

Reduction of Soot Formation in an Optical Single-Cylinder Gasoline Direct-Injected Engine Operated in Stratified Mode Using 350 Bar Fuel Injection Pressure, Dual-Coil and High-Frequency Ignition Systems

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ABSTRACT

The current trend toward more fuel efficient vehicles with lower emission levels has prompted development of new combustion techniques for use in gasoline engines. Stratified combustion has been shown to be a promising approach for increasing the fuel efficiency. However, this technique is hampered by drawbacks such as increased particulate and standard emissions.

This study attempts to address the issues of increased emission levels by investigating the influence of high frequency ionizing ignition systems, 350 bar fuel injection pressure and various tumble levels on particulate emissions and combustion characteristics in an optical SGDI engine operated in stratified mode on isoctane.

Tests were performed at one engine load of 2.63 bar BMEP and speed of 1200 rpm. Combustion was recorded with two high speed color cameras from bottom and side views using optical filters for OH and soot luminescence.

The results indicated that increasing the fuel injection pressure led to faster burn as well as a reduction in soot luminescence. The ionizing ignition system generated faster initial combustion. Increasing the tumble level reduced the soot luminescence at all injection pressures, but the influence was largest at the lowest fuel injection pressure. The combination of an ionizing ignition system and high fuel pressure was most beneficial for lowering soot luminescence.

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INTRODUCTION

Increasingly stringent emission legislations and demands for lower fuel consumption in passenger vehicles have led to the development of new powertrain technologies. One such technology that can reduce fuel consumption at low to medium load and engine speed is stratified operation. Stratified operation is utilized in gasoline direct injected engines (GDI). In stratified operation, fuel is injected late in the compression stroke, in contrast to early in the intake stroke for homogenous operation. Ideally, by injecting late in the compression stroke, a cloud of ignitable mixture can be created in the vicinity of the spark plug, thus reducing the risk of over-diluting the mixture, which can lead to ignitability issues. Because a cloud of ignitable mixture is created, there is no need to reduce the air mass in the cylinder. Therefore, the engine can in theory be operated at wide open throttle, thus reducing the pumping losses that occur in an engine operated in homogenous mode at low to medium load. However, stratified operation may be hampered by issues regarding combustion stability [1][2], particulate emissions [1][3][4] and NOx emissions[1]. To gain a better understanding on how to reduce these issues, data from optical engines are useful.

Stratified operation is characterized by a short delay between fuel injection and the ignition event. The time window where ignition is possible is defined from the time at which the air-fuel mixture is ignitable, shortly after the end of fuel injection, to the time where the air-fuel mixture is too lean to be ignited. In practice, the spray from the fuel injection and the spark are subject to cyclic variations, which causes them to vary in both time and space. These variations are small but have an impact on the ignitability and combustion stability. The variations are thought to be caused by, for example, variations in air motion, spark initiation and spray formation. The combustion stability depends on both the ignitability and fuel mixing process occurring after the ignition event. Therefore, stratified combustion may, in the worst cases, suffer from a too rich mixture in the center of the flame and an over-lean flame in the perimeter. Too early ignition will result in more soot due to the small time for fuel evaporation, whereas too late ignition will result in ignitability problems.

Particulate emissions consist mainly of soot formed in the combustion process. The amount of soot an engine emits depends on the relation between how much soot is formed and how much is oxidized. In stratified operation a large part of the fuel is oxidized in

a fuel-rich environment, which generates soot. Fuel-rich combustion is characterized by yellow flames originating from the black body radiation of soot particles. The fuel injection process is characterized by atomization and subsequent evaporation, as well as interaction with the air motion. Increased evaporation is beneficial for reducing soot owing to increased fuel and air mixing. The evaporation process is, in turn, benefited by smaller droplets from the atomization process. A higher level of atomization is achieved by, for example, increasing the fuel injection pressure. Currently, most GDI engines on the market utilize a fuel pressure of around 130-200 bar. Recently, Volkswagen introduced a new 1.5 liter FSI engine that utilizes a fuel injection pressure of up to 350 bar and several manufacturers are likely to follow. The trend within GDI engines is toward higher fuel injection pressures.

A further issue associated with stratified combustion is NO_x emissions. NO_x emissions are in general higher in stratified mode than in homogenous mode. NO_x is formed in regions with high temperatures and excess air. However, this only applies up to a lambda value of 1.2. Above this value, NO_x emissions decrease. In stratified operation, the air-fuel mixture is inhomogeneous, with a fuel-rich mixture in the center and a lean mixture at the perimeter of the fuel cloud. Therefore, conditions where NO_x can be formed are only fulfilled in parts of the fuel cloud. If the fuel cloud could be made more homogenous and at a lambda value above 1.2, NO_x emissions could theoretically be reduced. Stratified operation is also characterized by low exhaust temperatures. Even though the engine out levels of NO_x is reduced, a standard three way catalyst cannot operate in conditions with excess air. Thus other ways of reducing NO_x has to be introduced in lean operating regimes. Such methods include Selective Catalyst Reduction (SCR) or Lean NO_x traps. Also in some cases in combination with boosting, the temperatures can reach levels as low as 120 °C [5]. Low exhaust temperatures may be problematic for the exhaust after treatment system, which has to operate above a minimum temperature to function properly.

In this study, the abovementioned issues with particulate emissions and combustion stability were studied by using an increased fuel injection pressure, novel ignition systems and various tumble motion levels. A fuel injector allowing a maximum injection pressure of 350 bar was studied together with two ignition systems, i.e., a dual coil ignition (DCI) system allowing an increased spark duration and a high frequency ignition (HFI) system. The engine utilized was a single cylinder optical research engine with a spray-guided direct-injection (SGDI) system.

Increased fuel injection pressure has been studied by Buri et al. [6]. They investigated the influence on particulate emissions by measuring filter smoke number (FSN) as a function of increasing injection pressure. They found that particulate levels decreased substantially with injection pressure up to 500 bar and then the FSN flattened out. The study utilized modified diesel injectors, which produced a fuel spray different from that of a gasoline injector. Utilizing a gasoline injector designed for 1000 bar would most likely result in a more suitable fuel spray. The influence of fuel injection pressure on the particulate size distribution has also been investigated by Johansson et al. [1]. They investigated the influence on particulate emissions at three injection pressures, i.e., 100, 150 and 200 bar.

They found that the size of the particulates remained nearly constant but the amount of particulates decreased with increasing fuel injection pressure.

One way to increase the likelihood of successful ignition is to improve the ignition process. The simplest way to do this is to increase the power of the spark, but more refined systems are available. The environment around the spark plug is harsh, with high air velocities, liquid fuel, and sometimes also wet electrodes. All these factors hamper spark development, and may extinguish it. Single coil systems are usually incapable of reigniting an extinguished spark because of the low residual energy levels in the coil. One way to overcome this problem is to use multi-spark systems. For example, Daimler [7] use a multi-spark system in their direct injected gasoline engines that can operate in stratified mode. The definition of multi-spark ignition systems encompasses both systems that fire several sparks in succession and those with extended spark durations. Systems of both kinds are intended to increase the time during which a spark is present to increase the chance of successful ignition. The fuel cloud's composition and distribution change constantly as it shifts and moves. Consequently, there is no guarantee that the spark will be close to an ignitable mixture at any given point in time. Increasing the spark's duration increases the likelihood that it will come into contact with an ignitable fuel mixture at some point. Delphi [1] has published a study comparing single spark ignition systems to more advanced multi-spark ignition systems which suggests that multi-spark systems increase robustness during stratified operation. Another useful technology is so-called Corona discharge systems. These systems differ substantially from conventional spark plugs: whereas a spark plug generates a spark between a center and a ground electrode, a Corona ignition system fires into free air. In a normal spark ignition system, the spark is the result of an electric breakdown, which requires a lot of energy to create. The Corona ignition system instead ionizes the surrounding air-fuel mixture with an alternating current, which creates an electric discharge. This allows the system to deliver more energy to the igniting mixture and to maintain a spark over a long period. Perhaps more importantly, it permits the formation of multiple ignition points because the spark does not jump between electrodes as in a conventional spark plug. This means that successful ignition can be achieved even if the fuel cloud is spread across a relatively large volume, as is normally the case during stratified operation. DCI and HFI ignition systems have been examined in several studies, e.g., [1] [8][9][10][11]. Both systems were found to increase the combustion stability and reduce misfires. Of the two systems, HFI systems performed best in terms of increased combustion stability with less cyclic variation. One issue associated with dilution of the air/fuel mixture, with either air or EGR, is the ignitability limit will be reached. All the studies showed that the ignitability limit can be extended with HFI systems. HFI systems can also help to shorten the burn duration. In the study by Pineda et al. [12] on a boosted single cylinder research engine operated in homogenous mode, use of a HFI system was found to decrease the cycle-to-cycle variability and promote more complete combustion. However, little is known about the influence on stratified combustion from an optical point of view.

This study aimed to contribute to the field of stratified combustion by investigating the influence of novel ignition, injection and combustion systems in a single cylinder optical research engine. The study attempted to address the issues of combustion stability, particulate emissions and NOx emissions associated with stratified combustion.

EXPERIMENTAL SETUP

Engine

A single cylinder optical research engine was utilized in this study. The engine allowed optical access through the piston and cylinder liner. The engine head was also modified to allow optical access through the pent-roof part of the combustion chamber. Stratified operation can sometimes benefit from a piston with a bowl to direct and center the fuel cloud toward the ignition. However, the engine used in this study was designed for homogenous operation, and therefore utilized a piston with a flat head. A flat piston head is also beneficial for distortion free optical access. The specifications of the engine are presented in Table 1.

Table 1. Engine specifications

Engine type	Spray-guided gasoline direct-injected
Displaced volume	489 cm ³
Bore	82 mm
Stroke	92 mm
Number of valves	4
Compression ratio	10:1
Charge motion	Tumble motion
Piston type	Flat
Connecting rod length	143.8 mm
Spark plug	Single electrode / 5 electrode HFI system
Fuel injector	Six holes, solenoid actuated
Fuel injection pressure	175/350 bar

As discussed in the introduction, a GDI engine operated in stratified mode has to also allow the homogenous mode to offer a satisfactory operating range. In practice, the main differences between the two modes are in the spray targeting and air flow. In the homogeneous mode, the fuel spray targeting is wider than desirable for stratified operation and the piston also lacks the bowl for concentrating the fuel spray. The air flow is also optimized for a regular spark plug rather than for the HFI system, which extends slightly longer into the combustion chamber. The engine was operated at a maximum fuel pressure of 350 bar on isooctane. Isooctane was chosen owing to restrictions in the engine rig. It is worth to mention that isooctane in general has lower tendency to form soot due to its molecular properties in comparison to gasoline which consists of several different chemical species. The results in this paper are therefore not directly applicable to gasoline but serves to indicate trends.

The engine head was equipped with an adjustable flap to vary the air flow from a tumbling motion with ultra-high intensity to tumbling motion with high intensity. In Figure 1 normalized values of the tumble levels and Turbulent Kinetic Energy are presented for the two tumble levels.

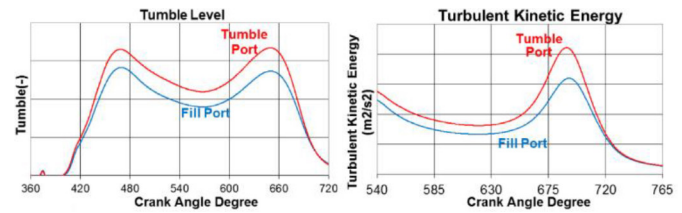


Figure 1. Transient CFD results for the two tumble levels of this engine head: Tumble level (left) and Turbulent Kinetic Energy (right).

A similar engine head has been used in a study by Ogink and Babajimopoulos [14] where a more thorough description of the engine head design is presented.

Cylinder pressure sensors were utilized in conjunction with a real-time system to monitor combustion characteristic variables. In Figure 2 an image of the combustion chamber of the engine head utilized in this study is presented. The image has the same orientation as all piston view images presented in this study with the exhaust valves in the upper part of the image and the intake valves in the bottom. The left of the holes in the middle is for the spark plug and the right is for the injector.



Figure 2. Image of combustion chamber layout used in this study.

Ignition Systems

In stratified combustion, the type of ignition system is even more crucial than in homogenous combustion. Two different ignition systems were used in this study: a DCI system utilizing a regular spark plug and a HFI system. The DCI system was built around two ignition coils, which were charged and discharged continuously during the ignition event. This technique enables the spark duration to be extended without deteriorating the energy level while still using a conventional spark plug.

The HFI system, normally referred to as “volume ignition”, was based on the technology of Corona discharge. The system consisted of a spark plug with five electrodes (without corresponding ground electrodes) and a control unit. In this type of system, each electrode ionizes the surrounding gas, which results in several ignition points. The Corona discharge occurs when the strength of the electrical field around the electrodes is high enough. However, the strength should not be so high as to cause electrical breakdown or flash-over, as happens with a conventional spark plug. Therefore, this technology allows more energy to be put into the ignition process than with a conventional spark plug. The ignition event of both the DCI and HFI systems are depicted in [Figure 5](#).

Optical Engine Setup

An optical engine with a Bowditch design was utilized in the tests. The engine allowed for optical access through the piston and cylinder liner. Two cameras were used: a Phantom Miro M310 and a Vision Research V7.3. A schematic of the optical engine setup is shown in [Figure 3](#).

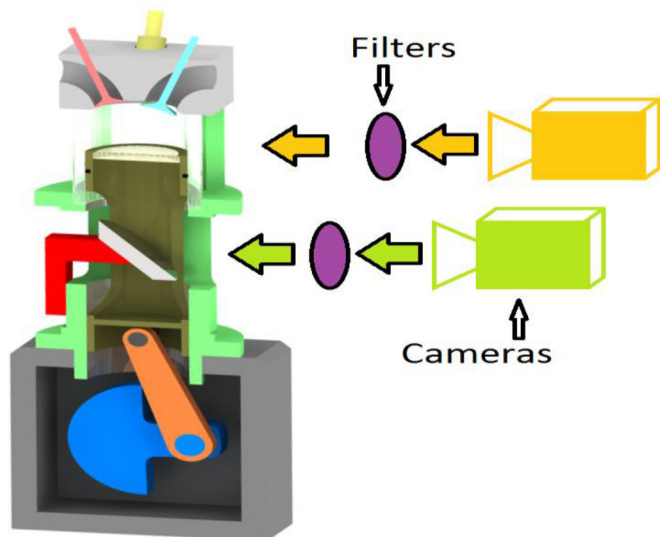


Figure 3. Illustration of the optical engine measurement setup.

Videos of the combustion process were recorded through the cylinder liner and piston top. Combustion from both the side and bottom views was recorded with a 308 nm OH narrowband filter, a high-pass filter of 610 nm or without a filter. The OH narrowband filter was utilized in conjunction with a Hamamatsu C9548 image intensifier. The OH narrowband filter was used to visualize the flame development, whereas the 610 nm high-pass filter was used to visualize areas where soot was oxidized. Videos were sampled with a frame rate of 6000 fps and a resolution of 512x512 pixels. Side view videos were recorded for approximately 70 cycles, whereas bottom view videos were recorded for approximately 100 cycles.

EXPERIMENTAL METHODOLOGY

The engine was operated in semi steady-state mode. It should be noted that whereas a metal engine can be operated at steady state, an optical engine can only be operated for a limited number of cycles to avoid mechanical failure. Therefore, an optical engine will never

reach true steady state. This means that the combustion characteristics, e.g., in-cylinder temperature, will never be identical to the corresponding load case in a metal engine. In this study, the optical engine was operated for about 50 cycles before filming was initiated. These initial 50 cycles were chosen based on combustion information from the real-time sampling system.

The combustion phasing was held at 6-7 CAD for 50% MFB for the tests with a fuel pressure of 175 bar and low tumble. Stratified combustion is typically phased at between 0 and 20 CAD for 50% MFB, where the latter is often found in cold start operation. However, a phasing of 6-7 CAD was chosen as it is a commonly used value for homogenous operation to simplify comparisons. To restrict the number of parameters influenced and maintain similar conditions, the ignition timing was held constant for all operating points. The injection timing was advanced closer to the ignition timing at 350 bar fuel injection pressure owing to the shorter injection delay. By doing this, the influence of the cylinder pressure and piston position was reduced. Consequently, with a smaller burn duration, as was the case for 350 bar fuel injection pressure, the timing for 50% MFB occurred earlier than at 175 bar of fuel injection pressure. All load points were operated with a maximum CoV of net IMEP of 5%. The engine was operated at a single engine operating point of 1200 rpm and with an injected fuel mass that would result in a load of 2.63 bar BMEP in a multi-cylinder engine.

The DCI system was operated with a spark duration of 2000 μ s and a current of 10.1 A. The HFI system was operated at a current just below flash-over and a frequency of 50 Hz. All measurement cases are presented in [Table 2](#). Each of the measurement cases was filmed through both the bottom and side views with the 308 nm narrow-band filter, 610 nm high-pass filter or without a filter. The videos recorded in the two different views were not simultaneously filmed.

Table 2. Engine operating conditions.

No.	Tumble	Injection Pressure	Ignition system
1	High	175 bar	DCI
2	Ultra-high	175 bar	DCI
3	Ultra-high	350 bar	DCI
4	High	350 bar	DCI
5	High	350 bar	HFI
6	Ultra-high	350 bar	HFI
7	Ultra-high	175 bar	HFI
8	High	175 bar	HFI

Evaluation Method

Videos of the combustion recorded in the optical engine were analyzed in Mathworks Matlab. Each video frame was converted to RGB-images for analysis of the flame. A floating threshold for each RGB-value was set and the flame was identified based on this threshold. The flame area was summed and plotted as a function of CAD. The averaged images presented show the combustion chamber as seen from below, through the piston; the upper part is the exhaust-side and the lower part is the intake side. The spark plug was located to the left of the centrally mounted injector.