. While the shot-to-shot deviations remain constant under ideal conditions, they increase with decreasing back pressure in the measurements close to the test bench.

As Figure 12 shows, the injected mass increases with increasing inlet pressure. The opening delay is shortened as the higher gas pressure supports the opening behavior of the nozzle. Closing delay and injection duration decrease and remain relatively constant in the full lift range (from approx. 15 bar). In partial lift operation, on the other hand, significantly higher delay times and thus longer injection durations can be observed.

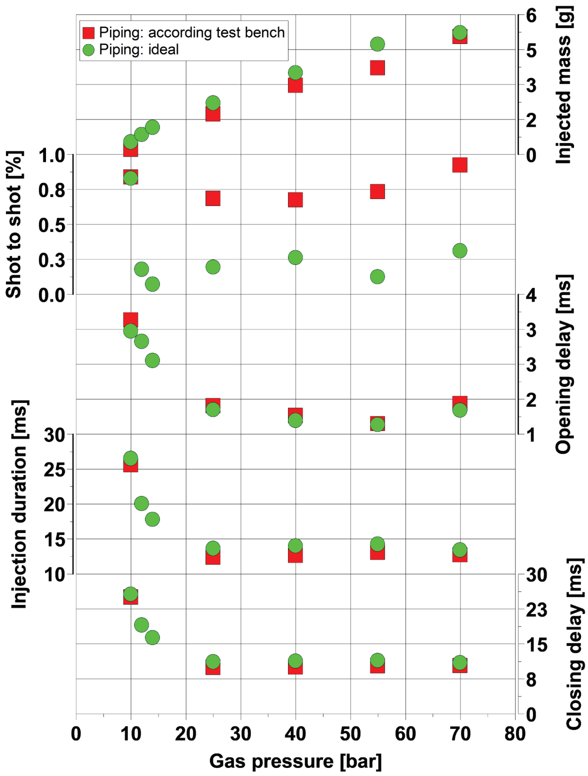

Figure 12. Gas pressure variation with measuring chamber pressure = 5 bar, energization duration = 4 ms (mass-related)

Figure 13 illustrates that more gas mass is injected as the energization duration increases, as the nozzle remains open for longer and more mass can flow through it. The opening delay remains relatively constant as the initial conditions are unchanged. The closing delay, on the other hand, increases with increasing actuation time, as the residual remanence of the solenoid takes longer to dissipate.

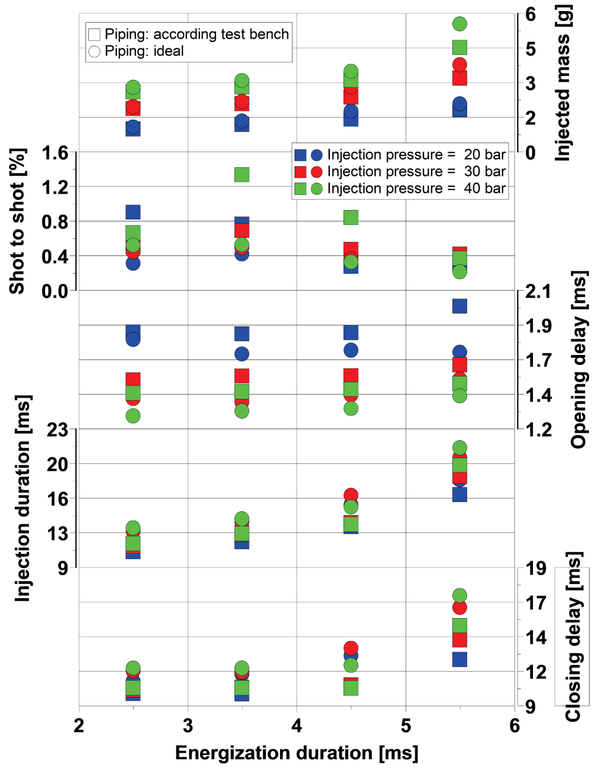

Figure 13. Energization duration variation with measuring chamber pressure = 5 bar (mass-related)

4.2 Visual analysis

This study analyzes the injection characteristics of a gas injector with jet guidance in an HPHT injection chamber. The medium-pressure variant of the gas injector was investigated, whereby various parameters such as actuation duration, gas pressure, back pressure and temperature were varied. The aim of this analysis is to determine the effects of these parameters on the propagation velocity of the gas jet and the cone angle. The results are based on lateral spray images, while investigations with frontal images without jet guidance were still pending at the time of submission of the paper.

The cone angle of the outflowing gas jet corresponds to twice the angle measured between the edge axis of the nozzle and the direction of propagation of the gas jet in an orthogonal plane to the injector axis. This angle refers to the area between the nozzle outlet and a distance of 150 mm. Within this range, the jet geometry was analyzed in detail. Therefore, detection was not possible before the detection limit was exceeded.

As in the previous tests, a drop in gas pressure can be observed during the gas penetration process. This is due to the fact that the gas cannot flow quickly enough to maintain a constant pressure level during injection. This has a considerable influence on both the jet propagation and the gas dynamics.

The jet penetration depth is determined by a combination of injector pressure, ambient influences (e.g. back pressure) and thermodynamic properties of the gas. A higher injector pressure leads to a higher velocity of the gas particles, which increases the penetration depth. At the same time, the jet penetration depth is limited by the resistance of the surrounding gases, which increases as the back pressure rises.

The cone angle of the gas jet is a result of turbulent mixing with the environment. Higher temperatures lead to greater expansion of the gas after the nozzle outlet due to the reduced density. At the same time, the cone angle increases with increasing injection duration, as the internal flow forces stabilize over time and promote a wider jet expansion.

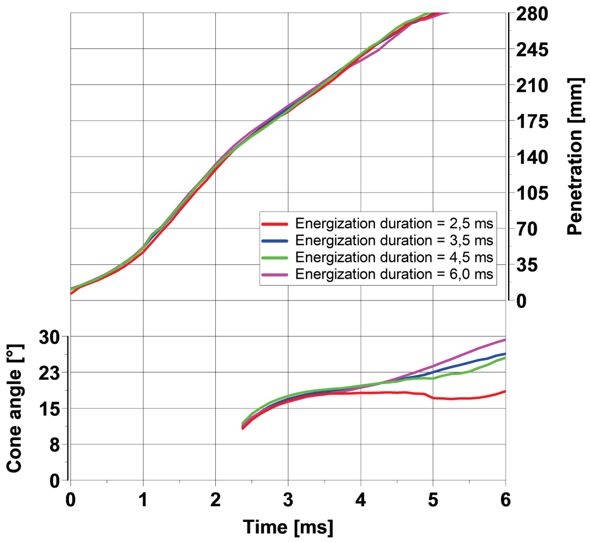

Figure 14. Energization duration variation with gas pressure = 40 bar, measuring chamber pressure = 5 bar, measuring chamber temperature = 30°C

A variation of the energization duration as shown in Figure 14 showed that the propagation velocity of the gas jet remains constant. However, it was observed that with a longer energization duration, a stronger propagation of the cone angle occurs. This is due to the fact that a greater mass of gas is introduced into the chamber, causing the jet to diverge more strongly. As the gas flow expands continuously with increasing duration, the cone angle increases proportionally. At the same time, the longer injection duration influences the jet penetration depth, as more gas is injected with a higher momentum density.

The investigation of the gas pressure variation showed that the propagation velocity decreases proportionally to the upstream pressure in the injector (see Figure 16). This indicates that higher pressures lead to a more compact jet propagation. The cone angle showed a relatively constant leveling off in the range between 16-20°, regardless of the exact pressure level. An increase in gas pressure also leads to a deeper penetration depth of the jet, as the higher kinetic energy of the gas particles transmits a greater momentum.

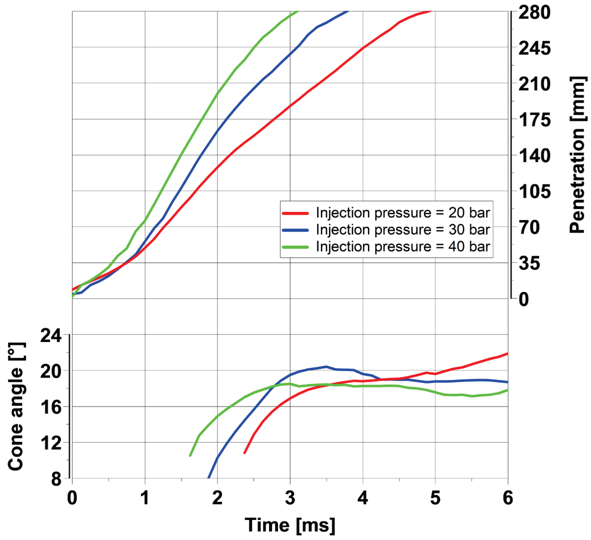

Figure 15. Gas pressure variation with chamber pressure = 5 bar, activation duration = 4 ms, chamber temperature = 30°C

As Figure 17 illustrates, an increasing back pressure leads to a reduced propagation speed of the gas jet. This is due to the fact that a higher ambient density increases the resistance for the escaping gas. It was found that the back pressure has a significantly greater influence on the density and thus on the gas dynamics than the temperature (about a factor of 10). This is of particular interest for different Miller cycles in engine operation.

After the pressure drop of the gas in the injector, the increasing back pressure also has an increased influence on the gas dynamics. Nevertheless, the cone angle remains relatively constant even under these conditions.

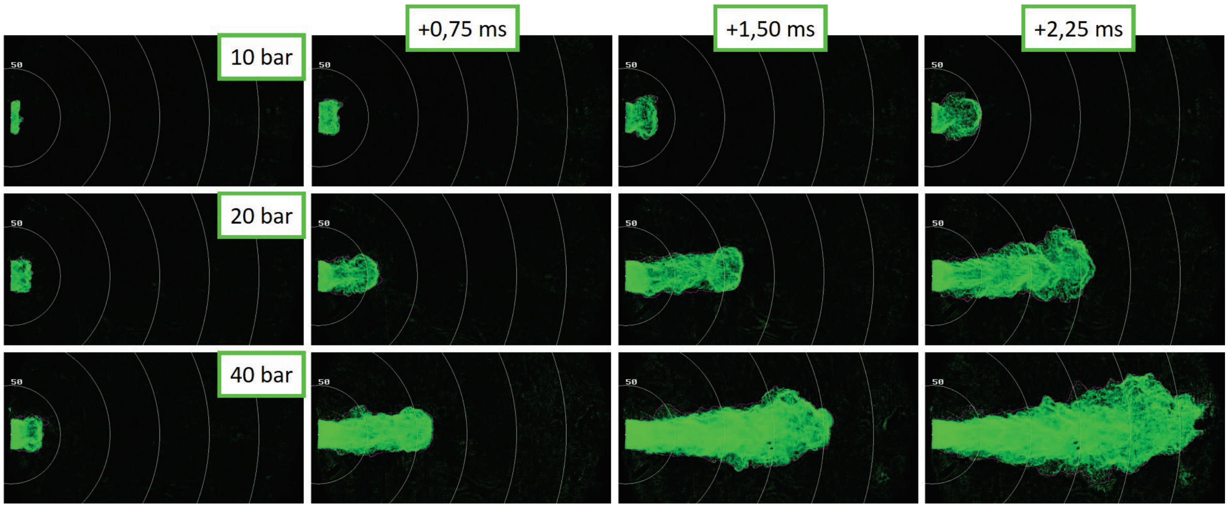

Figure 16. Visualization of gas dispersion at different injector pressures with Δr = 50 mm, measuring chamber pressure = 5 bar, measuring chamber temperature = 30 °C, energization duration = 4 ms

At the same time, the jet penetration depth decreases, as the increased ambient pressure increases the resistance to the penetrating gas mass and thus reduces the maximum range.

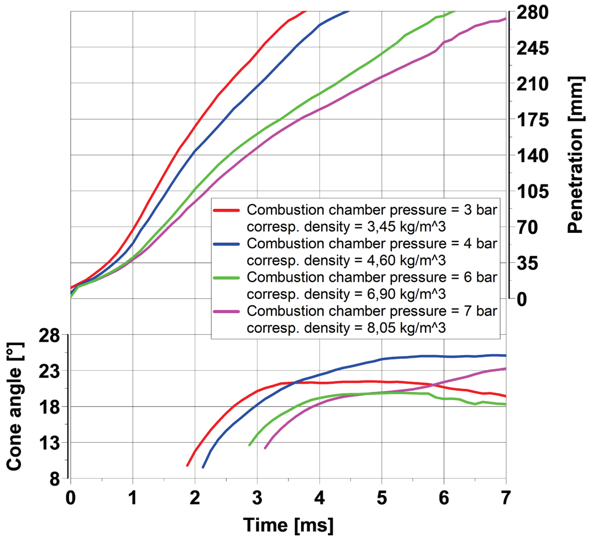

Figure 17. Measuring chamber pressure variation with gas pressure = 40 bar, measuring chamber temperature = 30°C

An increase in the propagation speed of the gas jet was observed with increasing measuring chamber temperature and the associated decrease in density (see Figure 18). This is consistent with the thermal expansion of the gas, which leads to a lower resistance effect of the environment. It was also found that the cone angle increases during injection. This is due to the fact that at higher temperatures the gas dynamics are increasingly characterized by expansion and turbulent mixing processes increase. The penetration depth of the jet increases as the ambient gas has less kinetic energy and therefore less resistance due to its lower density and subsequently interacts with the ambient air.

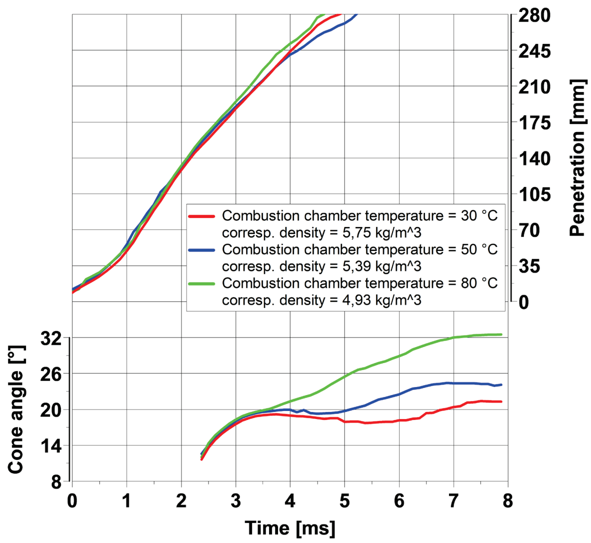

Figure 18. Measuring chamber temperature variation with gas pressure = 40 bar, measuring chamber pressure = 5 bar, energization duration = 4 ms

To confirm the previous findings, a variation of pressure and temperature was carried out at constant density (see Figure 19). This showed that the injection characteristics remain unchanged at constant density. The cone angle behavior also remained relatively constant, which shows that the density is a decisive parameter for the jet dynamics. The jet penetration depth also remained almost unchanged, which confirms that momentum transfer and jet propagation remain stable when the density is kept constant.

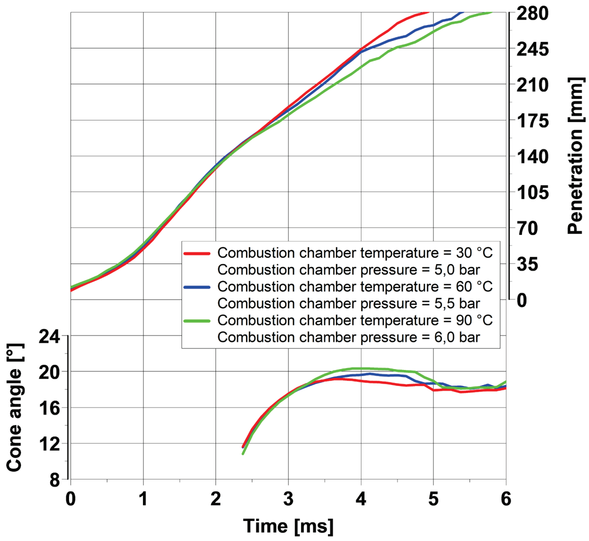

Figure 19. Variation of measuring chamber pressure / temperature with gas pressure = 40 bar, energization duration = 4 ms, density = 5.75 kg/m^3

5 CONCLUSIONS

This study deals with the characterization of direct-injection medium-pressure gas injectors for large engines as part of the BMWK-funded TEME2030+ project. The detailed experimental and simulative analyses have shown that injector characterization plays a central role in optimizing the injection process and thus contributes significantly to increasing efficiency and reducing emissions.

By using the Gas Injection Rate Analyzer and the High Pressure High Temperature Injection Chamber, essential preliminary knowledge about injection dynamics, jet propagation and mixture formation could be gained. The investigations have made it clear that both the system inertia and the specific boundary conditions of the test setup have a considerable influence on the measurement results.

The analysis of the time-resolved injection rates under varying operating conditions provided valuable data for optimizing the injection characteristics. It was found that the pipe geometry of the fuel supply and the ambient parameters of the combustion chamber play a significant role in the injection rate and the flow behavior of the gas. Differences between idealized laboratory conditions and real operating conditions were investigated and demonstrated in detail. The optical measurements in the HPHT chamber have shown that both the injection parameters and the combustion chamber environment have a significant influence on jet propagation and the jet opening angle.

The knowledge gained forms a sound basis for the further development of injection strategies and the optimization of numerical models for the simulation of gas injection processes. They thus make a decisive contribution to the development of efficient and low-emission large engines that meet the increasing requirements for sustainable drive technologies.

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