

Combustion Stratification with Partially Premixed Combustion, PPC, Using NVO and Split Injection in a LD - Diesel Engine

Slavey Tanov, Robert Collin, and Bengt Johansson
Lund Univ.

Martin Tuner
Lund Univ.

ABSTRACT

Partially Premixed Combustion (PPC) is used to meet the increasing demands of emission legislation and to improve fuel efficiency. PPC with gasoline fuels have the advantage of a longer premixed duration of fuel/air mixture which prevents soot formation at higher loads.

The objective of this paper is to investigate the degree of stratification for low load (towards idle) engine conditions using different injection strategies and negative valve overlap (NVO). The question is, how homogenous or stratified is the partially premixed combustion (PPC) for a given setting of NVO and fuel injection strategy. In this work PRF 55 has been used as PPC fuel.

The experimental engine is a light duty (LD) diesel engine that has been modified to single cylinder operation to provide optical access into the combustion chamber, equipped with a fully variable valve train system. Hot residual gases were trapped by using NVO to dilute the cylinder mixture. Optical measurements were carried out for OH chemiluminescence imaging to track sequentially the combustion process and to analyse the degree of stratification. Initial results show that the combustion with triple injection is more homogenous compared to single and double injection. Furthermore the results show that the 55 octane number fuel can be operated at low load condition with the lowest NVO used, 60 CAD.

CITATION: Tanov, S., Collin, R., Johansson, B., and Tuner, M., "Combustion Stratification with Partially Premixed Combustion, PPC, using NVO and Split Injection in a LD - Diesel Engine," *SAE Int. J. Engines* 7(4):2014, doi:10.4271/2014-01-2677.

INTRODUCTION

Low temperature combustion concepts as homogenous charge compression ignition (HCCI) can offer the potential of achieving high efficiency in combination with low NO_x and soot emissions [1,2]. The low emissions of soot come from the absence of rich zones required for particulate formation. In the same manner is low NO_x emission due to the low maximum temperature during the cycle. A problem with HCCI is high concentrations of Unburned Hydro-Carbons, HC, and Carbon Monoxide, CO. These can result from low temperature zones giving incomplete or partial combustion. Most of the unburned Hydrocarbons has been shown to come from crevices and only a small amount from wall quenching [3]. Another challenge with HCCI include combustion control prevent pressure rise rates. As a result new branches of HCCI arose, spark assisted compression ignition (SACI) and partially premixed combustion (PPC) [4,5]. SACI is defined as an intermediate process between SI flame propagation and HCCI auto ignition [6]. HCCI mode can be achieved through trapping of hot residual gases with early exhaust valve closing. The intake valve is opened

symmetrically later after top dead centre. The interval in crank angles from exhaust valve closing to intake valve opening is called negative valve overlap (NVO). The idea to use negative valve overlap for HCCI was first proposed by Willand et al. [7] in 1998 and demonstrated by Lavy et al. [8] in 2000.

Partially premixed combustion can be considered as an intermediate process between the fully mixed HCCI concept and conventional spray and diffusion controlled compression ignition (diesel) combustion [9,10,11,12]. The benefit compared to traditional HCCI combustion is that the fuel injection timing can be used as control parameter for the combustion timing. It should not be fully mixed as combustion rate will be high. On the other hand should fuel be mixed enough to prevent overly rich mixtures that forms soot and stoichiometric zones giving NO_x. The PPC is normally generated by applying direct fuel injection rather late in the cycle. Fig. 1 shows the principle. With very early fuel injection there is time enough to mix and combustion will be HCCI-like. With very late fuel injection there is no time to mix sufficiently and it will be a classical CI event

with high concentrations of NO_x emissions. With fuel injection early enough to mix to some extent the charge will be partially premixed i.e. PPC [13].

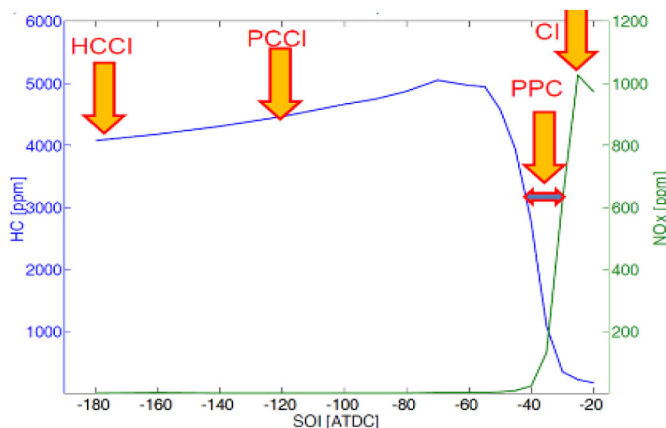


Figure 1. The effect of unburned fuel, HC and nitric oxides NO_x when fuel injection timing (SOI) is changed from early (-180) to late (-20)

In 2006 Kalghatgi [14] published the concept of gasoline PPC. He announced, the combustion is better with fuels that have a high resistance to auto-ignition, because the higher ignition delay allows more time for mixing of the fuel and oxygen before combustion starts. Results from a light-duty engine were published in [10,12,15].

At Lund University, Manente et al. [2,8,9] developed a gasoline PPC strategy running a variety of gasoline fuels with different octane numbers in a heavy duty engine. Gross indicated efficiencies up to 57 % with low NO_x, HC and CO emissions and soot levels below of 0.5 FSN were demonstrated. Light duty engine experiments were performed in [9]. He demonstrated in a heavy-duty engine, there is a clear decrease in attainable gasoline-PPC engine operating region with increased fuel octane number in [8]. The challenge is to operate the engine with high octane number fuels at low engine speed where the available boost is expected to be limited. There are different ways to try to expand the attainable operating region, for example, using more advanced injection strategies and negative valve overlap to trap hot residuals.

The objective of this work was to find the stratification level by employing different injection strategies such as single, double and triple injection together with negative valve overlapping. The aim is to improve the understanding of the PPC combustion process in light duty engines. This experimental study includes also high speed imaging of the combustion process. The images were captured from below, via a mirror through the optical piston.

EXPERIMENTAL APPARATUS

Engine Setup

The engine used in this investigation is based on a Volvo D5, which is a five cylinder compression ignition (CI) engine. The engine was converted to single cylinder operation with a Bowditch [5,16] piston extension. The remaining four pistons are motored and are equipped with counter weights to compensate for the extra mass of the piston elongation.

The engine speed were controlled by an alternating current (AC) dynamometer. The inlet temperature was controlled with an electrical heater in the intake manifold.

The engine was fitted with a pneumatic valve train system supplied by Cargine [13,17,18]. It had the features of fully flexible valve lift, duration and timing. And it can control each valve individually. In this work a 60 to 180 CAD symmetrical NVO was used, but the results will be shown only for the NVO 60 setup. Intake closing and exhaust opening have been fixed at 160 cad BTDC and 160 CAD ATDC respectively. External EGR was not used. Table 1 shows the engine parameters.

Table 1. Engine parameters

Displaced volume	480 cc
Stroke	93.2 mm
Bore	81 mm
Compression ratio (metal configuration)	16.5:1
Compression ratio (optical configuration)	11.3:1
Number of Valves	4
Fuel	PRF 55 (55% Iso- octane, 45 % n- heptane)
Valve Timings	Fully flexible
Exhaust Valve Open	34° BBDC @ 0.15 mm lift
Exhaust Valve Close	6° BTDC @ 0.15 mm lift
Inlet Valve Open	2° BTDC @ 0.15 mm lift
Speed	800 rpm

Optical Engine Setup

For the optical investigations the operational cylinder was equipped with a Bowditch design. The original piston was replaced by a fused-silica (FS) piston crown, which has the bowl like in the production Volvo D5 piston. The FS piston crown allows an imaging from below the piston during combustion process, through a 45 degree mirror which is placed in the slot of the piston extender.

Some injection strategies cause the temperature of the optical parts to become quite high after some time and a too high temperature would lead to failure of the glass. The engine thus is equipped with a thermocouple mounted directly onto the

glass ring in order to monitor the temperature and see if it becomes dangerously high; if that happens, the measurement would be halted and restarted at a later time.

For the high speed measurements, a Phantom camera is used, equipped with a Hamamatsu image intensifier, a 105mm UV-Nikkor lens and an OH interference filter to capture the chemiluminescence of OH radicals. The camera settings can be found in [Table 2](#).

Table 2. Camera Data

Frame rate	9367 pps
Chip resolution	368x600
Exposure time	50 microseconds
OH interference filter	310nm
FWHM	10nm
f – number	5.6
Number of images per cycles	10

Cylinder Pressure

During recording all combustion image events the cylinder pressure was simultaneously recorded at every 0.2 CAD. The heat release model is based on the first law of thermodynamics for a control volume using the recorded cylinder pressure trace. Heat transfer was estimated by using the Woschni equation [19].

Operating conditions

The experimental study is focused on determining the degree of stratification for very low load (towards idling) gasoline PPC using different injection strategies and constant NVO setting. The fuel used is Primary Reference Fuel with 55% iso-octane and 45% n-heptane (PRF55)

The measurement points are chosen such that the conditions are comparable to previous measurements performed with the Volvo D5 engine in the conventional metal configuration (without the optical components). The [Table 3](#) shows the main experimental conditions used in this study. Different injection strategies were chosen:

- A. single injection
- B. main + pilot injection
- C. triple injections

Table 3. Operating condition used for the study in which the injection strategy was varied

CASE	SOI [CAD BTDC]	Duration [μs]	NVO [CAD]	Inlet Pressure [bar]	Lambda [-]	Inlet Temper- ature [°C]
A	60	600	60	1.3	3.5	80
B	60/6	410/380	60	1.3	3.5	80
C	50/28/ 5	310/310/ 430	60	1.3	3.5	80

The engine was run at 800 rpm, using a constant rail pressure of 500 bar. The optical engine was skip-fired with only one injection event every 10 engine cycles in these experiments. This approach was used to reduce the risk of window failure due to the corresponding thermal and mechanical stresses. Since the compression ratio of the engine in optical configuration is lower than in metal configuration as shown in [Table 1](#), the intake pressure were increased up to 1.3 bar to get nearly the same peak in-cylinder pressure for the motored pressure trace compared to the reference pressure trace. As mentioned above an electrical heater was used to control the inlet temperature at approximately 80°C. For Case C an early injection strategy at around 50 crank angle degrees (CAD) before top dead centre (BTDC) was chosen, which creates a charge that is well premixed. A second injection was used to control the combustion phasing and the last injection to work as an actuator for main heat release. Combustion phasing (CA 50) was kept at 5 CAD after TDC.

For the control of combustion stability NVO was used. The NVO strategy incorporates early exhaust valve closing (EVC) and late intake valve opening (IVO) in order to retain large quantities of residuals. NVO thereby provides, in an efficient manner, the usual thermal and dilution advantages of residual retention [18].

For the injection strategies described above the NVO was set to 60 CAD. Lambda was approximately 3.5 at NVO 60 CAD.

Image Processing

The aim is to estimate the degree of stratification of the combustion for the different injection strategies and NVO settings, by using chemiluminescence imaging. For each operating point 10 images are collected and the measurement interval reaches from -10 to 30 CAD ATDC.

The images below obtained with the high speed camera and are showing the inside of the combustion chamber with the engine standing still ([Fig. 2](#) and [Fig. 3](#)). In [Fig. 3](#) a sheet with a grid of dots is used to illustrate the asymmetric distortion in the centre of the combustion chamber.