

Comparison of Negative Valve Overlap (NVO) and Rebreathing Valve Strategies on a Gasoline PPC Engine at Low Load and Idle Operating Conditions

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ABSTRACT

Gasoline partially premixed combustion (PPC) has the potential of high efficiency and simultaneous low soot and NO_x emissions. Running the engine in PPC mode with high octane number fuels has the advantage of a longer premix period of fuel and air which reduces soot emissions. The problem is the ignitability at low load and idle operating conditions.

In a previous study it was shown that it is possible to use NVO to improve combustion stability and combustion efficiency at operating conditions where available boosted air is assumed to be limited. NVO has the disadvantage of low net indicated efficiency due to heat losses from recompressions of the hot residual gases. An alternative to NVO is the rebreathing valve strategy where the exhaust valves are reopened during the intake stroke. The net indicated efficiency is expected to be higher with the rebreathing strategy but the question is if similar improvements in combustion stability can be achieved with rebreathing as with NVO.

The results show that the rebreathing valve strategy has similar improvements on combustion stability as NVO when the same fuel injection strategy is used. This work also includes results with the NVO valve strategy where a fuel injection is added during the NVO. When a fuel injection is added during the NVO, an additional improvement on combustion stability can be seen which is unmatched by the rebreathing valve strategy.

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INTRODUCTION

Homogeneous charge compression ignition (HCCI) combustion has the potential of achieving high efficiency in combination with low NO_x and soot emissions. The challenges with HCCI include combustion control, low power density and steep pressure rise rates. As a result, two branches of HCCI emerged, spark assisted compression ignition (SACI), and partially premixed combustion (PPC). SACI is the intermediate process between SI flame propagation and HCCI auto ignition. HCCI mode is typically achieved through trapping of hot residual gases with early exhaust valve closing. The intake valve is usually opened symmetrically after top dead center. 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. [1] in 1998 and was demonstrated by Lavy et al. [2] in 2000.

PPC combines traditional diesel combustion with HCCI. With PPC, the fuel injection is completed before start of combustion to promote mixing of fuel and air, but the charge is not homogeneous. One benefit compared to traditional HCCI combustion is that the fuel injection timing can be used as control actuator for the combustion timing. In order to get enough separation from start of injection to start of combustion with diesel fuel, a high fraction of EGR has to be used. This concept was used by Nissan [3] and is called Modulated Kinetics (MK). Toyota used high EGR rates to suppress both soot and NO_x with the smokeless rich diesel combustion concept [4]. In a different concept, as an alternative to using excessive EGR rates, Toyota used a double injection system with some of the fuel injected early to promote mixing with air. This concept is called UNIBUS [5, 6].

Kalghatgi introduced the concept of gasoline partially premixed combustion in 2006 [7, 8], and something similar was shown by Johansson in 2005 [9]. With a fuel that is harder to ignite, a longer mixing period from end of injection

to start of combustion can be achieved without using high EGR fraction, very early injection timing or very low compression ratio. Results from a light-duty engine were published in [10,11,12]. At Lund University, Manente et al. [13, 14] 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 as well as soot levels below of 0.5 FSN were reported. Light duty engine experiments were reported in [15].

At Delphi Corporation, Sellnau et al. [16, 17] achieved higher efficiency with gasoline compared to diesel in a single cylinder light duty Hydra engine with a gasoline direct injection compression ignition (GDCI) strategy using an optimized triple injection strategy. At low load operating condition, a rebreathing valve strategy was used to expand the low load limit.

As demonstrated in a heavy-duty engine, there is a clear decrease in attainable gasoline PPC operating region with increased fuel octane number [14]. One alternative strategy is to use two fuels with different auto-ignition properties. At University of Wisconsin - Madison, the reactivity controlled compression ignition (RCCI) strategy has been investigated [18,19,20,21,22]. The low cetane number fuel, for example gasoline, is typically port injected and the high cetane number fuel is direct injected. The idea is to adjust the auto-ignition properties of the fuel depending on engine speed and load.

The focus of this work is gasoline PPC. Only the gasoline fuel is used and it is direct injected. Running gasoline PPC with higher octane number fuels at low load and idle operating conditions is a challenge. At low load and engine speed operating conditions it can be assumed that the available boost is limited and that reaching auto-ignition conditions will be difficult with a standard turbo-charger. There are different tools that can be used to extend the attainable operating region, for example, using more advanced injection strategies, using for example NVO or rebreathing valve strategies to trap hot residuals, and to use a glow plug. The focus of this work is on the valve strategies. Application of NVO is usually associated with SACI and is used to achieve HCCI combustion in a spark ignition engine [23,24,25,26]. PPC is a diesel engine concept and it is not aimed at achieving traditional HCCI. The compression ratio is higher compared to what is usually seen with SACI and there is no spark plug (there is usually a glow plug).

In previous work by Borgqvist et al. [27,28,29] it was found that it was possible to operate the light duty diesel engine with 87 RON gasoline fuel down to approximately 2 bar IMEP_{gross} with a significant fraction of trapped hot residual gases. The low load limit could be extended from approximately 3.2 bar IMEP_{gross} down to 2.2 bar IMEP_{gross} by increasing NVO. The penalty with NVO is the decrease in gas-exchange efficiency due to increased heat losses from recompression of the residual gases. More advanced injection strategies have been investigated as an alternative to NVO. The conclusion was that a more

advanced injection strategy could match combustion stability of the high NVO case but the combustion efficiency is higher with NVO regardless of injection strategy. A second approach is to use a different valve strategy. In this work a rebreathing strategy is used where the exhaust valves are reopened during the intake stroke. If the residual gases are first exhausted and then re-inducted during the intake stroke, recompression of the residual gases is avoided. But the question is if similar improvements of combustion stability and efficiency can be achieved with rebreathing as with NVO. According to Lang et al. [30] the charge mixture is more stratified and the temperature is higher with the NVO strategy compared to the rebreathing strategy. But this comparison was made for the CAI combustion concept. With PPC it can also be expected that the temperature is lower with the rebreathing strategy due to an expected lower residual gas temperature after re-induction. But the charge mixture stratification is expected to be high because of the relatively late fuel injection timing. In this work, results with a rebreathing strategy at low engine load and engine speed in comparison with the NVO strategy is presented.

In this first comparative investigation, a single fuel injection strategy is used. But an opportunity that is available with the NVO valve strategy is fuel injection during the NVO to promote fuel reformation. Urushihara et al. [31] were able to extend the lean limit of HCCI by injecting a portion of the fuel in the NVO. An investigation with a NVO injection strategy for low load gasoline PPC is presented after the NVO and rebreathing comparisons. And these results are finally compared to the rebreathing and NVO results with a single injection with emphasis on the possibility of low load limit extension of gasoline PPC in a light duty engine.

EXPERIMENTAL APPARATUS AND SETUP

The experimental engine is based on a Volvo D5 light duty diesel engine. The engine properties can be seen in Table 1. It is run on only one of the five cylinders and is equipped with a fully flexible pneumatic valve train system supplied by Cargine Engineering. The Cargine valve train system was first demonstrated by Trajkovic et al. [32]. The valve actuators are placed on an elevated plate above the fuel injector and are connected to the valve stems with push-rods. Intake valve closing (IVC) timing is constant, 180 CAD BTDC @ 1 mm valve lift, and exhaust valve opening timing is constant, 180 CAD BTDC @ 1 mm valve lift. Maximum valve lift is approximately 5 mm. The fuel injection system is a common rail system with a 5 hole nozzle solenoid injector. The umbrella angle is 140 degrees and the nozzle hole diameters are 0.159 mm.

The engine control system was developed by the author in LabVIEW 2009. The control system is run from a separate target PC, NI PXI-8110, which is a dedicated real-time system. The target PC is equipped with an R series multifunctional data acquisition (DAQ) card with re-

programmable FPGA hardware, NI PXI-7853R, and an M-series data acquisition card, NI PXI-6251. The user interface is run on a separate Windows based host PC. The host and target PCs communicate over TCP/IP. In-cylinder pressure and valve lift curves are measured simultaneously with the FPGA DAQ card. The in-cylinder pressure and valve lift curve measurements are crank angle based with resolution 0.2 CAD/sample. For each operating point 500 cycles are collected. Post-processing of the data is made in Matlab.

Table 1. Engine Properties.

Displacement (one cyl.)	0.48 Liters
Stroke	93.2 mm
Bore	81 mm
Compression ratio	16.5:1
Number of Valves	4
Valve train	Fully flexible
Fuel	87 RON gasoline

Experimental data is collected with varying settings of NVO from 60 CAD to 220 CAD and with varying settings of rebreathing with a second exhaust valve opening duration from 0 to 110 CAD. The NVO and rebreathing valve lift curves are seen in [Figure 1](#) and [Figure 2](#), respectively. The valve open speed is fast compared to conventional systems. In order to ensure valve clearance around top dead center a minimum NVO of 60 CAD is used. The same minimum NVO is used also for the rebreathing valve strategy. The consequence is that the 0 CAD rebreathing case is the same as the 60 CAD NVO case. With the current setup of the valve control system there is also a limit on the shortest possible valve open duration that can be used. For this reason, the shortest rebreathing setting that is used is 50 CAD.

The contour plots were generated in Matlab with the commands *contourf* and *TriScatteredInterp* using linear interpolation. The measurement points are indicated with magenta colored circles in the contour plots.

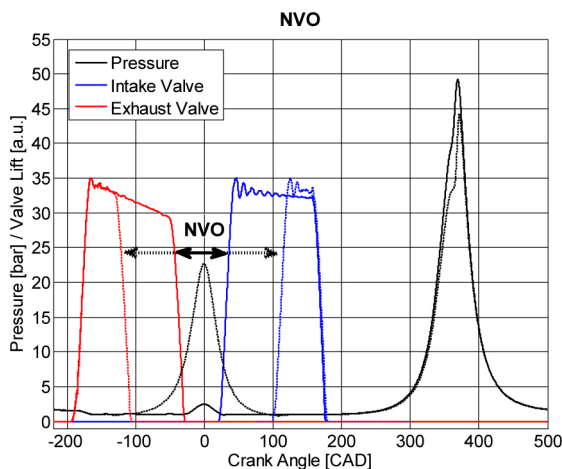


Figure 1. NVO valve strategy valve lift curves.

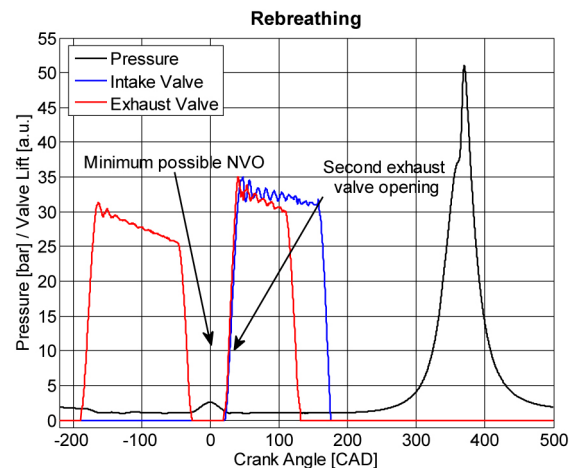


Figure 2. Rebreathing valve strategy valve lift curves.

Engine load is varied by increasing the fuel injection duration. The glow plug is continuously on. The engine is run without boosted air and without external EGR. Intake air temperature is controlled with a heater in the intake manifold to 40°C. The engine speed is 800 rpm. Lambda is calculated from air and fuel flow measurements. The air flow is measured with a Bronkhorst F-106AI-AGD-02-V air flow meter and the fuel flow is calculated from a Sartorius CP 8201 precision balance. The fuel balance is sampled for approximately 8 minutes after reaching stable operating conditions at selected operating points. The injector was calibrated assuming a linear correlation between fuel injector opening durations and the calculated fuel flows. Different fuel injection strategies were calibrated separately. At least four measurement points were sampled for each fuel injection strategy. Soot is measured with an AVL 415 smoke meter. HC, CO, CO₂ and NO_x emissions are measured with a Horiba Mexa 7500 analyzer system. The CO measurements were saturated for the most operating points presented in this work and are therefore not presented. The saturation limit of the CO measurement instrument is 10000 ppm.

RESULTS AND DISCUSSION

Valve Strategy Comparison

The NVO against rebreathing results are presented in this section. The outline of this section is to first identify similarities and differences in combustion characteristics, ignition delay, and combustion duration. And then compare combustion stability, unburned hydrocarbon emissions and finally net-indicated efficiency. The question is whether or not the rebreathing valve strategy has similar improving effects on combustion as NVO and what the gain is on efficiency. The results with the NVO strategy are discussed also in a previous work by Borgqvist et al. [28].

The engine load is varied from approximately 1.9 bar IMEP_{gross} to 3.4 bar IMEP_{gross}. The fuel that is used is an 87 RON gasoline. The fuel injection strategy is a single

injection with start of injection (SOI) at 22 CAD BTDC. At a few operating points with relatively high load, the start of injection has to be retarded in order to have combustion timing after top dead center. The common rail pressure is constant at 500 bar.

The relative air fuel ratio (λ) of the NVO and rebreathing strategy is shown in Figure 3. As expected, since there is no external EGR or boosted air, increasing NVO or rebreathing results in a larger fraction of trapped residual gases and a lower fraction of inducted air. An increase of rebreathing from 0 to 100 CAD results in approximately the same decrease in λ as is achieved from increasing NVO from 60 to 200 CAD. At the 110 CAD rebreathing case, λ is higher compared to the highest setting of NVO which can possibly be explained by a limited capability to re-induct the exhaust gases after a certain limit. There is no back-pressure valve to control the maximum possible amount of re-inducted residuals.

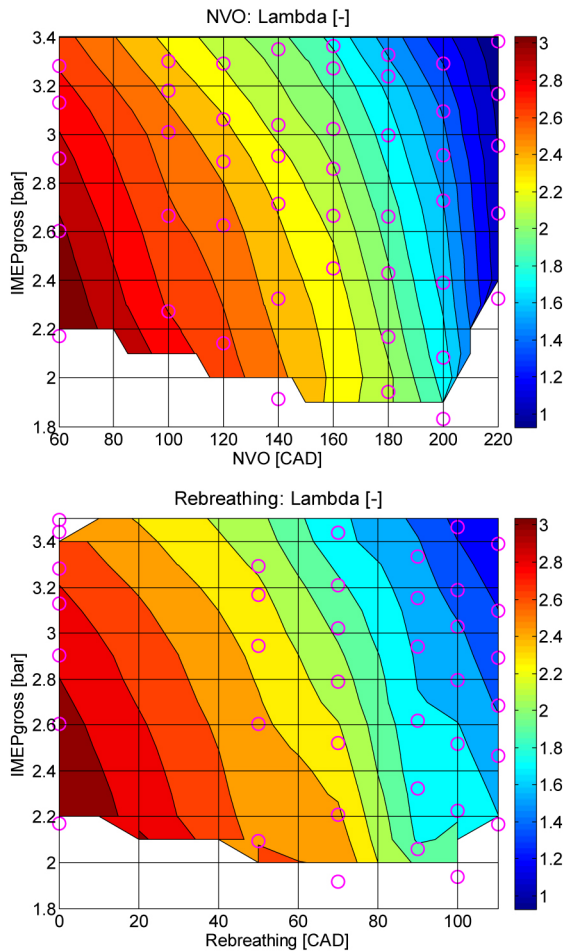


Figure 3. Relative air/fuel ratio (λ) with the NVO strategy compared to the rebreathing strategy.

The ignition delay, defined as the difference in crank angles from the crank angle of 10% accumulated heat release and start of fuel injection timing, is shown in Figure 4. Similar trends are observed with rebreathing compared to

NVO. There is an intermediate setting of NVO at relatively high engine load from 120 to 200 CAD and 50 to 70 CAD rebreathing where the ignition delay is the shortest. As already mentioned, it was not possible to collect data with a rebreathing setting below 50 CAD. The ignition delay is long with both the highest setting of NVO and rebreathing. The ignition delay of the NVO case was discussed in a previous work by Borgqvist et al. [28]. Here it is interesting to observe that similar trends are seen regardless of valve strategy.

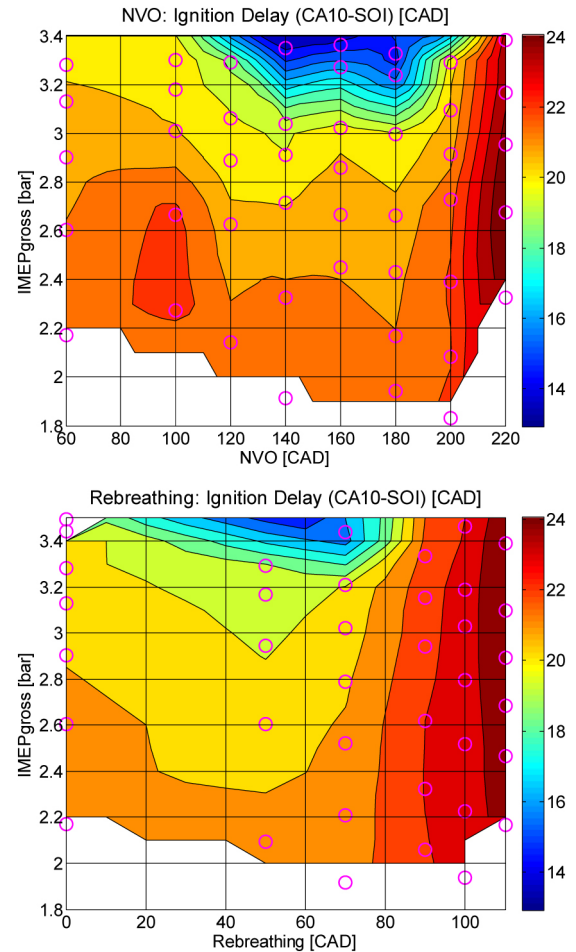


Figure 4. The ignition delay in crank angles with the NVO strategy [28] compared to the rebreathing strategy.

The combustion duration, defined as the difference in crank angles from crank angle of 90% accumulated heat release to crank angle of 10% accumulated heat release, is shown in Figure 5. Similar trends are observed also in combustion duration with rebreathing compared to NVO. The combustion duration becomes shorter with increased NVO up to 180 CAD and rebreathing up to 70 CAD. If even higher settings of NVO and rebreathing are used, the combustion duration becomes longer again. Globally, when the residual gas concentration is changed, the auto-ignition and combustion of the fuel is expected to be affected by the changes in in-cylinder temperature and oxygen concentration. If the global in-cylinder temperature is low, it takes more