

Experimental Investigation of the Influence of Boost on Combustion and Particulate Emissions in Optical and Metal SGDI-Engines Operated in Stratified Mode

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ABSTRACT

Boosting and stratified operation can be used to increase the fuel efficiency of modern gasoline direct-injected (GDI) engines. In modern downsized GDI engines, boosting is standard to achieve a high power output. However, boosted GDI-engines have mostly been operated in homogenous mode and little is known about the effects of operating a boosted GDI-engine in stratified mode.

This study employed optical and metal engines to examine how boosting influences combustion and particulate emission formation in a spray-guided GDI (SGDI), single cylinder research engine. The setup of the optical and metal engines was identical except the optical engine allowed optical access through the piston and cylinder liner.

The engines were operated in steady state mode at five different engine operating points representing various loads and speeds. The engines were boosted with compressed air and operated at three levels of boost, as well as atmospheric pressure for comparison. The fuel used was market gasoline (95 RON) blended with 10% ethanol. The spark plug and injector were mounted in parallel with the intake valves. The gas motion induced by the engine head was primarily tumble motion with a small amount of swirl.

Results on particulate emissions indicated that nucleation mode particulates increased with increasing boost. In contrast, agglomeration mode particulates decreased with increasing boost pressure. The combustion was found to consist of a yellow flame in the center of the combustion chamber and a pre-mixed blue flame in the perimeter. The optical studies indicated that the flame area decreased with increasing boost.

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INTRODUCTION

Increasing concerns regarding global warming and environmental pollution have stimulated more restrictive emission legislation and a demand for better fuel efficient vehicles. Currently in Europe, there is a legal limit on CO₂ emissions (which directly correspond to fuel consumption) of 130 g/km. This limit is planned to be decreased to 95 g/km in 2021 and will most likely be reduced even further. Alongside the CO₂ limits, other emissions are currently regulated by legislation, e.g., Euro6, which was introduced in Europe in September 2014. Counterparts to the European emission legislation exist in other parts of the world.

The increasing demands for reduced fuel consumption have led to the introduction of new powertrain technologies, such as hybridization and electric vehicles. Even though alternatives exist, a vast amount of development work is still invested in the internal combustion engine. One area of interest is the operation of gasoline engines in more beneficial combustion modes compared to the traditional stoichiometric homogenous mode, e.g., lean homogenous or lean

stratified modes. The latter combustion mode is the focus of this study. In the stratified mode, fuel is injected late in the compression stroke in order to generate an ignitable cloud of fuel in the proximity of the spark plug. In theory, such a fuel cloud will be surrounded by air, which acts as an insulator and reduces heat losses to the combustion chamber walls. This late injection of fuel removes the need to reduce the air mass inside the chamber, thus reducing pumping losses and the need for throttling.

Spray-guided gasoline direct-injected (SGDI) engines operated in stratified mode have been shown to emit large quantities of particulates [1]. Several factors may contribute toward high levels of particulate emissions, including fuel impinging on the walls of the combustion chamber and improper fuel mixing generating locally rich mixtures. One way to address these issues is to utilize boost overpressure for the intake air charge.

The influence of boost on emissions and combustion has been investigated in previous studies performed on gasoline direct-injected (GDI) engines operated in stratified mode [2-3, 4]; in studies by

Kneifel et al. [2, 3], a SGDI engine was used, whereas Wirth et al. [4] utilized a wall-guided GDI engine. These two engine types behave differently in terms of spray targeting. In both cases, the goal is to create an ignitable fuel cloud in the vicinity of the spark plug. However, the SGDI engine utilizes the injector to direct fuel toward the spark plug, whereas the wall guided engine utilizes an optimized piston shape to direct fuel toward the spark plug. The above studies found that the upper load limit of stratified operation could be extended owing to the increased air mass and also investigated the fuel smoke number (FSN), which was found to decrease with increasing boost pressure. However, the studies obtained contradictory results regarding nitrous oxides (NO_x): Wirth et al. reported an increase in NO_x with boost, whereas Kneifel et al. reported only a slight influence with increasing boost pressure. Conflicting results were also obtained regarding hydrocarbon (HC) emissions: Wirth et al. observed an increase with increasing boost, whereas Kneifel et al. observed a decrease with increasing boost. These results may be explained by the differences in the spray targeting system mentioned previously. In one of the studies, the spatial spread of the fuel cloud was simulated as a function of the cylinder pressure [2]. The fuel cloud was found to be more compact with increasing cylinder pressure. This suggests that the amount of fuel impinging on the piston could then be theoretically lowered, thus leading to lower particulate emissions. However, Kneifel et al. also argued that a compact fuel cloud might lead to insufficient evaporation, which would not be beneficial for the mixing process.

Studies by Hemdal et al. have also shown that soot oxidation slows down in the late stages of stratified combustion [5]. An increased combustion rate obtained with boosting may therefore enhance soot oxidation, and thereby reduce soot emissions.

The present study contributes to the field of stratified operation in boosted GDI engines by investigating the influence of boost on particulates and standard emissions. The study examined a single cylinder research engine in both metal and optical configurations. The aim was to provide an insight into how the use of boost and associated increased cylinder pressure influence emissions by employing optical investigations. However, the study did not account for the increased losses encountered when operating a belt or exhaust driven boosting device, as would apply in real applications.

EXPERIMENTAL SETUP

Engines

Two single-cylinder research engines were utilized in this study: one engine had an optical configuration, whereas the other had a full metal configuration. The optical engine incorporated optical access through the piston top and the cylinder liner. The engine setups were kept as similar as possible by utilizing the same engine head design with respect to gas motion and combustion chamber design. Both engines used the same type of fuel injection system and spark plugs, as well as alignment between them. The valve timing and valve lift profiles were the same for the two engines. The engine settings and hardware were also kept as similar as possible between the two engines. [Figure 1](#) shows the engine head with optical access, whereas [Figure 2](#) shows the engine head in the full metal configuration.

Both engines were operated on standard 95 RON gasoline blended with 10% ethanol. The engines were operated with 10 CAD of valve overlap to avoid trapping of exhaust gases as internal exhaust gas recirculation.

The full metal engine was boosted by a motor driven roots blower, whereas the optical engine was boosted using compressed air obtained from the compressed air supply in the local facilities. No charge cooling was utilized in any of the engines. The differences between the two charging systems most likely affected the intake air temperatures, with the metal engine subjected to higher temperatures than the optical engine. However, the tests were performed at two locations with different facilities, hence the use of different charging systems. The implications of this are discussed later.

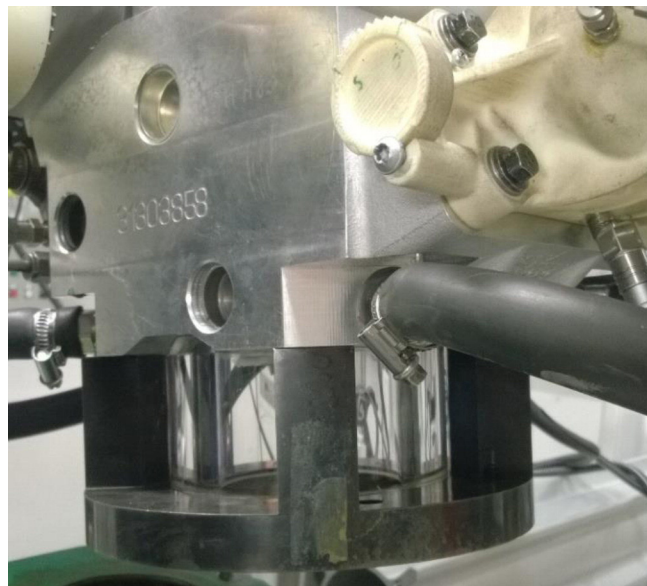


Figure 1. Engine head and liner with optical access



Figure 2. Engine head without optical access

The engines used were SGDI engines with the specifications presented in [Table 1](#).

Table 1. Engine specifications

Engine type	Spray-guided gasoline direct-injected
Displaced volume	475 cm ³
Bore	82 mm
Stroke	90 mm (metal), 92 mm (optical)
Number of valves	4
Compression ratio	10.6:1 (metal), 10.8:1 (optical)
Charge motion	Tumble with a small amount of swirl
Piston type	Bowl with valve clearance pockets (metal), flat (optical)
Connecting rod length	143.8 mm
Spark plug	Single electrode
Fuel injector	Six holes, solenoid actuated
Fuel injection pressure	200 bar

An ignition system with extended spark duration was utilized. The ignition system was constructed around two ignition coils with alternating discharge, allowing a spark duration of 2000 μ s. The spark plug was oriented with the electrode gap facing toward the fuel injector. This configuration was found to give the best results in terms of ignitability and combustion stability of this combustion system. The fuel spray was targeted so that the rays would not impinge on the spark plug. The setup of the spark plug and fuel spray is presented in [Figure 3](#).

The metal engine was equipped with high speed pressure sensors at the intake, cylinder and exhaust. The optical engine was equipped with high speed pressure sensors at the intake and the cylinder.

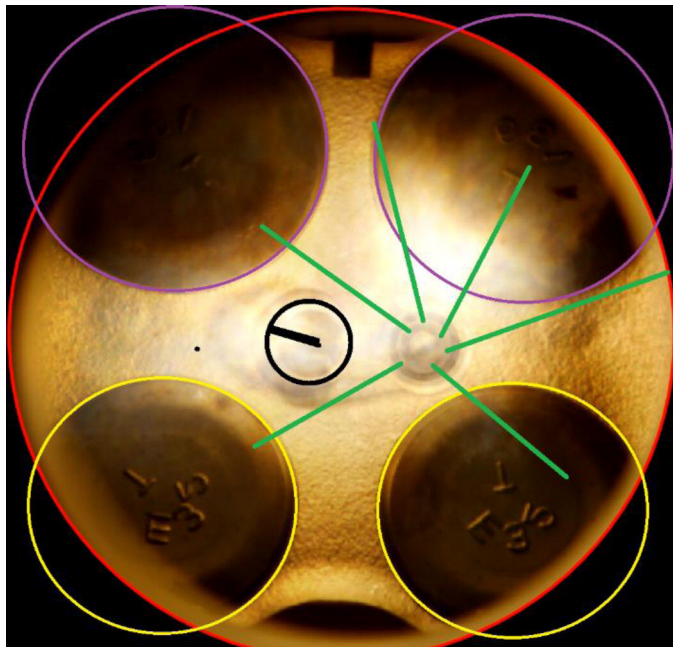


Figure 3. Image of bottom view through the piston with valves and spray targeting system marked with green lines. The intake valves are marked with purple circles and the exhaust valves are marked with yellow circles. The total possible image area is marked by a red circle.

Emission Testing

The engine with full metal configuration was used for emission sampling. The sampling points for emissions were located approximately 30 cm downstream of the exhaust valves. Two outlets were used to direct emission samples to either a particulate measurement system or standard emissions measurement equipment. Particulates were sampled using a Cambustion DMS500 MKII fast particle analyzer, which operates according to the electrical mobility principle. The sampling point was connected to the stock sample conditioning system of the DMS500 MKII, which consisted of a primary diluter, a 5 meter heated hose and a rotary disc diluter. The sampling system was operated at specific temperatures in order to keep nucleation and agglomeration processes in the sampling system to a minimum. The primary diluter and the heated hose were operated at 130 °C. The rotary disc diluter was operated at a temperature of 30 °C. Standard emission measurement systems used in this study are listed in [Table 2](#).

Table 2. Standard emissions measurement equipment

HC	Jum Engineering Model VE7
CO	Maihak Unor 611
CO₂	Maihak Unor 6N
NO_x	Eco Physics CLD 822 M hr
O₂	Maihak Unor 611
Exhaust pump	Jum Engineering Model 222

Optical Engine Setup

The high speed camera utilized in this study was a Phantom V7.3 operated at a resolution of 608x600 pixels and frame rate of 8316 fps. The optical engine allowed optical access through the cylinder liner and the piston top via an elongated piston. The optical engine design was of the “Bowditch” type, as illustrated in [Figure 4](#).

An example of an image captured through the piston is shown in [Figure 3](#).

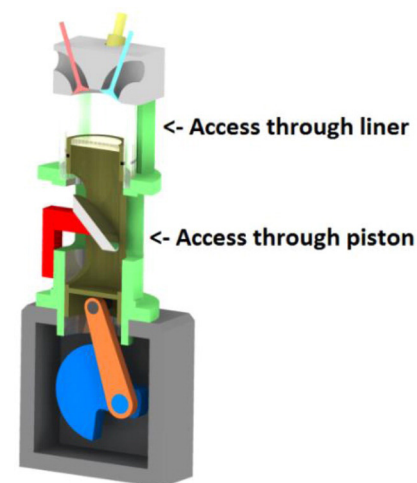


Figure 4. Diagram of optical engine setup

EXPERIMENTAL METHODOLOGY

Tests were performed on two engines, one optical and one metal engine. Both engines were operated at five different engine operating points, as indicated in [Table 3](#), and at various boost pressures ranging from 0 to 0.6 bar at intervals of 0.2 bar. The combustion phasing was held at 0 CAD for 50% Mass Fraction Burned (MFB) by utilizing high speed cylinder pressure sensors in combination with AVL Indicom pressure analyzing software. The ignition and fuel injection events were held as close as possible without endangering misfire free combustion. Fuel injection pulse width was decreased slightly (by maximum ~ 0.1 ms) with increased load at the high load operating points (4 bar BMEP) in order to maintain the engine load. At all other engine operating points, the fuel injection pulse width was kept constant. The impact of the changed fuel injection pulse width is discussed later in this article.

Table 3. Engine operating points

Number	Speed [rpm]	BMEP [bar]
1	1000	1.5
2	1000	4
3	2000	1.5
4	2000	4
5	1500	2.5

All tests in the metal engine were performed according to the following requirements:

1. Each measurement case was run for at least 3 minutes until all values had stabilized and data sampled.
2. Particulate measurements were performed for at least 3 minutes at a rate of 1 Hz.
3. A total of 200 cylinder pressure curves over the full engine revolution (720 CAD) were sampled for each measurement case.
4. An average over the last 100 seconds of the standard emission values was calculated for each measurement case.
5. The sampling order of all measurement cases was randomized.
6. All measurement cases were repeated at least three times.

Engine operating points were considered stable if they fulfilled the criteria presented in [Table 4](#).

Table 4. Engine operation stability criteria

std (net IMEP) for net IMEP < 3.3 bar	0.1 bar
CV (net IMEP) for net IMEP > 3.3 bar	5 %

Due to limitations in the design of the optical engine, steady state operation of this engine was not possible. Instead, the engine was operated in sequences where the injected fuel mass and ignition were adjusted to mimic the operating conditions of the metal engine with respect to 50% MFB, which was held at around 0 CAD for both the optical and metal engine. When appropriate fuel and ignition timing was achieved, the combustion was recorded with high speed cameras. The engine was operated for approximately 30-40 cycles to allow

some heating before the high speed camera recording was initiated. Approximately 30-60 cycles were recorded for each engine operating point before the engine temperature reached critical values and combustion ceased.

Evaluation Method

Movies from the high speed cameras were recorded and processed into a raw image file format with RGB representation for analysis in Mathworks Matlab software. Each frame of the movie was converted to an image. A Matlab script was used to analyze all frames to distinguish blue and yellow flames: blue flames were used as an indicator of pre-mixed flames, whereas yellow flames were used as an indicator of fuel-rich flames where soot was formed. The yellow color of a flame is due to incandescence of black body radiating soot particles. As soot constitutes the majority of particulate emissions, the study of yellow flames can provide useful information about particulate emissions of stratified combustion. Thresholds were set to identify which pixels could be regarded as yellow, blue or other color. All pixels in the images were examined and the number of blue and yellow pixels compiled.

Stratified combustion ranges from a small portion of lean combustion with low intensity to a fuel-rich flame with high intensity. Capturing both of these modes photographically requires a trade-off between not saturating the image due to the high intensity fuel-rich flame and still capturing the low light intensity lean combustion. The combustion chamber of an optical engine should also be kept free from soot to allow undisrupted optical access through the piston and liner. The glass and metallic parts therefore reflect light from the combustion. When the fuel-rich flame reaches the highest intensity, the whole combustion chamber and liner may therefore appear yellow or even white due to the reflection, which might be mistaken for a flame. To avoid over-estimation of the flame size, the threshold for identifying yellow pixels was increased as the intensity of the flame increased. In such situations, a small amount of information will inevitably be lost. However, we took extensive lengths to minimize such losses. [Figure 5](#) shows three examples of areas that might be mistaken for flames. The majority of the flame occurs in the center of the combustion chamber. The intensity of the flame in this image is high enough to saturate the picture. Arrow number one indicates an actual flame but instead of it being part of the main flame, it is only a satellite-flame that illuminates the surrounding. The surface to the left of the flame reflects light from the flame and has to be accounted for when identifying the extent of the flame. Arrows 2 and 3 indicate areas that are approximately as yellow as the main flame at the beginning of the combustion process. The exact criteria for judging a flame were therefore adjusted throughout the cycle based on the maximum intensity of the flame.

Due to irregularities in the direction of flame development, as shown later in [Figure 18](#), averaging of the images proved difficult. Averaging frames captured at the same CAD for different cycles tended to produce an image where the flame appeared transparent. Thus, few raw images of the actual combustion are presented. Instead, mean values were calculated by identifying the flame in each frame and then calculating the mean flame size over all cycles.