

Investigation of Small Pilot Combustion in a Heavy-Duty Diesel Engine

Carlos Jorques Moreno and Ola Stenlaas
 Scania CV AB

Per Tunestal
 Lund University

ABSTRACT

Factors influencing pilot-injection combustion were investigated using heat release analysis in a heavy-duty diesel engine fuelled with standard diesel fuel.

Combinations of pilot-injection parameters i.e. pilot start of injection, pilot mass, pilot-main injection separation, and rail pressure were studied for various operating conditions and combustion phases. An experiment was designed to investigate the factors influencing the combustion of the pilot. For improved injected fuel-mass accuracy, reference data for the injectors were measured in a spray rig prior to the engine experiments.

Results show that cycle-to-cycle variations and cylinder-to-cylinder variations influence pilot autoignition and the amount of heat released. Rail pressure and injected pilot mass affect the obtained variance depending on the chamber conditions. The obtained combustion modes (premixed, diffusive) of pilot combustion were found to be a function of the injected mass and rail pressure.

CITATION: Jorques Moreno, C., Stenlaas, O., and Tunestal, P., "Investigation of Small Pilot Combustion in a Heavy-Duty Diesel Engine," *SAE Int. J. Engines* 10(3):2017, doi:10.4271/2017-01-0718.

INTRODUCTION

The increasingly stringent regulations on particulate matter (soot), oxides of nitrogen (NOx) and other emissions have driven major efforts in research on closed-loop control of internal combustion engines [1]. Closed-loop combustion control aims to regulate the engine close to optimal operating conditions and to reduce the effects of external disturbances and cycle-to-cycle variations [2]. Furthermore, these methods allow the use of low emission combustion modes such as HCCI [3] or PPC [4], for which external disturbances could yield unstable behaviour [5]. Even though only common rail diesel combustion is studied in this paper, similar methods can be used to counteract disturbances such as rail pressure variations, injection quantity variations, intake conditions, mixture composition, etc. that disturb the desired (optimal) combustion.

Closed-loop combustion controllers usually use in-cylinder piezo-resistive or piezo-electric sensors to measure the pressure in the combustion chamber [6]. The in-cylinder pressure signal is used to estimate heat release during combustion [7]. An appropriate control algorithm uses this information to adjust the fuel injection timing and other actuators to regulate the engine. Load, combustion phasing [7] and NOx formation [8] are some examples of controlled variables. By controlling them, cycle-to-cycle variations can be reduced [9].

Single injection schemes are not always sufficient to control combustion. The availability of fast piezo-electric injectors with common rail technology allows multi-injection strategies [1]. Multi-injection hardware provides new degrees of freedom in combustion control. One common multi-injection scheme is the use of pilot-main injection. The pilot-injection effect on main combustion and engine performance has been investigated in a number of articles [10, 11, 12, 13, 14, 15, 16, 17, 18, 19]. The previous work shows that pilot injection can be used to reduce combustion noise for improved comfort [20, 21, 22, 23] and, if properly optimized, it can reduce oxides of nitrogen and particle emissions [20, 21, 24] with only a small penalty on efficiency [25].

The combination of in-cycle control with multi-injection strategies has been applied to split main-injection schemes. The injection pattern is controlled in-cycle by adjusting the first injection duration, the start of injection of the following injection, and its duration [7]. A number of variables have been used as a feedback reference to split the main injection. Some examples are the heat release trajectory [7] and the NOx formation trajectory from a real-time virtual sensor [26].

The factors that influence autoignition of the pilot, the heat release and the accumulated heat release were investigated. The objective is to quantify the cycle-to-cycle and cylinder-to-cylinder variation as a function of the studied variables. The results are relevant in studying the possibilities of in-cycle control taking into account the pilot

injection influence on the main injection. The results provide the necessary background to design pilot-injection controllers as well as information on how the cycle-to-cycle and cylinder-to-cylinder variations of pilot combustion can be counteracted by controlling the start of main injection and main-injection duration.

BACKGROUND

Diesel Combustion

Figure 1 illustrates the combustion process of common rail diesel combustion. Diesel combustion can be separated into four phases [27]. The fuel is injected between the start of injection (SOI) and end of injection (EOI). The combustion phases can be distinguished from the heat release rate (HR): initial jet development (physical delay and chemical delay) when the fuel starts to vaporize (SOV); triggering autoignition or start of combustion (SOC), premixed combustion and diffusive combustion, also called mixing-controlled, until end of combustion (EOC).

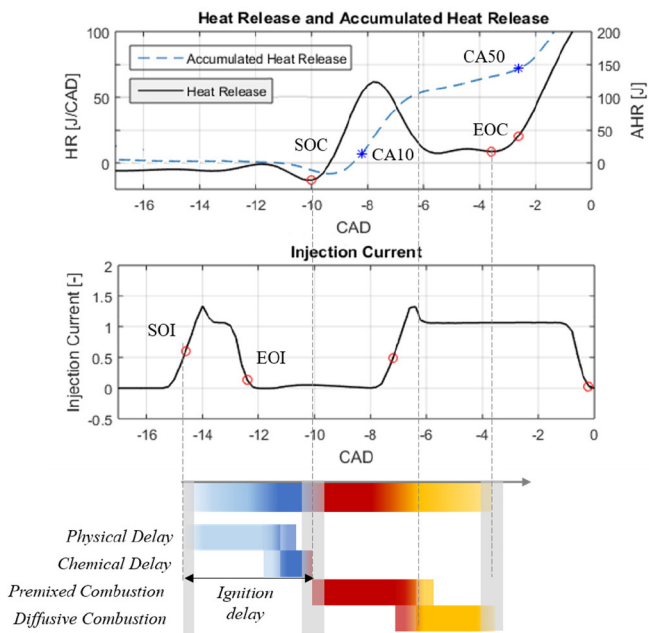


Figure 1. Heat release rate, accumulated heat release and pilot-injection traces at 1200rpm 10bar IMEP, -15CAD SOI pilot. The combustion phases are identified from the heat release. Identified combustion parameters are presented: Start of injection (SOI), start of combustion (SOC), end of injection (EOI), end of combustion (EOC), crank angle at 10%, 50% and 90% of the total heat release (CA10, CA50 and CA90). CA90 overlaps with main-injection heat release and is not plotted.

Physical delay consists of the time required for droplet break-up, air entrainment and vaporization. Even though fuel physical properties such as density, specific heat and volatility have an effect on the physical delay [28], with high pressure injection jets, the fuel injection pressure has a deterministic impact on the spray break-up and vaporization [29].

Chemical delay is controlled by the fuel's autoignition kinetics. This is dependent on fuel chemical composition, molecular structure and associated reactivity. Hence, pressure, charge temperature and local equivalence ratio conditions affect chemical ignition delay [28].

Physical delay and chemical delay usually overlap in time [27,30]. For compression ignition engines, physical delay is much longer than chemical delay [31]. The chamber conditions at SOI influence the duration of the physical and chemical processes [32]. Higher temperature reduces both delays: the higher thermal energy entrainment for the same mass of air speeds up the vaporization [33]. In addition, the chemical kinetics are faster and the chemical delay is shorter [34].

The chamber conditions also affect the chemical reactions that result in NOx and soot emissions [27,35].

PREVIOUS WORK

Previous investigations on pilot injection explain its effect on main injection in the following way [16,18,19,25]: pilot injection modifies the mixture and chamber conditions by the start of main injection. The new chamber thermodynamic conditions are a result of pilot combustion and the heat released. Results in [15] show that pilot-injection timing has an effect on the amount of heat released for the same pilot injected mass. The more heat released from pilot injection, the higher the chamber temperature resulting in a reduction in main-injection ignition delay. Higher load and engine speed both benefit pilot combustion due to a higher pressure and temperature in the combustion chamber.

EXPERIMENTAL SETUP AND METHOD

Engine Setup

A modified Scania D13 heavy duty engine was used to perform the experiments. These modifications could mean that the results could be different to those obtained with a production engine. The geometrical specifications are listed in Table 1. The engine setup is illustrated in Figure 2.

Table 1. Engine Specification.

Cylinder number	6
Displaced volume	12.74 L
Stroke	160 mm
Bore	130 mm
Compression ratio	18:1
Number of Valves	4
Intake Valve Closing timing (IVC)	-151 CAD ATDC
Exhaust Valve Opening timing (EVO)	146 CAD ATDC

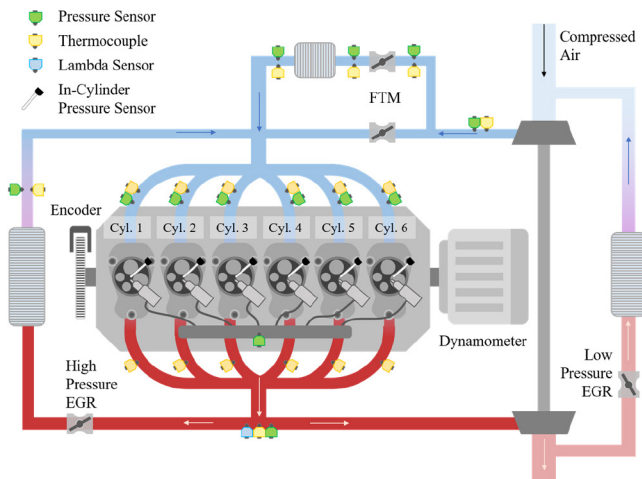


Figure 2. Engine Setup used in the experiment.

Engine speed is kept constant by the dynamometer, a 355kW AC motor, which also operated as an engine brake.

A Fast Thermal Management (FTM) system can be used to control the intake charge temperature through two regulated throttles, a hot and a cold with a cooler. The advantage is that the total cross-section can be kept constant to minimize the pressure loss. Low-pressure and high-pressure EGR are controlled from two regulated ball valves. No EGR was used in the experiments in this paper. An OEM turbocharger with wastegate is installed with the wastegate always closed. The engine is supplied with compressed air at a controlled pressure.

Sensor and Emission System

A Leine-Linde crank angle encoder with 0.2 CAD resolution was used.

Inlet manifold and exhaust pressures were measured using Keller PAA-23S absolute pressure sensors. K-type thermocouples were used to measure inlet manifold and exhaust temperatures.

The cylinder pressure was measured using six water-cooled Kistler (7061B) in-cylinder pressure sensors. A torque sensor (T40B) from HBM measured the engine brake torque after the fly-wheel.

Fuel mass flow was measured using a mini CORI-FLOW™ M15 Mass Flow Meter from Bronkhorst with 10Hz sampling frequency. A Horiba MEXA-9100E was used to measure UHC, CO, CO₂ and NO_x. An AVL Micro Soot Sensor was used to measure soot concentration.

Engine Control System

The engine controller uses LabVIEW™ from National Instruments and NI hardware with a PXI chassis (NI PXIe-8135 2.3 GHz quad-core processor). The user interface was run on a PC with Windows 7 communicating with the real-time system over TCP/IP.

The real-time system consisted of two FPGA boards NI PXI-7854/7854 R (Multifunction reconfigurable I/O with Virtex 5-LX110/LX30 FPGA). The FPGA was used as flexible reconfigurable AO/DIO hardware for AD acquisition, triggered by the crank-angle encoder. The ADC resolution was 16-bits.

For the injectors and common rail pressure, external drivers from Driven were used to execute the control action which was sent from the PXI system and commanded from the PC.

Combustion Control

For pilot injection, measured reference data were used to create maps for which the injection on-time for different rail pressures is used to inject the commanded masses.

For the main injection, two PI controllers were used. One controlled the IMEP of the cylinder by controlling the injection duration. The fuel mass injected during main injection was estimated using the maps of the injectors.

The second PI controlled the CA50 position by defining the start of main injection. The CA50 reference was set by placing the HR-peak from the CAD from the experiment design.

CA50 and HRR peak were obtained from online heat release analysis implemented in LabVIEW™. The implemented HR algorithm was a simplified version of the one used in the analysis of the results.

Calibration of the Pilot Mass Injection

To estimate the injected pilot mass, data were collected in a spray rig for each of the six injectors. The transfer function from the injectors on-time to the injected mass was calibrated. The threshold in the current trace for estimating the SOI and EOI was selected so that the mass estimated agreed with the transfer function and the values measured in the spray rig.

The pilot injection generates rail pressure oscillations that can influence the main injection. The oscillations from a second injection do not affect the pilot, but they can originate from a different injector. For this reason, even though the injected mass was measured for single injections, an additional method was used to estimate the mass for double injections. The injected mass was estimated from lambda measurements with a stoichiometric balance. The results were compared for single and multiple injections. Both methods gave the same result for estimation of the injected mass.

Heat Release Analysis

In this paper, heat release analysis is according to the previous work presented by Tunestål in [36] and Johansson [37]. The method described in [38] is used to estimate the offset of the top dead centre (TDC). For the heat transfer, the adopted model is Woschni's [39].

The combustion parameters used are presented in Figure 1. The following definitions apply:

- **Start of injection (SOI)** is when the injector opens. It is estimated from the injection current at a calibrated threshold where mass estimated by the difference between SOI and EOI i.e. injection duration, agrees with measurements of injected mass in a spray rig. The threshold was set at half of the level of injection current at steady open state.
- **End of injection (EOI)** is when the injector closes. It is estimated from the injection current as done for the SOI. The threshold was set at 0.05 of the steady current.
- **C_{Ax}** is the required crank angle degrees (CAD) to complete the fraction X of the maximum accumulated heat released.
- **Start of combustion (SOC)** is the crank angle at which the first chemical energy is released. Different algorithms have been developed for on-line computation of SOC [40]. These algorithms use in-cylinder pressure measurements [41,42] or the heat release rate [43,44]. The latter approach is used in this paper as performed in [34,45]. A good trade-off between detectability and accuracy was found by placing SOC when the HR derivative is above a threshold of 18 J/CAD² after the minimum found after the main SOI, i.e. between SOV and SOC, see Figure 1.
- **End of combustion (EOC)** is the point at which the accumulated heat release (AHR) reaches 95% of its maximum.

Experimental method

To investigate the effects of small pilot injections, three different variables were investigated for a combination of operating conditions:

- Rail pressure
- Pilot start of injection
- Injected pilot mass

The experiment produces a central point test matrix. For 1200rpm, loads ranging between 2.5 to 15bar IMEP were studied in increments of 2.5bar IMEP. For 10 bar IMEP, engine speeds ranging from 600 to 1800 rpm were studied in increments of 300rpm. All combinations of variables were studied at the central point. To complete the experiment and study the interaction between engine speed and load, data was acquired for low engine speeds at low load, and for high engine speeds at high loads. The combinations of variables in those cases were reduced to avoid exponential growth of the number of data points. In total, 26 different operating points were studied (Table 2).

The operating conditions are listed in Table 3 which presents a summary of the combinations of variables studied for each operating condition.

Table 2. Operating conditions for each experimental case.

Engine Speed (RPM)	Engine Load (IMEP, bar)						
	Motoring	2.5	5	7.5	10	12.5	15
600	#1	#6	#9	#12	#16		
900	#2	#7	#10	#13	#17		
1200	#3	#8	#11	#14	#18	#21	#24
1500	#4			#15	#19	#22	#25
1800	#5				#20	#23	#26

Table 3. Combinations of variables for each experimental case.

Case Number	Rail Pressure (bar)	CAD at Maximum HRR	Pilot Separation (CAD)	Pilot Mass (mg)
#6, #7	900	5	7.5, 10	0, 8, 10, 12
#8	900, 1050	0, 5, 10	5, 7.5, 10	0, 6, 8, 10, 12
#9, #10	900, 1050	0, 5	7.5, 10	0, 8, 10, 12
#11	1050, 1200	0, 5, 10	5, 7.5, 10	0, 6, 8, 10, 12
#12	1050	0, 5	7.5, 10	0, 8, 10, 12
#13	900, 1050, 1200	0, 5	5, 7.5, 10	0, 8, 10, 12
#14	1050	0, 5, 10	5, 7.5, 10	0, 6, 8, 10, 12
#15	1050	5, 10	7.5, 10	0, 8, 10, 12
#16	1200	0, 5	5, 7.5, 10	0, 8, 10, 12, 14
#17, #19	1200	0, 5, 10	5, 7.5, 10	0, 6, 8, 10, 12
#18	900, 1050	0, 5, 10	5, 7.5, 10	0, 6, 8, 10, 12
	900, 1050, 1200	5	7.5	0, 6, 7, 8, 9, 10, 12
#20	1200	5, 10	5, 7.5, 10	0, 6, 8, 10, 12
#21	1350	0, 5, 10	5, 7.5, 10	0, 8, 10, 12, 14
#22, #23	1350	5, 10	7.5, 10	0, 9, 12, 15
#24	1500	0, 5, 10	5, 7.5, 10	0, 8, 10, 12, 14
#25, #26	1500	5, 10	7.5, 10	0, 9, 12, 15

Prior to the experiment, the engine was run for at least 30 min to ensure completely warmed-up conditions. When changing operating conditions and variable set-points, the engine was run for a minimum of 500 cycles until stationary conditions were reached. For each working condition and variable combination, data was logged for 200 cycles.

The fuel used for the experiment was standard Swedish Diesel fuel without RME.