Use of Late IVC and EGR to Enhance Diesel Engine Optimization

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Abstract The increasing demand for improved efficiency of diesel engines requires more advanced combustion solutions. In addition to traditional methods such as EGR, turbocharging and advanced injection systems, variable valve timing is now available at a reasonable production cost. The use of variable inlet valve timing provides an efficient way for Low-Temperature Combustion (LTC) which provides high thermal efficiency in combination of low emission levels. Furthermore, by modifying the characteristics of the charge air (i.e. by means of EGR, boost pressure and late inlet valve closing, LIVC), further hardware optimization becomes possible, e.g. by increasing compression ratio without reaching critical peak pressures. In the present study, the effect of LIVC was investigated together with the effect of EGR in a single cylinder heavy duty diesel engine. The engine was equipped with pneumatically controlled inlet valves and a high pressure common rail injector. Different injection timings and injection pressures were investigated at two different load points. The mass flow of oxygen was kept constant in order to show how the physical properties (density and temperature) affect the combustion and emission characteristics. The combustion results showed that if the oxygen mass flow is kept constant, EGR is a more efficient way (compared to LIVC) to lower the fuel consumption since it is accompanied with the largest gas flow and thus increased fuel conversion efficiency. The LIVC decreased the fuel consumption at low loads and reduced the emissions at both loads. Transportation of people and goods tend to increase and since internal combustion engines will remain a major power supply for many years to come, reduced fuel consumption is an utmost important way to decrease the CO_2 emissions and to move towards a sustainable society. The results in this study show that variable inlet valve timing can be used as one important complementary tool to obtain better combustion characteristics and thus enabling more efficient powertrains.

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Abbreviations

atdc/abdc	After/Before top dead center
CA50	50 % of total heat release
CAD	Crank Angle Degrees
EGR	Exhaust Gas Recirculation
EOI	End of Injection
IMEP	Indicated mean effective pressure
ISFC	Indicated specific fuel consumption
IVC, IVC_{eff}	Inlet Valve Close, effective Inlet Valve Close
LIVC	Late Inlet Valve closing
LTC	Low-Temperature Combustion
P_{inj}	(rail) Injection Pressure
PPCI	Partially Pre-mixed Compression Ignition
RoHR	Rate of Heat Release
SOC	Start of Combustion
SOI	Start of Injection
tdc, bdc	Top dead centre, bottom dead centre
VVA	Variable Valve Actuation

1 Introduction

The world faces grand challenges to mitigate the effects of an un-sustainable usage of fossil fuels. While alternative fuels will become more important, fossil fuel will be a major energy source for transportation in many years to come. Improved efficiency of the internal combustion engines provides one important way to reduce CO_2 emissions and present and future legislations will make an important contribution to reduce these CO_2 emissions.

There are many ways to improve the efficiency but improved combustion efficiency is often accompanied with high local temperature which results in unacceptably high NO_X emissions. NO_X is mainly formed by the Zeldovic mechanism which is favored by high temperature (as well as oxygen concentration and time). One method to reduce NO_X formation is by lowering the oxygen concentration by means of EGR. The lowered oxygen concentration will also result in lower peak temperature and significant reductions in NO_X formation can be obtained. However, EGR also slows down the combustion rate and the efficiency is not as high as for non-EGR systems. Another way to obtain lower peak temperatures is by obtaining a cooler gas mixture at the time for fuel injection. Even though charge air cooling is commonly applied, the gas compression itself inevitably rises the temperature. Yet another NO_X reduction strategy is reducing the compression stroke itself by means of changing the timing of the inlet valve closure (IVC).

This method was proposed by Ralph Miller in 1957 [1] and it appears in the literature under a variety of names depending on the technical implementation. In this study we will use the name "late Miller" even though "supercharged Atkinson cycle" is also appropriate. Since reduced compression stroke will result in lower amount of air, the volumetric efficiency will be low unless compensated for by a turbocharging system. Until recently, systems for changing the IVC haven't been economically attractive for implementation in heavy duty powertrains, but upcoming regulation changes and the need for more fuel-efficient powertrains have changed this situation. In a current EU project (CORE, CO_2 Reduction for long distance transport) [2], different Variable Valve Actuation (VVA) systems are being evaluated and promising results are being obtained by coupling the approach with an efficient turbocharging system.

Over-expanded cycles are well established [3] showing an increase in efficiency but with a decrease in IMEP and power density. The Miller cycle has been studied for the Otto-cycle (e.g. [4, 5]), the diesel cycle (e.g. [6–14]) or both (e.g. [15, 16]). The concept has also been studied for alternative fuels (e.g. [17]). Supercharging was already envisaged in the Miller patent, but in cases where fuel efficiency alone is sought the Miller cycle without supercharging (i.e. the Atkinson cycle) is applied, for example in hybrid vehicles [18].

In the literature, different aspects of various Miller cycles have been investigated. Since the lower compression ratio lowers the peak temperature, many studies demonstrate reduced NO_X emissions e.g. [6, 7, 17, 19]. Another aspect of the system to consider is the need for supercharging during high load [11, 12]. The lower cylinder pressure (i.e. lower gas density) will increase the risk of the spray hitting the wall e.g. [6, 8, 20] which could be detected by particulate matter (PM) analysis [13]. Even though many studies report on the importance of spray atomization, most studies keep the injection pressure constant (e.g. [6, 13, 21–24]. In some cases the injection pressure is varied as a means to vary the load point [7, 17, 19].

Many studies explore the possibility of having a larger amount of pre-mixed combustion (e.g. [6, 24]) and the effects of EGR to lower both NO_X and peak pressures [5, 9, 10, 12].

In this study the effect of LIVC was investigated together with the effect of EGR in a single cylinder heavy duty diesel engine. Different injection timings and injection pressures were investigated at two different load points. The mass flow of oxygen was kept constant in order to show how the physical properties (density and temperature) affect the combustion and emission characteristics.

2 Experimental

The engine was a single cylinder heavy duty diesel engine equipped with a common rail injector system (from Delphi) and a VVA system (from Cargine). The EGR was controlled by adjusting the back pressure and in the case of no EGR the back pressure was set equal to the boost pressure, as in [9]. Ultra low sulfur diesel fuel

Table 1 Single cylinder engine and nozzle specifications

Displacement	2 dm^3
Bore/stroke	131/150 mm
Geometrical compression ratio	17:1
Nozzle design	5 hole, 150° angle
Nozzle flow number	2.00, d_0 = 256 μm

Table 2 Evaluated experimental conditions

Variable	Levels
Load points	1000 rpm/120 Nm, 1500 rpm/180 Nm
IVC (set values)	0; 40; 70; (90, 110) CADabdc
EGR	0; 20; 40 %
P_{inj}	1500; 2400 bar
CA50	Approx. 2; 5; 8 CADatdc

(Swedish MK1) was used throughout this study. The engine details are given in Table 1. The common rail system was pressurized with a pumping injector and can deliver rail pressures up to 3000 bar [25]. The rail pressure, injection timing and duration was controlled by a separate software (ATI Vision).

Two different load points were investigated; one low load (1000 rpm, 120 Nm, 25 % of full load) and one medium load (1500 rpm, 180 Nm, 50 % of full load). In order to isolate the physical properties of the charge air (temperature and density) from chemical property (oxygen concentration), the oxygen flow into the cylinder was kept constant by adjusting the Boost pressure. Other factors affecting the system were explored (by applying factorial designs) over the design space by varying IVC, EGR, injection pressure and timing, see Table 2. The start of injection (SOI) was adjusted to get 50 % burnt (CA50) at three different timings.

In total, about 120 experiments were performed and a number of intermediate responses were measured along with the end performance responses which were fuel consumption (ISFC) and emission (NO_X, CO, HC and soot) results.

Emissions (NO_X, CO and HC) were measured with an AVL AMAi60 and the soot was measured with a smoke meter (AVL 415). The rate of heat release was calculated in Osiris (D2T). The fuel consumption is given as ISFC (indicated specific fuel consumption) since compressor work is not included in the system but rail pressure is included (rocker arm driven by the camshaft).

3 Results and Discussions

3.1 Analysis of Pressures and Heat Release

A few examples of Rate of Heat Release (RoHR) are given in Fig. 1 (low load, without EGR) and Fig. 2 (high load, without EGR).

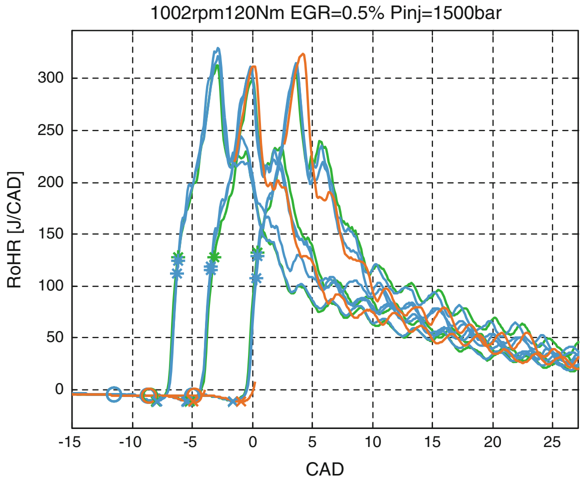

Fig. 1 Rate of heat release for experiments at low load and without EGR. *Circles* indicate SOI, *cross* indicates SOC and *stars* indicates EOI. Three different timings are displayed (CA50 = 2, 5 and 9 CADatdc). The *colors* represent different IVC (*green* $IVC_{set} = 0$, *blue* $IVC_{set} = 40$ CADabdc, *orange* $IVC_{set} = 70$ CADabdc)

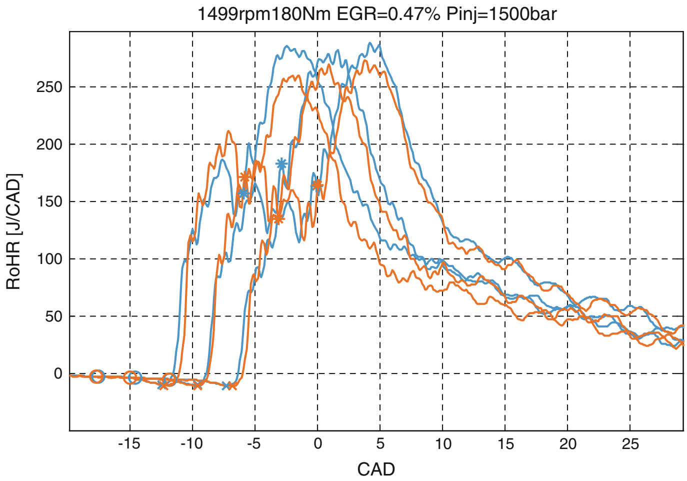

Fig. 2 Rate of heat release for experiments at high load and without EGR. *Circles* indicate SOI, *cross* indicates SOC and *stars* indicates EOI. Three different timings are displayed (CA50 = 1, 4 and 8 CADatdc). The *colors* represent different IVC (*blue* $IVC_{set} = 40$ CADabdc, *orange* $IVC_{set} = 70$ CADabdc)

The experiments at low load (Fig. 1) show more premixed combustion (the first peak of the RoHR is relatively larger than the later part) compared to the experiments at high load (Fig. 2). Generally (shown in both figures) the mode advanced (earlier) injection timings and the later IVC, the more (partially) premixed combustion is observed. The LIVC also results in faster combustion (narrower RoHR curve) which will be discussed more subsequently.

3.2 Results from the Combustion Results by Change in SOI, P_{inj} and LIVC

In order to visualize the effect of injection timing and the interaction of injection pressure and LIVC, the two load points are compared and EGR versus non-EGR at different injection pressures are compared in the figures.

In Fig. 3 it is clear that higher EGR give lower fuel consumption due to the increased gas charged into the cylinder and consequently lower temperature and less heat losses. Also the ISFC is lower at higher injection pressure (due to better fuel-air mixing and more efficient combustion). The changes in ISFC when varying LIVC are relatively small. However, from Fig. 3 it is clear that ISFC does not always decrease with increasing LIVC, e.g. at high load. The reason for different sensitivity on LIVC is because the combustion is different: In the low load case, the combustion is mainly partially pre-mixed combustion which benefices from LIVC whereas in the high load case, the combustion has more diffusion-controlled combustion and the lower temperature from LIVC is not beneficial for the ISFC.

The NO_X emissions are displayed in Fig. 4. The NO_X emissions are lower with EGR (due to the lower oxygen concentration) and NO_X emissions are also decreased by later injection (SOI) and later IVC. High injection pressure makes a

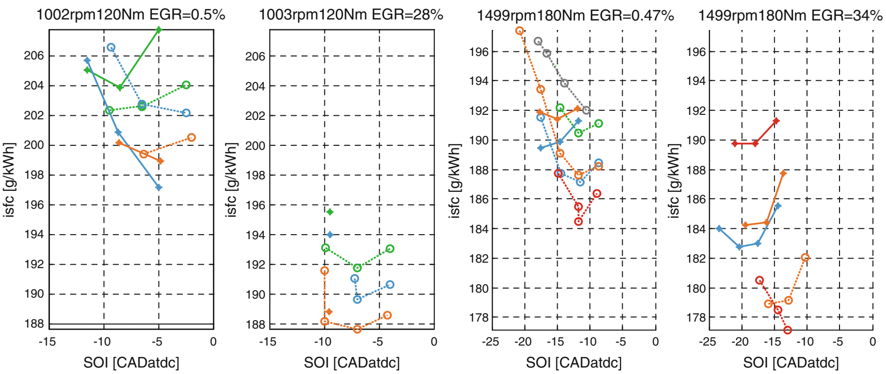

Fig. 3 Indicated fuel consumption versus SOI for two load points and different amount of LIVC, EGR and P_{inj}. Different injection pressures are indicated by *symbols* (*solid-cross* P_{inj} = 1500 bar, *dashed-circle* P_{inj} = 2400 bar). The *colors* represent different IVC (*green* IVC_{set} = 0 CADabdc, *blue* IVC_{set} = 40 CADabdc, *orange* IVC_{set} = 70 CADabdc, *red* IVC_{set} = 90 CADabdc, *black* IVC_{set} = 110 CADabdc)

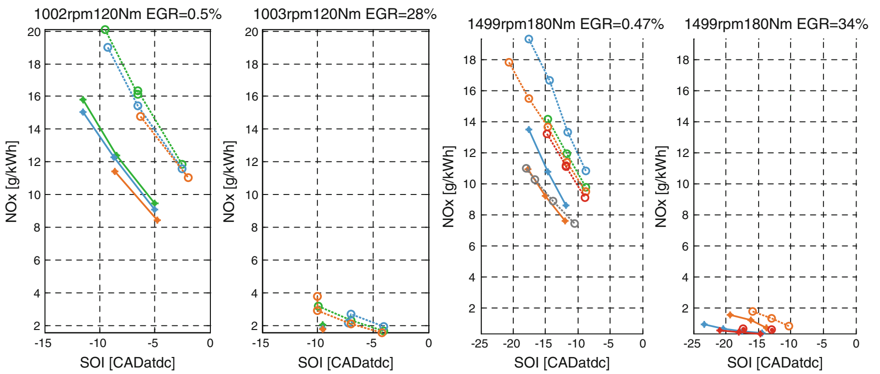

Fig. 4 NO_X emissions versus SOI for two load points and different amount of LIVC, EGR and P_{inj}. Different injection pressures are indicated by *symbols* (*solid-cross* P_{inj} = 1500 bar, *dashed-circle* P_{inj} = 2400 bar). The *colors* represent different IVC (*green* IVC_{set} = 0 CADabdc, *blue* IVC_{set} = 40 CADabdc, *orange* IVC_{set} = 70 CADabdc, *red* IVC_{set} = 90 CADabdc, *black* IVC_{set} = 110 CADabdc)

more rapid combustion and the NO_X emissions increases, especially for cases without EGR.

HC emissions (for the low load case) and PM emissions (for the high load case) are displayed in Fig. 5. The reason for displaying this combination is because the PM emissions for the low load were zero for all cases. The HC emissions for the high load shows similar trend as for the PM (increasing emissions with later SOI).

From Fig. 5 it is clear that the combustion processes are different for the two load points as already seen for the ISFC. For the low load point, the combustion improves with later IVC, since increased amount of pre-mixed combustion is

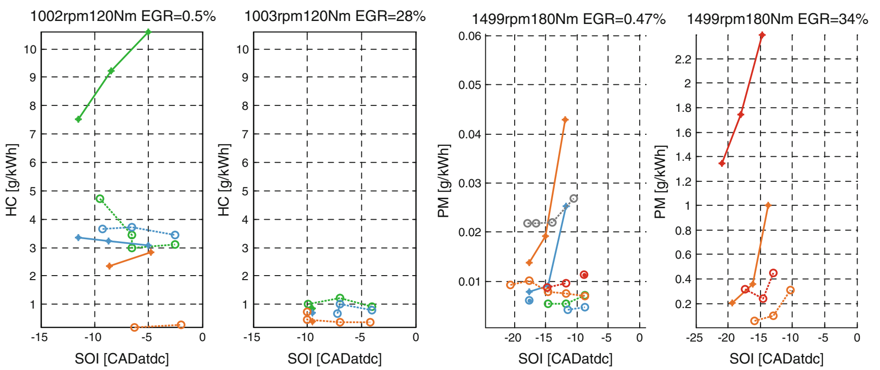

Fig. 5 HC emissions for the low load point (*left*) and PM emissions for the high load point (*right*) versus SOI and different amount of LIVC, EGR and P_{inj}. Different injection pressures are indicated by *symbols* (*solid-cross* P_{inj} = 1500 bar, *dashed-circle* P_{inj} = 2400 bar). The *colors* represent different IVC (*green* IVC_{set} = 0 CADabdc, *blue* IVC_{set} = 40 CADabdc, *orange* IVC_{set} = 70 CADabdc, *red* IVC_{set} = 90 CADabdc, *black* IVC_{set} = 110 CADabdc)

beneficial for the performance. Note that the HC emissions also decrease with increased injection pressure. This shows that improved mixing (thereby enabling more pre-mixed combustion) can be achieved by both high injection pressure as well as increased ignition delay (enabled by lower temperature for LIVC).

For the high load case, it can be concluded that the PM emissions are much higher with EGR than without. The effect of LIVC without EGR is not very clear (as seen also for ISFC), but for the EGR experiments, the PM increases with LIVC (same trend as for ISFC). Also a higher injection pressure decreases the PM emissions for the EGR case.

4 Conclusions

In the presented investigation, LIVC has been explored by varying most engine parameters except the oxygen flow. One consequence from this methodology is that higher EGR requires higher charge gas flow which gives better efficiency. From the experiments performed here, one might be tempted to conclude that EGR provides a more efficient means to reduce ISFC than LIVC, but the current experimental setup cannot prove this conclusion since the EGR is highly correlated with the gas flow. This issue is presently under investigation.

The sensitivity of the results for LIVC at different load points are somewhat different which indicates that the two load point have different types of combustion where the high load had more of a traditional Diesel combustion. Therefore, general statements of the benefits of LIVC cannot be given without characterizing the combustion conditions (such as injection pressure, Boost pressure and EGR). However, the results show that the combustion characteristics are very sensitive to LIVC. In combination with turbo charging and EGR, the use of LIVC enables independent control of the charge density, temperature and oxygen concentration. Therefore LIVC can be used as an important tool for optimizing future powertrains.

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