

Optical Investigations of Soot Formation Mechanisms and Possible Countermeasures on a Turbocharged Port Fuel Injection SI Engine

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ABSTRACT

Despite the known benefits of direct injection (DI) spark ignition (SI) engines, port fuel injection (PFI) remains a highly relevant injection concept, especially for cost-sensitive market segments. Since particulate number (PN) emissions limits can be expected also for PFI SI engines in future emission legislations, it is necessary to understand the soot formation mechanisms and possible countermeasures. Several experimental studies demonstrated an advantage for PFI SI engines in terms of PN emissions compared to DI. In this paper an extended focus on higher engine loads for future test cycles or real driving emissions testing (RDE) is applied. The combination of operating parameter studies and optical analysis by high-speed video endoscopy on a four-cylinder turbocharged SI engine allows for a profound understanding of relevant soot formation mechanisms. For selected operating points, engine operating parameters such as injection timing, inclination of a charge motion flap, and engine coolant temperature were varied. Furthermore, the impact of two different spray layouts on the mixture formation was evaluated. Parameter sets showing significant reduction of PN emissions were subsequently analyzed using high-speed video endoscopy. Optical access to both the intake port as well as the combustion chamber allows visualization of fuel transport mechanisms leading to diffusion flames and soot emissions respectively. In summary, this study shows that port fuel injection at high engine loads can lead to significant PN emissions. Three locations within the combustion chamber could be identified as sources for diffusion flames leading to particulate emissions. The governing parameters allowing substantial reduction of PN emissions at these locations were found to be the injection timing and the charge motion.

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INTRODUCTION

For spark ignition engines, port fuel injection still holds a significant market share of 54 % next to direct injection in the US [1]. Based on an analysis by Bosch for 2015, around 70 % of world-wide gasoline passenger car sales, including light commercial vehicles below 6 t, were still equipped with port fuel injection [2]. PFI offers an attractive cost-benefit ratio in terms of achievable emission targets combined with the simplicity of the fuel system. In the context of real driving emissions testing operating points with higher engine load will present a challenge for both DI and PFI engines in regards to pollutant emissions. Especially the particulate emissions from DI SI engines are known to raise with increasing load [3,4]. Currently there is no legislation limiting the particulate number emissions of PFI engines [5,6,7,8]. It can be expected though, that PN emissions will be regulated for PFI in future legislations as well.

When comparing PN emissions of an engine with both port fuel injection and direct injection, previous studies demonstrated a significant advantage for PFI [9]. In [10] PN concentrations were reported to be lower by one order of magnitude using PFI at an indicated mean effective pressure (IMEP) of 8 bar and 1500 rpm. Nevertheless, the presence of particulate emissions from PFI engines has been reported in several previous studies [4,11,12,13,14,15]. The particulate mass (PM) emissions from a boosted PFI SI engine were investigated by empirical relations of opacimeter measurements and two-color pyrometry in [16], giving clues to the intake valves being an important source for diffusion flames.

The primary objective of this work is the identification of soot formation mechanisms within the combustion chamber using high-speed video endoscopy. With the help of high-speed video endoscopy, which allow

the acquisition of color images, diffusion flames leading to soot formation can be recognized as flames ranging from yellow to red in color. This color range of soot luminosity can be explained by Planck's law for radiance from a black body, even though soot is not a perfect black body, considering its lower emissivity ($\epsilon \lesssim 1$). The maximum spectral energy density emitted at typical soot temperatures during combustions in SI engines occurs at wavelengths in the near-infrared part of the spectrum. But the emission emerging in the visible spectrum, especially in the red and yellow, is also significant enough to be recorded by the cameras. The distinction from the mostly blue (and UV) chemoluminescence of a homogeneous pre-mixed flame is unambiguous. The physical background for the incandescence of soot particles can be found in more detail in [17,18].

The work presented in this paper intends to obtain an overview for both the influencing parameters and the root causes for PN emissions, specifically from a PFI engine. The identification of PN-critical operating points was the first step in this context. Detailed engine operating parameter studies - in particular injection timing, charge motion, coolant temperature, and fuel injector variations - were performed considering the effects on PN emissions. Injection timing and the intensity of the charge motion are known influencing parameters on PN emissions for DI SI engines [19]. Finally the distinct sources for diffusion flames for PFI were visualized by optical access via endoscopes to both one combustion chamber and one intake port using PCO Dimax high-speed cameras. This will help to understand the underlying soot formation mechanisms of a combustion with mixture preparation by port fuel injection.

EXPERIMENTAL SETUP

The investigations were carried out on a 2.0 l four cylinder turbocharged SI engine with port fuel injection. The fuel injectors are located in the intake manifold, each closely positioned near the interface to the intake ports of the cylinder head. Detailed specifications of the research engine can be found in Table 1. Throughout all measurements RON 95 fuel with an ethanol content of 10 % was used. The engine was equipped with indicating pressure sensors. Gaseous emissions were acquired by a Horiba Mexa 7100D. The particulate number emissions were measured by a Condensation Particulate Counter (CPC) from TSI, which is integrated in a Horiba Mexa 2100 SPCS. The built-in volatile particle remover (VPR) reduces the risk of measuring small liquid droplets. The particles counted by the SPCS range in sizes from 23 nm to 3 μm . The cut-off curve for small particles is defined by counting efficiencies of 50 % $\pm$ 12 % at 23 nm and > 90 % at 41 nm [20]. Depending on the level of PN emissions total dilution ratios of 1500 or 3000 were applied. The location of the measurement probe for PN is downstream of the catalyst and upstream of the final muffler.

Table 1. Specifications of the research engine used for this study.

Displacement	2000 cc
Compression ratio	11.5
Number of cylinders / no. of valves	4 / 4
Injection system	port fuel injection
Fuel system pressure	7 bar
Charging system	turbocharged (t/c)
Exhaust Valves	cam phasing
Intake Valves	2-step valve lift, cam phasing
Charge motion device	2-step charge motion flap (CMF)

Optical access to the combustion chamber of cylinder 4 was prepared for an endoscope and a fiber optic light guide, the latter to provide illumination for images before the start of combustion. That way the fuel transport mechanism into the combustion chamber can be visualized. A second set of endoscope and light conducting fiber was integrated into the intake manifold to give insight to the intake port of the same cylinder as shown in Figure 1:

- Intake valve (IV)
- Outlet valve
- Spark plug
- Tumble plate
- Charge motion flap (CMF)
- Fuel injector (Bosch EV14)
- Endoscope into combustion chamber
- Connector for cooling system of endoscope
- Endoscope into intake manifold / intake port
- Additional access into port (used for additional light source)
- Optic light guide into intake port
- Optic light guide into combustion chamber

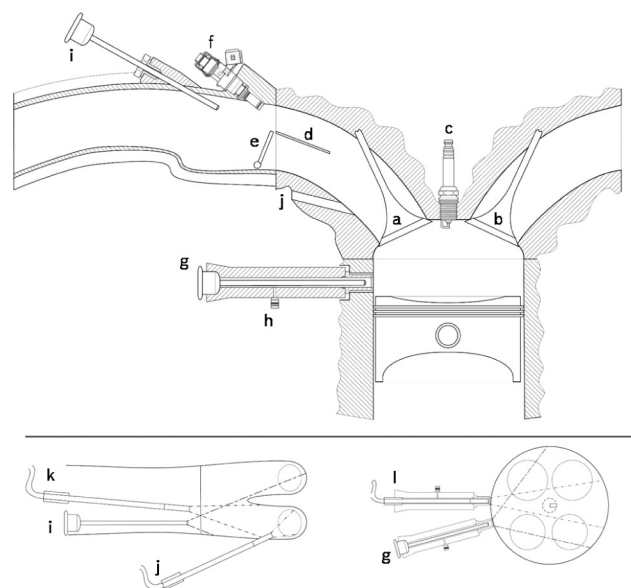


Figure 1. Design of optical access to both combustion chamber and intake port

The viewing angles of both endoscopes are sketched at the bottom of [Figure 1](#). Special attention was also paid to the stiffness of the mounts holding the high-speed cameras. Severe vibrations during engine operation can present a risk of damage to the cameras. The trigger signals of both cameras were recorded by the indicating system. This allows a synchronization of the simultaneously recorded high-speed videos of both cameras with the measurement data from the indicating system. Each recorded frame can be assigned to a certain degree of crank angle. The rate of image acquisition by the PCO Dimax high-speed cameras was set to a framerate of 6000 frames/s.

The highest possible engine load and speed, which could be measured, was limited by the temperature at the tip of the combustion chamber endoscope. Therefore, full-load measurements were possible up to the engine speed of 1500 rpm. Operating points which were analyzed with optimized air and fuel path parameters are listed in [Table 2](#).

Table 2. Engine operating points for high speed video endoscopy and simultaneous PN measurements.

N [rpm]	IMEP [bar]	T _{coolant} [°C]	Comment	Injectors
1500	12.7	92	full load / LET	A
2000	15.0	92	high PN emissions	A
3000	13.6	92	higher engine speed	B
1750	7.6	35 & 92	cold engine / part-load	A

Two different fuel injectors were used during this study. Both are Bosch EV14 fuel injectors with extended tips and compact injector bodies. Injector A was designed for minimized fuel wall films in combination with a tumble plate and a charge motion flap (CMF). The second injector B takes advantage of the space gained by removing the tumble plate. The different spray layouts are illustrated in [Figure 2](#).

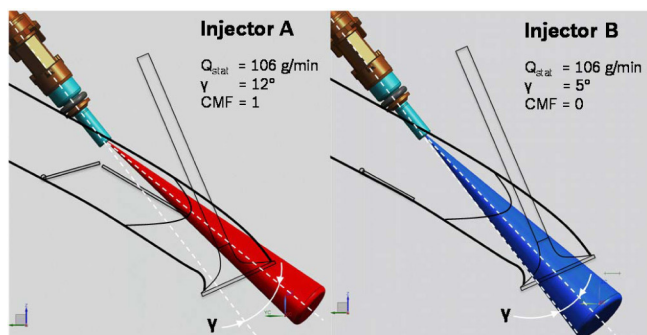


Figure 2. Comparison of spray layouts for injectors A and B.

The gamma angle describes how far the spray coils are tilted relative to a virtual plane defined by the mid-axis of the injector. From the perspective of [Figure 2](#), this plane appears as a white dashed line going through the injector body.

RESULTS AND DISCUSSIONS

Identification of PN Relevant Operating points

In order to determine the engine operating points, which are critical in terms of PN emissions, steady-state measurements in warm operating temperature conditions were performed over a wide range of the engine map without the endoscopy system. This also helped to gain a more global assessment regarding PN emissions from a t/c engine using PFI. Since this was a first step of the investigations, no specific optimizations were applied and the charge motion flap was left deactivated. Spark timing was set up for minimal fuel consumption and for avoiding knocking combustions. Knocking was monitored using the indicating system. A closed-valve injection (cVI) strategy was applied over the whole map. The PN concentration results of this map are summarized in [Figure 3](#).

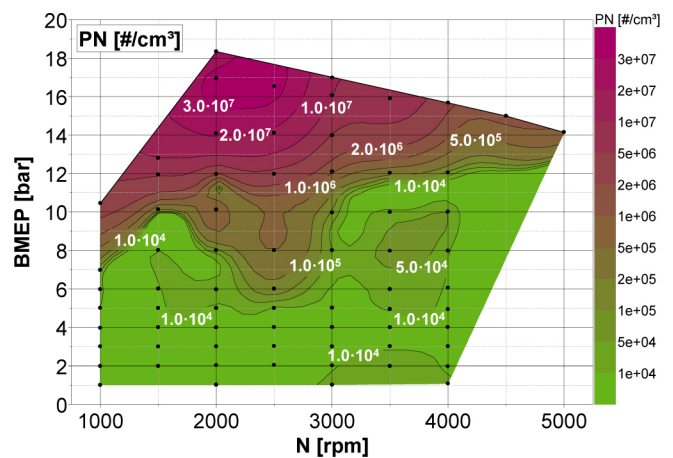


Figure 3. PN measurements over engine map, for closed-valve injection (cVI) and deactivated charge motion flap.

For engine loads up to brake mean effective pressures (BMEP) of about 10 bar the particulate concentrations measured are low. In this area of manifold pressures below 1000 mbar the PN concentrations scarcely exceed $1e+04$ #/cm³. Just above BMEP > 10 bar, where manifold pressure is increasing, PN emissions raise strongly by finally 3 orders of magnitude at 2000 rpm and full-load. It can be concluded that for PFI operating points with high manifold pressures are especially critical in terms of PN emissions.

Engine Operating Parameter Studies

For a more detailed understanding of the influencing parameters on PN emissions with PFI, load sweeps were performed. Two injection strategies and both charge motion flap positions were investigated using injector A, and the tumble plate in the position shown in [Figure 2](#) on the left. For the closed-valve injection strategy, shown by all dark-blue lines in [Figure 4](#), the end of injection (EOI) was set to 300 °CA before intake valve closes (IVc). The open-valve injection strategy (oVI) was applied by EOI of 60 °CA before IVc. A logarithmic scale was used for the PN concentrations on the y-axis.

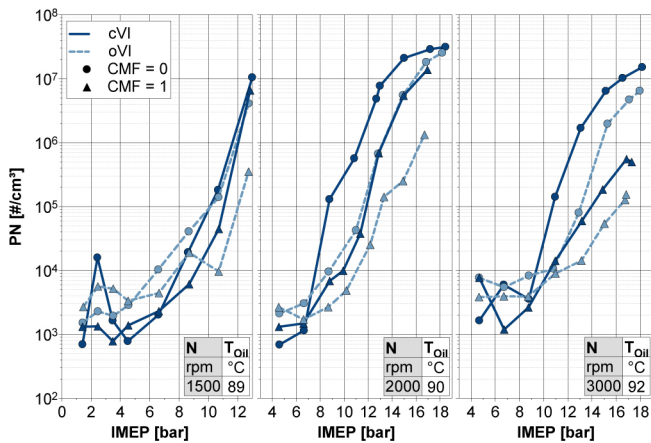


Figure 4. Loads sweeps of parameter study regarding PN emissions using injector A (log.-scale).

The highest PN concentrations were found to occur for the case of closed-valve injection and deactivated charge motion flap. As previously seen for the engine map, PN emissions raise rapidly with increasing load. Switching to open-valve injection, still with the charge motion flap deactivated, leads to an improvement regarding PN concentration. The level of PN emissions decreases even further, when the CMF is activated. Combining the open-valve injection strategy with the enforced tumble by the charge motion flap yields the lowest PN emissions. The described effects apply best for the engine speeds of 2000 and 3000 rpm. At the engine speed of 1500 rpm only the high loads show these trends for oVI and activated CMF. The conventional cVI strategy seems to work well for low engine loads at 1500 rpm, where PN emissions are generally very low.

Since the injection strategies showed a significant effect on PN, variations of injection timings were carried out. EOI sweeps with both positions of the CMF are plotted in Figure 5 using injector A. The x-axis represents the crank angle for the end of injection relative to IVc. PN concentrations for an early injection are found on the far left of the diagram, for example. Smaller increments of injection timing were chosen in the region just before and during intake valve open. The duration of the injection is shown only for the latest theoretically possible EOI = 0 °CA before IVc, for a visual comparison with the event length of the intake valve.

Both curves plotted in Figure 5 represent mean values for PN concentrations from up to three EOI sweeps. If the tumble is not enforced, given by CMF = 0, PN emissions increase for open-valve injection by nearly one order of magnitude. The same measurements repeated with activated CMF = 1 leads to an improvement for PN of around two orders of magnitude. A small benefit by tumble enforcement is also visible for the cVI case. An explanation of such opposing effects regarding PN emissions upon different CMF positions for the oVI strategy was one of the goals for the high-speed video endoscopy measurements.

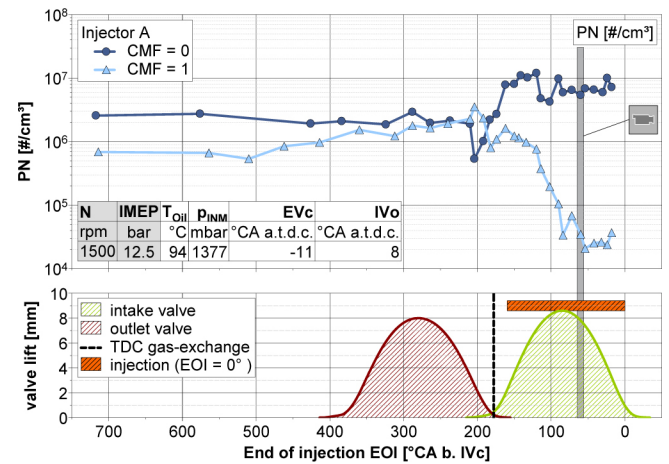


Figure 5. EOI sweeps with injector A for active and deactivated charge motion flap, (CMF = 1 and CMF = 0 respectively).

High-Speed Video Endoscopy

Minimal Soot Emissions Operating Point - Low Engine Load

Before investigating the soot formation mechanisms at high engine loads, an operating point with very good emission results was measured. The objective was to understand how the apparently good mixture formation works for low engine loads, where PN emissions are very low.

Figure 6 shows the injection and intake stroke phase relevant for the fuel transport into the cylinder at 1750 rpm and IMEP = 7.6 bar. Important parameter settings were: usage of injector A without tumble plate, CMF = 0, and cVI set to EOI = 300 °CA b. IVc. The images illustrate an example of ideal mixture preparation for port fuel injection:

- First droplets of fuel jet approach intake valves.
- Fuel accumulates at closed intake valves. Injection has ended.
- IVo: back flow of burnt gas from combustion chamber into intake port starts due to negative pressure gradient over the IVs.
- Build-up of back flow still ongoing, facilitating evaporation of fuel droplets and fuel wall films on IVs and intake port.
- Back flow moved most liquid droplets away from IVs.
- Transition of back to forward flow.
- Forward flow is accelerating. Most fuel droplets evaporated by now.
- Few left-over fuel droplet pass IV.

One rather large fuel droplet was marked with a white circle to demonstrate the process of back flow and forward flow after IVo. This back flow of hot exhaust gas entering the intake port supports several elements of the mixture preparation: the evaporation and strip atomization of fuel films, the fuel-air mixture process, the break-up of fuel droplets, and generally the evaporation of left over liquid fuel droplets. Since the fuel amount at this operating point with low engine speed and low engine load was small, and since the low