

# Is a High Pressure Direct Injection System a Solution to Reduce Exhaust Gas Emissions in a Small Two-Stroke Engine?

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## ABSTRACT

Small gasoline engines are used in motorcycles and handheld machinery, because of their high power density, low cost and compact design. The reduction of hydrocarbon emissions and fuel consumption is an important factor regarding the upcoming emission standards and operational expenses. The scavenging process of the two-stroke engine causes scavenging losses. A reduction in hydrocarbon emissions due to scavenging losses can be achieved through inner mixture formation using direct injection (DI). The time frame for fuel vaporization is limited using two-stroke SI engines by the high number of revolutions. A high pressure DI system was used to offer fast and accurate injections. An injection pressure of up to 140 MPa was provided by a common rail system, built out of components normally used in automotive engineering. A standard electromagnetic injector is applied for the fuel injection. This injection unit is dimensioned for multi-point injections in diesel engines. It allows short injection durations and thus low injection rates. An air-assisted direct injection system was investigated to show the potential of a low-cost solution for direct injection. A controlling unit linked to the test rig software provides the signals for the injector. The fuel pressure in combination with the injector controlling unit allows flexible adjustment of injection parameters during the investigations.

Another topic of these investigations is the use of alternative fuels. These fuels show high potential for further reduction of exhaust emissions while simultaneously increasing the engine power output.

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## INTRODUCTION

The two-stroke spark-ignition (SI) engine is limited to specialized applications because of poor fuel economy, high exhaust gas emissions and the need to mix lubricating oil with the fuel. Especially in the mid-1980's the potential of the two-stroke engine featuring direct injection for automotive applications was investigated [1; 2; 3; 4] but not introduced commercially. However, two-stroke DI engines are still a field of research [5; 6].

The emission legislation for small two-stroke SI engines limits the emissions of hydrocarbon (HC) and nitrogen oxides (NO<sub>x</sub>). The piston-ported two-stroke SI engine emits only small amounts of NO<sub>x</sub> because of high concentration of residual gas and operation with rich mixture. The high emissions of HC are caused by scavenging losses, rich mixture and incomplete combustion. The incomplete combustion therefore is a result of cyclic changes by the in-cylinder flow and thus the mixture preparation.

In the past the emissions of HC resulting from scavenging losses could be reduced on a large scale by using charge stratification. The charge stratification thereby is mostly realized by stratified scavenging. Another possible option to stratify the charge is the use of a DI system [7; 8]. By injecting the fuel into the combustion chamber after the exhaust port closes, the scavenging losses can theoretically be reduced to a minimum. Because of the high engine speeds, the flow velocity in the cylinder of a small two-stroke SI engine is very high [9]. In combination with the late fuel injection after exhaust port closing, the mixture preparation using direct injection is sophisticated.

The first part of the paper describes the constructive adaption of the injector at the cylinder and the test rig setup. A 92 cm<sup>3</sup> small SI engine was used for the test. The injector was mounted to the top of the cylinder via an adapter.

The second part describes engine tests at static operation points. Therefore the performance, emissions and engine behaviour are analyzed. With a high pressure DI system it is

possible to reduce scavenging losses resulting in a reduction of the hydrocarbon emissions in combination with a higher power output and lower fuel consumption.

The third part shows the potential of an air assisted DI system compared to the high pressure DI system. With both systems, ethanol or ethanol blends were used to show the capability of a fuel consumption- and emissions reduction using alternative fuels.

## MEASUREMENT SETUP

The application of the two injection systems to the small two-stroke SI engine is described in the following section. Both injection systems were triggered by an ADwin Pro 2 crank-angle based control unit. The transistor coil ignition system used was a conventional pencil coil with >55 mJ (dwell time set to 1ms) coil energy and a series manufactured spark plug.

## Fuels

Most of the experiments were performed using commercially available RON95. Because of the limited supply of fossil fuels, biogenic fuels become more and more important. Biogenic fuels have a nearly closed carbon dioxide cycle. Of course this does not mean that no carbon dioxide is produced during the production process. The first generation of biogenic fuels is a temporary solution because only small parts of the plant are used for the fuel production process. Also the plants used are in direct competition to the food production. The second generation such as BTL is currently in the research process. The production process of BTL is based on a total gasification of the biomass followed by a synthesis of the fuel via Fischer-Tropsch-synthesis.

**Table 1. Physical properties of the fuels used**

|                                                    | <b>RON95</b>  | <b>Ethanol</b> |
|----------------------------------------------------|---------------|----------------|
| <b>Boiling range [°C]<br/>(at 1013 hPa)</b>        | <b>30-190</b> | <b>75-78</b>   |
| <b>Density [g · cm<sup>-3</sup>]<br/>(at 20°C)</b> | <b>0.74</b>   | <b>0.79</b>    |
| <b>Caloric value<br/>[MJ/kg]</b>                   | <b>42.13</b>  | <b>26.84</b>   |
| <b>RON [-]</b>                                     | <b>95</b>     | <b>109</b>     |
| <b>Carbon mass<br/>fraction [%]</b>                | <b>84.11</b>  | <b>52.1</b>    |
| <b>Hydrogen mass<br/>fraction [%]</b>              | <b>13.71</b>  | <b>13.1</b>    |
| <b>Oxygen mass<br/>fraction [%]</b>                | <b>2.18</b>   | <b>34.8</b>    |
| <b>Air requirement<br/>[-]</b>                     | <b>14.51</b>  | <b>8.97</b>    |

Because the use of alcoholic fuels show high potential to reduce the emission of the greenhouse gas CO<sub>2</sub> [10], several tests with the DI systems were done using ethanol and ethanol blends. The physical properties of these fuels are

shown in [Table 1](#). The fuel blends used were analyzed to determine the composition and the physical properties.

## Engine Setup

The handheld powertool used was a two-stroke spark ignition chainsaw with a volumetric displacement of 92 cm<sup>3</sup>. The engine was crankcase scavenged. The data of the engine is shown in [Table 2](#)

**Table 2. Engine data**

|                 |                          |
|-----------------|--------------------------|
| Displacement    | 92 cm <sup>3</sup>       |
| Bore            | 54 mm                    |
| Stroke          | 40 mm                    |
| Ignition system | Transistor coil ignition |

The engine was operated on a standard engine test bench using a dynamometer. The test bench was conditioned with a constant air temperature. Except for the investigations using ethanol, the fuel used was commercially available RON95 with about 5% ethanol. The lubrication of the engine was achieved with an additional oil pump. The oil was pumped in the intake port of the engine. The in-cylinder pressure was recorded with an indication system. The pressure sensor was adapted to the bore of the decompression valve, so the modifications to the engine were as small as possible.

## High Pressure Direct Injection

For the investigations, changes had to be done on the engine setup. For the implementation of the solenoid injection system, a bore was drilled into the center of the combustion chamber by using the same thread dimensions as the spark plug bore. Thus the position of the spark plug and the injector could be exchanged. The application is shown in [Figure 1](#).

The injector used was a series manufactured common rail injector for automotive diesel applications. The maximum pressure of the injector is 160 MPa. The injector had a multi-hole nozzle with six holes. Three of these holes were closed (laser-welded) because the hydraulic flow of all six nozzles was too large for the small two-stroke SI engine.

By using a commercially available diesel injector, the engine speeds were limited to 7000 rpm. This can be reduced to the slow opening behaviour of hydraulically controlled injectors. In consequence the experiments were performed with a constant engine speed of 6000 rpm and wide open throttle (WOT).

The timing of the high pressure direct injection is limited through the mixture formation. To reduce the scavenging losses, the beginning of injection (SOI) was set after exhaust port closing, shown in [Figure 3](#).

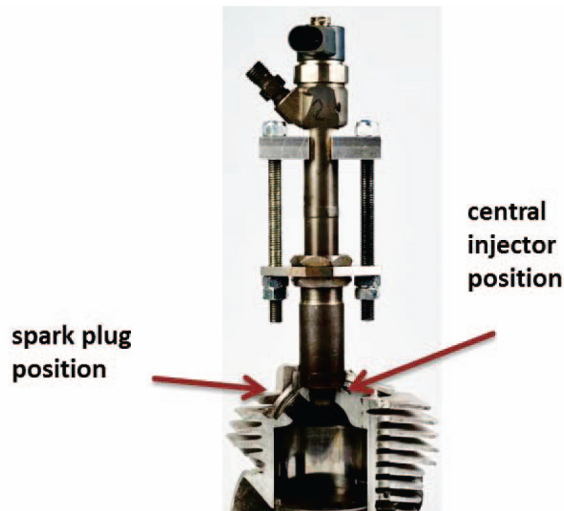


**Figure 1. Application of the high pressure direct injection system**

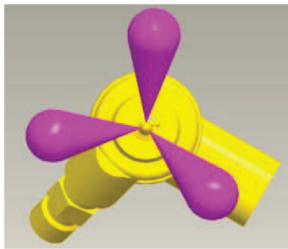


**Figure 2. Series manufactured high pressure diesel injector with three holes**

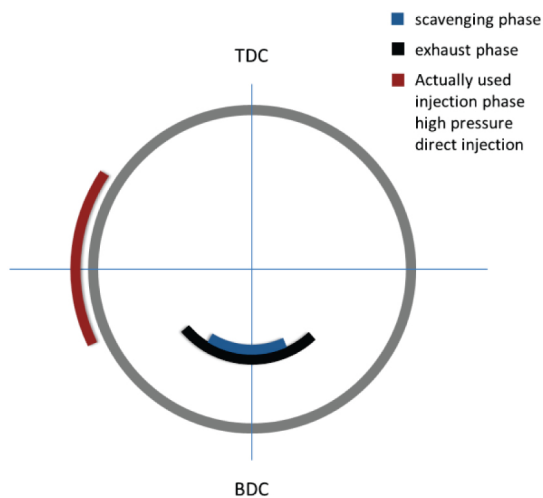


**Figure 3. Injection timing using high pressure direct injection**

A standard fuel pump for automotive applications was used to generate the pressure. It was powered by an electric drive. The minimum opening pressure of the injector was about 40 MPa.

The high injection pressure in combination with the small dimensions of the combustion chamber led to wall-wetting. This spray-wall-interaction led to material removal on the combustion chamber resulting in an engine failure. Therefore a sleeve was adapted to the nozzle, shown in [Figure 4](#). Thus the injection jet was broken up and the jet penetration was reduced.



**Figure 4. Adaption of the sleeve**

The last variation on the high pressure DI system was the use of a special nozzle. The nozzle was customized for gasoline DI systems for automotive applications, see [11]. Unlike the diesel nozzle, the special nozzle had a steeper injection angle and six holes with reduced hydraulic flow. Also, the six holes were not distributed symmetrically. Thus the injector could be mounted to the engine without a jet oriented to the exhaust port. The nozzle and the jets are schematically shown in [Figure 5](#).

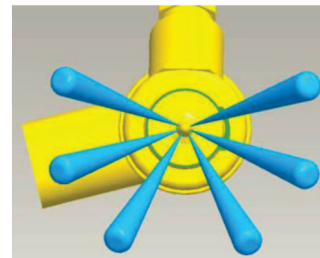


**Figure 5. Special nozzle for gasoline direct injection in automotive applications**

## Air Assisted Direct Injection

The air assisted injection system was a commercially available system for scooter applications. The associated compressor was replaced by stationary pneumatic pressure generation with maximum pressure of 0.5 MPa. The fuel was provided by a commercially available fuel pump with up to 0.8 MPa. The application of the air assisted injection system is shown in [Figure 6](#).