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Reduction in Particle Emissions with Gasoline Engines with Direct Injection

Within a FVV research at the Institute of Internal Combustion Engines (IFKM) at the KIT, investigations were carried out on a rapid compression machine and single cylinder engine, in order to identify the cause of particle emissions and the influencing parameters. Both test carriers were equipped with a gasoline direct injection with central injector position. Through the combination of comprehensive optical, thermodynamic and exhaust gas analysis measuring equipment and numerous applicative degrees of freedom on the test carriers, it was possible to examine individual engine-internal influential variables on an isolated basis and consider these in relation to the measured particle emissions.

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1 MOTIVATION

Reducing harmful emissions and enhancing efficiency are the primary targets of engine development. The gasoline engine with direct injection and exhaust gas turbocharging has established itself as a key technology in recent years. However, internal mixture formation is accompanied by an increase in the emission of particles, which are largely classified as harmful to health.

The aim of the research project was therefore to identify the engine-internal causes of particle emissions in gasoline engines with direct injection for automotive application, and to investigate the extent to which these can be reduced through engine-internal measures. To this end it was necessary to establish a comprehensive understanding of the engine-related influential factors pertinent to particle generation, oxidation, characteristics and emission. For this purpose, optical measuring methods were used to analyse the mixture formation and combustion, measure the particle concentration and size distribution, and examine the emitted soot with the aid of electron microscopy with respect to morphology and chemical composition.

2 TEST CARRIERS

The engine tests were conducted on a single-cylinder engine with central injection position. The fundamental engine data is summarised in **TABLE 1**. For optical investigations in the combustion chamber, two accesses were used for light source and camera, and equipped with endoscopes with an 8 mm outer diameter and 70° opening angle. The set-up is shown in **FIGURE 1** (left). **FIGURE 1** (right) shows the observation space in the combustion chamber accessible with this configuration.

3 PARTICLE MEASURING EQUIPMENT

An AVL 489 Particle Counter Advanced (APC, certified according to PMP specifications) was used in order to determine the particle concentration in the exhaust gas, and partly also a TSI 3090 Engine Exhaust Particle Sizer (EEPS). The systems were mutually operated on the sampling system of the AVL measuring system here, **FIGURE 2**. In order to keep the particle concentration in the diluted exhaust gas behind the Volatile Particle Remover (VPR) within a range suitable for the downstream measuring systems, dilution took place by a factor of 100 to 2000.

4 RESULTS

The following section presents the results of the three-year project in abridged form. The experimental investigations were conducted at three NEFZ-relevant operating points:
- 50 km/h constant travel: 2 bar indicated mean effective pressure, 2000 rpm engine speed
- end point of acceleration at 120 km/h: 8 bar indicated mean effective pressure, 2000 rpm engine speed
- catalyst heating operation: 1.8 bar indicated mean effective pressure, 1200 rpm, 50 % mass fraction burnt ≥ 75 °CA a. TDC, the operating point is additionally described by the respective exhaust gas enthalpy flow in kW/l displacement volume.

The expelled particle emissions are the fundamental result of a multitude of mutually interactive influencing variables, which have an effect on the one hand on the formation and on the other hand

Engine type	Single cylinder, direct injection (central injector), water cooled, four-valve
Working process	Otto four-stroke
Mixture	Homogeneous
Compression ratio [-]	12:1
Stroke [mm]	90
Bore [mm]	84
Displacement [cm³]	498
Valvetrain	Cam phaser (intake and exhaust) variable intake valve lift
Layout of injector and spark plug position	Longitudinal arrangement (parallel to crank shaft), central injector

TABLE 1 Engine data (© IFKM)

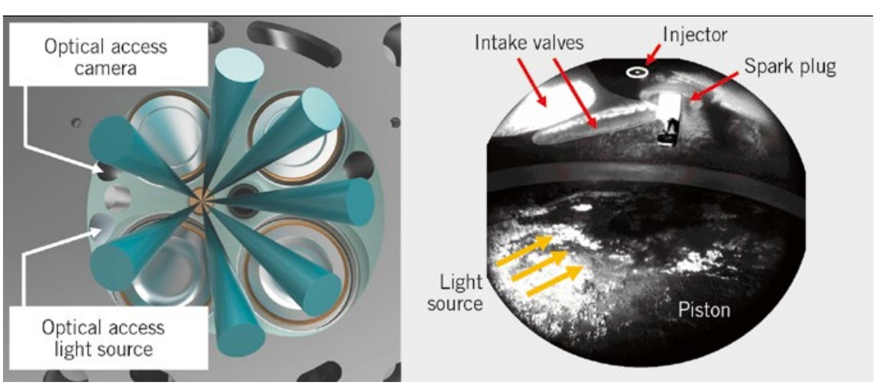

FIGURE 1 Set-up of the optical accesses (left) and observation space (high speed) visualisation of single-cylinder engine (right) (© IFKM)

on the oxidation. The following section discusses a number of parameters that influence the formation. Because the particles themselves largely consist of carbon, the fuel system, that is to say the injector nozzle geometry and the injection pressure, as well as the injection strategy and the resulting air-fuel ratio, play a decisive role. More detailed investigations into the fuel influence itself were presented at the 2013 SAE Conference in Seoul [1].

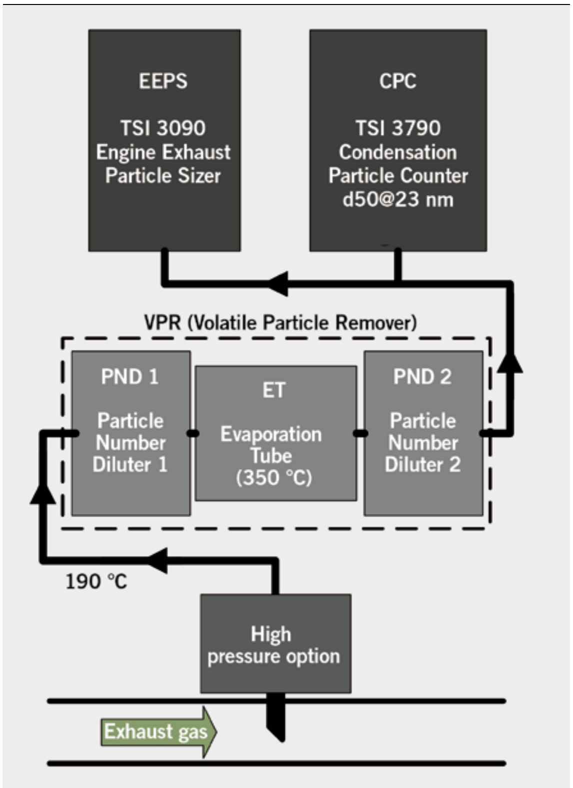

FIGURE 2 Particle measuring system set-up with mutual sampling and dilution system (© IFKM)

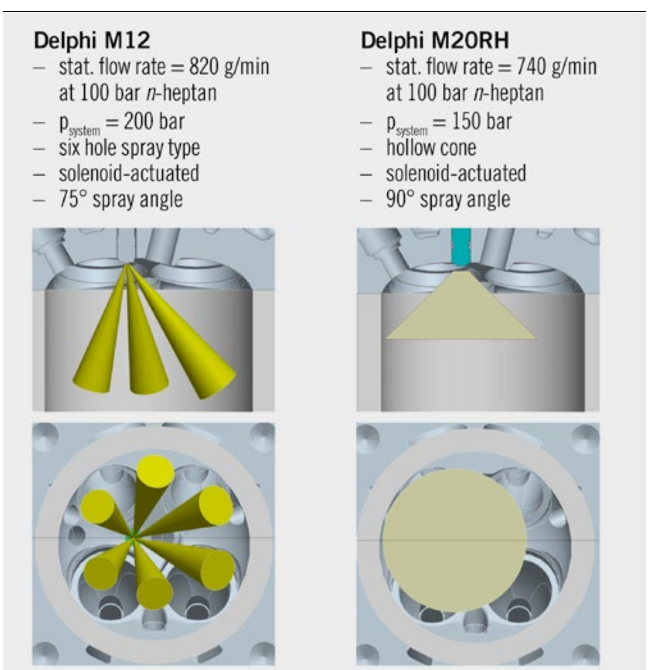

FIGURE 3 Injector overview (© IFKM)

4.1 NOZZLE TYPE

In order to analyse the influence of the fuel injection on the occurrence of particle emissions, multiple injectors were provided for the research project, which differ in terms of throughput, nozzle geometry, spray angle and actuation, **FIGURE 3**. During the first half of the project, comprehensive parameter variations were implemented with all injection valves [2]. In the second half of the project, two injectors were selected on the basis of the results: A multi-hole nozzle with suitable spray targeting (Delphi M12 injector) and an outwardly opening nozzle (Delphi M20 injector). The wide spray of the outwardly opening nozzle results in an exposed jet length of just 45 mm right to the cylinder wall. With an exposed jet length of 81 mm, the spray from the multi-hole nozzle offers considerably more favourable conditions with respect to the spray-wall interaction. During operation with the outwardly opening nozzle and individual injection quantities of over 25 mg in the intake stroke, it was no longer possible to avoid coating the inlet valve. In addition to fuel deposits, an increased proportion of oil in the exhaust gas was also observed due to flushing effects. With the multi-hole nozzle it was possible to avoid part interaction through the suitable selection of the injection start.

In order to investigate the effects of the spray characteristics (individual jets versus hollow cone) and the opening angle (multi-hole nozzle: 75° versus outwardly opening nozzle: 90°) on the particle emissions, long main injection (> 25 mg) was used in the catalyst heating operation in the intake stroke on the one hand, whilst short injection was applied in the ballistic operating range (≈ 0.3 mg) shortly before the ignition time point on the other.

During catalyst heating operation, the provision of a large exhaust gas enthalpy flow is of primary importance. The engine is driven almost de-throttled, with very late mfb50. Severe cyclical fluctuations arise due to the late combustion position with low turbulence level. With near-ignition small-quantity injection, enrichment and an increase in the turbulence level may be attained at the spark plug, and thereby also a stabilising of the combustion. In this way the engine can be operated with a globally light, lean mixture for the avoidance of excessively high HC emissions. However, considerable particle emissions can arise due to the rich mixture at the spark plug or any fuel that has not been fully vaporised.

FIGURE 4 shows the spray spread of the small-quantity injection in the ballistic operating range for both injectors. It is clear that the fuel preparation with the outwardly opening nozzle is significantly superior to that of the multi-hole nozzle. As such, no individual droplets are apparent with the outwardly opening nozzle and faster fuel preparation is also observed. In contrast, with the multi-hole valve – in particular in the area around the spark plug – individual droplets can be seen, which arise in particular towards the end of injection, that is to say when the injector needle is closed. The cause of this can be found in the better spray disintegration of the hollow cone spray, in comparison to the multi-hole nozzle. Whilst the fuel with the hollow cone spray is distributed evenly over the ring gap and even the smallest injection quantities are injected in the ballistic operating range at nominal pressure (150 bar), with the multi-hole nozzle the injection pressure does not yet reflect the rail pressure during the valve opening process due to the internal throttling points (needle, spray holes). Due to

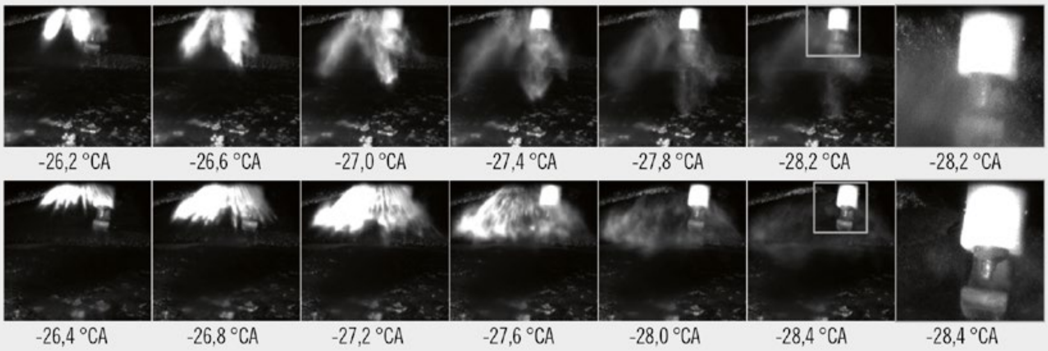

FIGURE 4 Spray spread of small-quantity injection (≈ 0.3 mg) (top: Multi-hole nozzle (M12); bottom: outwardly opening nozzle (M20)) (© IFKM)

the incomplete opening in ballistic operation, the valve is already closed again before the nominal pressure is present in the injection holes. The likelihood of fuel residues in the spray holes and so-called dripping effects is therefore also increased by the lower spray pulse. All of these effects, in combination with the very short time between injection and ignition, lead to a poorer preparation of thenear-ignition injection of the multi-hole nozzle in comparison to theoutwardly opening nozzle (multi-hole nozzle greater than 1.5×10^6 p/cm³; outwardly opening nozzle less than 0.5×10^6 p/cm³).

4.2 INJECTION STRATEGY AND AIR-FUEL RATIO

The correct timing and spatial placement of the near-ignition injection is of great significance for the aforementioned reasons, both in achieving minimal combustion fluctuations as well as low particle emissions. In order to examine this more closely, the LaVision ICOS fuel (SP for optical determination of the fuel concentration in the area of the electrodes) was used to examine the effect of near-ignition injection on the fuel concentration close to the ignition gap and this was discussed in the context of particle emissions and combustion fluctuations. For this purpose the engine was operated with global lambda of 1.05, a specific exhaust gas enthalpy flow of 6 KW/l, two injections in the intake stroke, a third shortly before the ignition time point, and a multi-hole nozzle (M12) and an outwardly opening nozzle (M20) in alternation. The influence of the timed placement of the near-ignition injection can be seen in **FIGURE 5**. The top two diagrams in **FIGURE 5** show the measured values with the multi-hole nozzle, the two bottom figures show the outwardly opening nozzle values. The left column shows the λ-course for the various injection time points of the third injection (SOI 3) around the ignition time point (IGN). The right column shows the associated values of the particle emissions

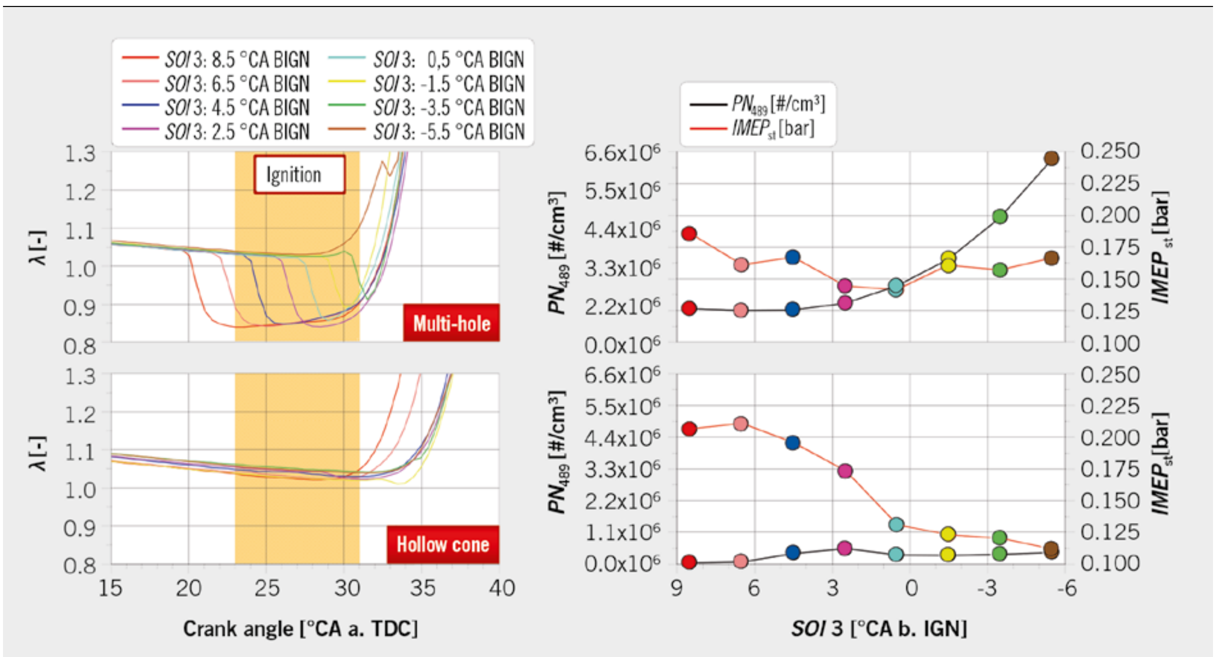

FIGURE 5 Influence of the near-ignition third injection (λ = air ratio at the spark plug, SOI 3 = start of the 3rd injection, vZZP = before ignition, PN489 = particle number measured with AVL Particle Counter 489, Pmi, st = standard deviation of the indicated mean effective pressure) (© IFKM)

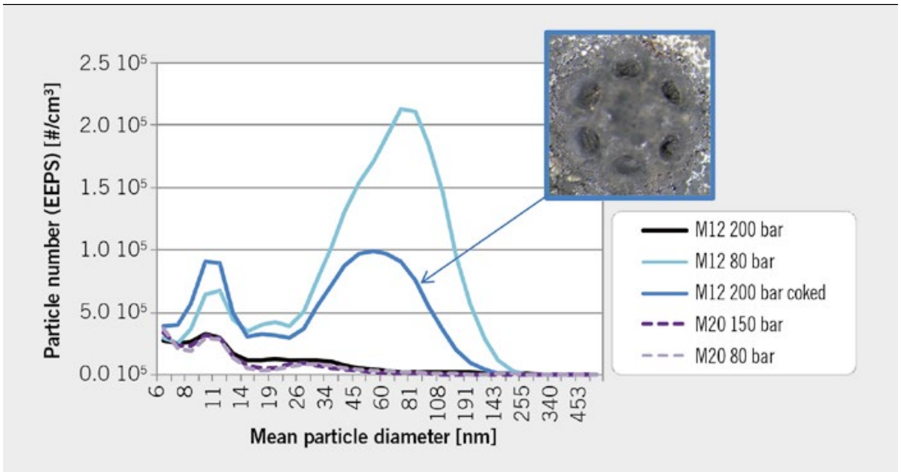

FIGURE 6 Influence of the injection pressure and injector state on the particle size (© IFKM)

(black line) and combustion fluctuation (grey line). Both injectors were operated with the third injection with the minimum actuation period of 0.22 ms. The resultant near-ignition injected quantities were approximate 0.3 mg (1.3 % of total fuel mass) with the multi-hole nozzle and approximate 0.9 mg (3.9 % of total fuel mass) with the outwardly opening nozzle. With the multi-hole nozzle, significant enrichment is observed at the spark plug across the entire variation range, which only decreases with injection after the ignition time point. In equal measure, low combustion fluctuations (IMEPst) can be observed, which constantly lie below the value without near-ignition injection (0.2 bar). On the other side, the particle emissions are at a higher level and increase constantly with a reduction in the period of time between injection and ignition. The measurements with the outwardly opening nozzle exhibit distinctly different behaviour. Irrespective of the SOI 3, almost no enrichment is apparent at the ignition gap, equally the particle emissions lie at a consistently lower level in comparison to the multi-hole nozzle, even if this is above the operating strategy without near-ignition injection. Unlike operation with the multi-hole nozzle, the combustion fluctuations initially increase with an SOI 3 > 0.5 °KW before IGN in comparison to operation without near-ignition injection, although these assume very low values across the remaining range. The comparison of the λ-measurement between both injectors clearly shows the considerably better mix-

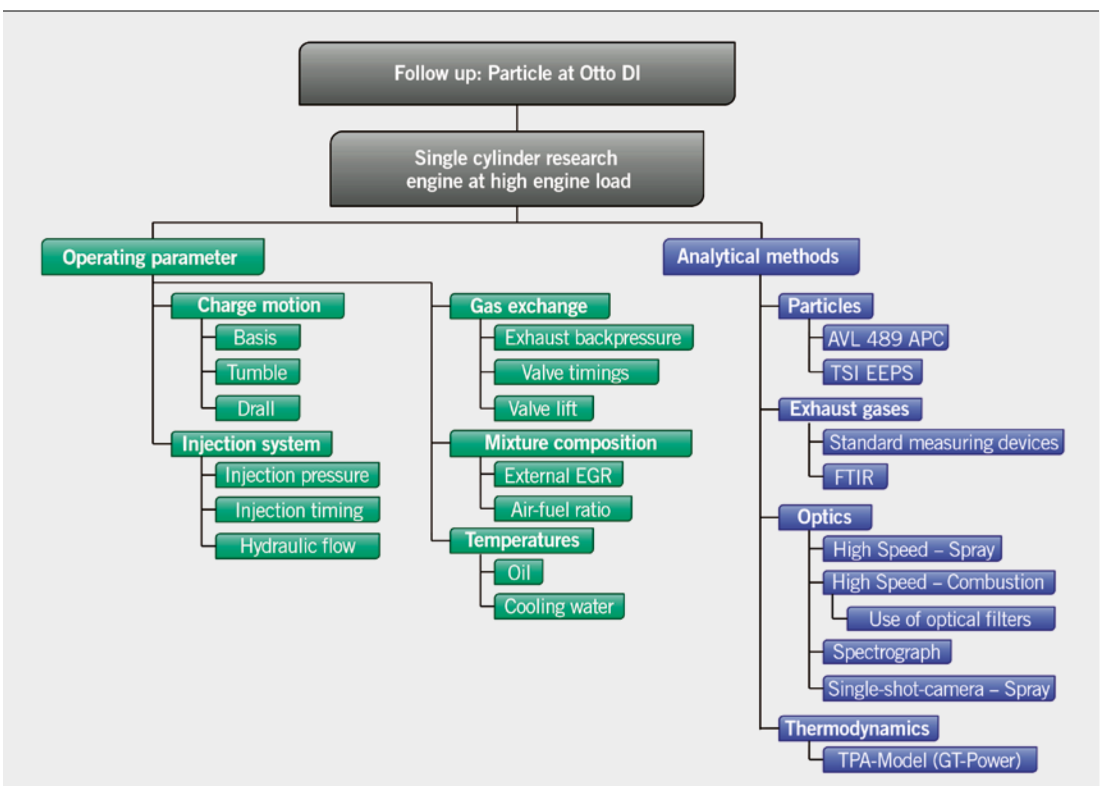

FIGURE 7 Main topics of the follow-up project (© IFKM)

ture preparation of the outwardly opening nozzle, in particular in the ballistic range. Whilst the full injection pressure is not yet present with the multi-hole nozzle due to throttling losses in the injector and the spray spread and jet disintegration are therefore negatively influenced and result in larger fuel droplets with a comparatively low pulse. With the outwardly opening nozzle the full injection pressure is also available in the ballistic operating range, so that even the smallest quantities are distributed with a high pulse and unlimited spray disintegration.

This injector-related characteristic explains the course of the λ-measurement in **FIGURE 5**. The correlation with the particle emissions and quiet running shows that localised enrichment at the ignition time point stabilises combustion, but also leads or can lead to increased particle emissions, in particular with a reduction in time between SOI 3 and the ignition time point. However, in order to definitively establish stabilisation without a significant increase in the particle emissions, it is necessary to avoid extensive enrichment in the area well below $\lambda = 1$ and achieve stabilisation insofar as possible exclusively through the turbulence generated with injection. For this purpose, a precise spatial and time-based positioning of the near-ignition injection is necessary, as well as the use of a mixture controller that is also able to inject small quantities with a high pulse.

4.3 INJECTION PRESSURE

The fundamentally positive influence of an increased injection pressure on the mixture formation and the reduction in particle emissions has already been discussed in numerous publications [2, 3]. However, it is also apparent that a reduction in the injection pressure to 80 bar with operation with an outwardly opening nozzle through alignment of the injection strategy must not necessarily lead to a noteworthy increase in particle emissions. For example, it has been possible to show a particle emission level of less than 1.0×10^5 particles/cm³, at an operating point with 8 bar indicated mean effective pressure, 2000 rpm engine speed and the outwardly opening nozzle. With the multi-hole nozzle it was not possible to reduce the particle concentration below 1.5×10^6 particles/cm³ with this injection pressure. However, this was not due exclusively to the poorer mixture preparation resulting from the lower injection pressure. Instead, the weaker injection pulse led to an incomplete vaporisation of the residual liquid fuel at the injector tip and therefore also to carbonisation, which is not fully removed with a renewed raising of the injection pressure to 200 bar. In this way, the particle emissions at 200 bar injection pressure increased tenfold from around 7.1×10^4 particles/cm³, due to the deposits forming at the injector tip. **FIGURE 6** shows the particle size distribution at the specified operating point for both injectors. The black line shows the reference measurement, the light blue line represents operation at 80 bar injection pressure optimised through applicative measures, and the dark blue line with the M12 multi-hole injector plots the course at 200 bar injection pressure and a carbonised injector tip due to previous operation at 80 bar injection pressure. The measurement of the size distribution also clearly shows that a reduction in the injection pressure is accompanied by an increase in the mean particle diameter in agglomeration mode. From this, it is possible to deduce that the reduction in the injection pressure results in a disproportionate increase in the emitted particle mass in comparison to the number of particles. This was also observed in other investigations [4].

5 SUMMARY AND OUTLOOK

Within the framework of the FVV research project, a combination of engine-internal investigation methods and measuring equipment for determining the number and size distribution of particles in the exhaust gas was used to examine the influence of various engine and operating parameters on particle formation, oxidation and morphology.

In the associated second part, which has been in progress since August 2013, the investigation scope was expanded to include higher loads (maximum 14 bar IMEP). In particular in turbocharged operation, the preparation of large injected fuel quantities poses a challenge for low-particle operation. Various charge movements and an increase in the injection pressure are under investigation as variation parameters for the improvement of the mixture formation. The exhaust gas counter-pressure can be adjusted on the single cylinder engine irrespective of the charge pressure. With this degree of freedom and the variable valve control times it is possible to set various thermodynamic framework conditions. Furthermore, it is also possible to influence the calorifics via an additional external EGR. **FIGURE 7** shows the various variation parameters, as well as the measuring equipment used in order to assess the particle formation and oxidation. In addition to conventional exhaust gas analyses and the previously applied optical and particle measuring equipment, an FTIR is also used to analyse the gaseous emissions.

The findings of this project generate a more detailed understanding of the influencing parameters, the interaction and mechanisms of particulate formation in gasoline engines. With this know-how the particle emissions of future engines can be reduced by means of selective optimisation of components and engine operating parameters.

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