

High Injection Pressures at the Upper Load Limit of Stratified Operation in a DISI Engine

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ABSTRACT

This paper presents the results of investigations that were carried out on a single-cylinder spray-guided direct injection engine. The effects of injection pressures of up to 1000 bar on combustion and emissions at the stability limit of stratified load are presented. It is known that at low engine speeds, problems in mixture preparation occur due to insufficient in-cylinder motion at higher loads in stratified charge operation. Additionally, adverse effects appear at high engine speeds due to limited time for vaporization and mixture formation. Therefore, investigations at various engine speeds ranging from 2000 to 4000 rpm were performed. As a baseline, a production multihole injector is compared with an injector that has been specially adapted for higher injection pressures.

INTRODUCTION

Spark ignition engines with direct injection, especially those that employ a spray-guided combustion strategy, demonstrate strong potential for improved fuel efficiency and therewith CO₂-emissions in part-load operation. This benefit results primarily from lean, unthrottled operation, which is realized with a highly-stratified mixture at part load. State of the art production engines with second generation spray-guided combustion systems are equipped with expensive outward-opening piezo injectors [1,2]. On the contrary, DI-engines that operate homogeneously are typically equipped with multihole solenoid injectors [3]. A limiting factor for the operation of stratified charge engines that use multihole injectors is the time necessary for injecting the required fuel mass at higher loads. When compared with outward opening piezo injectors at these higher loads, only insufficient

charge stratification is achieved with multihole injectors [4]. The longer injection timings, combined with the deep penetration of fuel into the combustion chamber and the slow rate of vaporization lead to locally-increased air-fuel ratios and, as a result, longer burning durations and increased hydrocarbon, carbon monoxide and soot emissions. One promising approach to using multihole injectors at higher loads with naturally-aspirated stratified charge operation is to increase the injection pressure.

EXPERIMENTAL SETUP

The test apparatus is a single-cylinder research engine with a centrally-positioned fuel injector for stratified operation (Figure 1). The crankcase and cylinder unit are based on a single-cylinder production engine from Rotax.

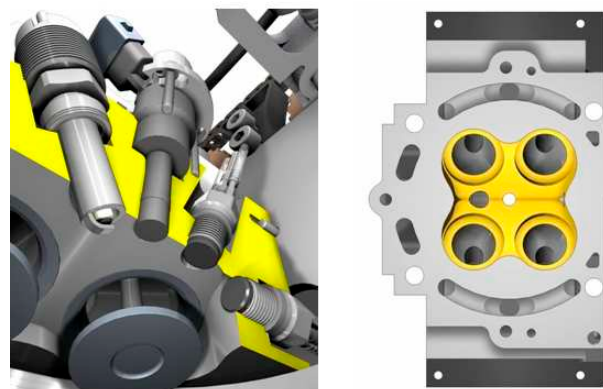


Figure 1: Cylinder Head Layout

The cylinder head was especially designed for spray-guided combustion at the Institut fuer Kolbenmaschinen in Karlsruhe. The cylinder head design features a relatively large squish area of approximately 20 % of the cross-sectional area of the cylinder; this counteracts the slow burnout of the lean air-fuel mixture in stratified operation. The charge motion induced when the flat-topped piston nears the squish area at the end of the compression stroke increases the turbulence intensity and pushes the mixture towards the center of the combustion chamber. The technical specifications of the engine are shown in Table 1:

Table 1: engine data

Operating mode	4-stroke gasoline
Displacement	652 cc
Bore x stroke	100 mm x 83 mm
Con-rod length	149 mm
Compression ratio	11.0 : 1
Intake-valve head diameter	31 mm
Exhaust-valve head diameter	31 mm
Intake-valve opening	12 °CA BTDC
Intake-valve closing	122 °CA BTDC
Exhaust-valve opening	130 °CA ATDC
Exhaust-valve closing	4 °CA BTDC

To eliminate the influence of residual gas on the results, the valve timing was set with minimal overlap. Cooling water and oil temperatures were set to 90 °C. The fuel used was premium gasoline with a research octane number of 95. All of the results presented here represent an average of three individual measurements, each of which is comprised of 200 consecutive cycles. In every case, spark timing was adjusted for best fuel consumption.

As a baseline, investigations were performed with a standard inward-opening multihole HP injection valve (HDEV 1.2) from Bosch. The spray pattern was optimized for spray-guided operation in terms of stability, fuel consumption and emissions. The injection pressure was held constant at 200 bar.

For the subsequent investigations with high injection pressures, various modifications had to be performed. The entire fuel system was customized to operate with a maximum pressure of 1000 bar. Therefore, several components were adapted from a diesel engine, including the high-pressure pump, fuel rail, pressure sensor, pressure control valve and injector. Special fuel

feed pipes and a specially-designed pressure control unit were constructed. The tip of a common rail solenoid diesel injector CRI1 was modified to have the same spray pattern as the baseline HDEV. Figure 2 shows the spray with 6 nozzle holes that are positioned around the spark plug; the spacing between adjacent spray jets is 40°, except for a 62° gap where the spark plug is positioned. The angle between any spray jet axis and the injector axis is 37°.

Due to the wide range of injection pressures used in this work, the nozzle hole diameters of the CRI1 had to be adapted. The minimal injection duration of this injector is 350 µs. To enable a net IMEP of 3 bar with an injection pressure of 1000 bar, the diameter of the nozzle holes had to be reduced from 0.18 mm, which is the diameter of the HDEV, to a diameter of 0.1 mm. As a result, the highest achievable net IMEP with a 200 bar injection pressure is 6 bar, because the maximum allowable hold time of the injection end stage is reached. The flow rate of the HDEV is rated at 512 g/min with a fuel pressure of 100 bar, while the CRI1's flow rate at the same fuel pressure is only 232 g/min as a result of its smaller nozzle holes. Further information about the spray characteristics of the modified CRI1 injector can be found in [3].



Figure 2: Spray geometry of the common rail injector CRI1

To evaluate the influence of increasing injection pressures on engine-out soot emissions, two soot measurement systems were utilized. By default, the AVL 415S Smoke Meter is used in the test bench. Due to the fact that even in stratified operation, the soot emissions from DISI engines are very low, an additional measuring system was added. The AVL 483 Micro Soot Sensor is a photoacoustic system for continuous measurement of minimal soot concentrations of as low as 5 µg/m³ (equivalent to FSN=0.0004).

ENGINE RESULTS

The intention of these investigations is to show the effects of increased injection pressures on combustion and emissions at higher loads. The experiments are performed at the stability limit of spray-guided operation.

LOAD SWEEP - As a first step, a load sweep at 2000 rpm and starting at 3 bar net IMEP was performed. To show the development of emissions with increasing load, the results performed with the HDEV at 200 bar are compared with those of the CRI1 at an injection pressure at 1000 bar. For comparison's sake, measurements in homogeneous operation were carried out with the HDEV. The limit of this sweep was defined by a Filter smoke number of greater than 0.15 FSN, which is intolerable for a spark ignition engine [7].

Figure 3 shows the results of this load sweep. The results of the production injector in stratified and homogeneous mode are compared with the results of the measurements with the CRI1. The specific fuel consumption in stratified operation is on the same level in both cases.

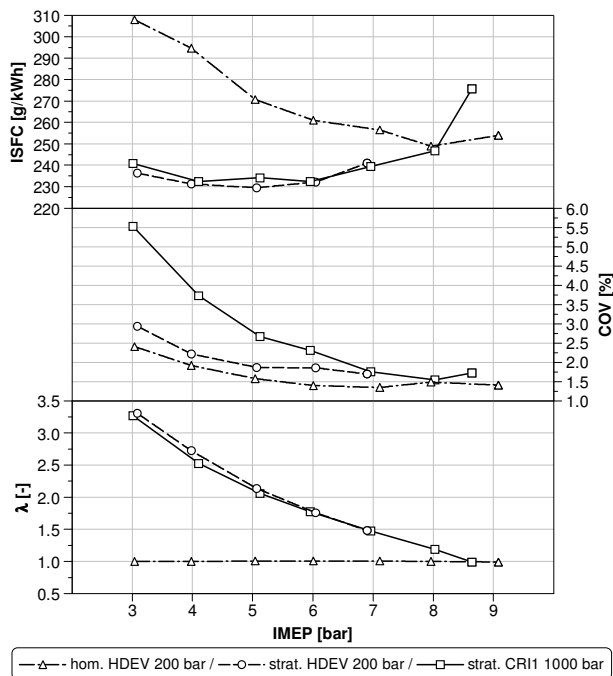


Figure 3: Load sweep at 2000 rpm, homogeneous and stratified mode, injection pressures of 200 and 1000 bar

In stratified load, the HDEV sets the benchmark for coefficient of variation in net IMEP. With the CRI1 at 1000 bar injection pressure, the coefficient of variation of net IMEP, especially at lower loads, is higher. Even with identical spray patterns, different flow rates occur for the same injection pressure because of the previously-described different nozzle hole diameters. This is also caused by differences in the designs of the two injectors.

The HDEV exhibits higher flow rates than the CRI1 at a given load with the same injection pressure. This enables shorter injection durations with the HDEV. At a net IMEP of 3 bar and an injection pressure of 200 bar, the injection duration of the HDEV is $t_{inj} = 900 \mu s$, whereas with the CRI1, the hold time is significantly longer at $t_{inj} = 1730 \mu s$. By increasing the injection pressure to 1000 bar, the injection duration drops to $t_{inj} = 405 \mu s$. The minimal injection duration of the CRI1 is $t_{inj} = 350 \mu s$, so at a net IMEP of 3 bar, it is operating at its lower limit. The CRI1's poor COV at lower loads is a result of a very short mixture formation time and variations in injected fuel mass from shot to shot. At low loads, the variance in the actual injection time becomes more significant compared to the short injection time. For the 3 bar net IMEP case, measurements with an IAV Injection Analyzer have shown fluctuations in the actual amount of fuel injected of $\pm 7\%$ of the desired amount. With increasing load and therefore longer injection times, this variance becomes less significant. The COV decreases until the load limit of net IMEP 8 bar is reached.

Figure 4 shows the emissions trends with increasing load. In the case of stratified operation at 200 bar injection pressure, soot emissions increase slowly until reaching 6 bar net IMEP. At a net IMEP of 7 bar, the measured FSN is 0.209, above the set limit (FSN = 0.15). With 1000 bar injection pressure, the soot emissions are at the lower detection limit of the Smoke Meter, even at 8 bar net IMEP.

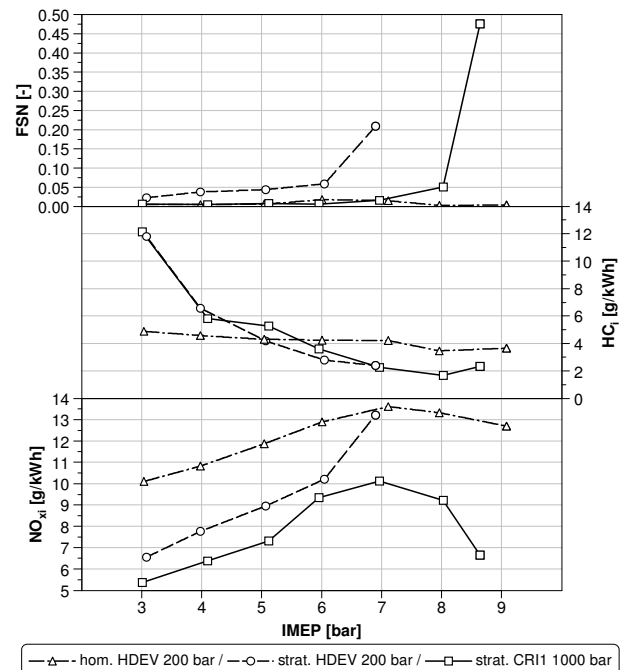


Figure 4: Load sweep at 2000 rpm, emissions

At this load, acceptable charge stratification is still generated. A marginal advantage in fuel consumption in