

Single Cylinder Diesel Engine Startup Experiments with Fast Cycle Resolved In-cylinder and Exhaust Sampling

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ABSTRACT

Single cylinder diesel engine cycle resolved startup experiments were performed at two different Compression Ratios. At CR18 ($CR = 18$) conventional engine starting resulted in a broad range of acceptable startup equivalence ratios (ϕ). However, reducing the CR to 16 resulted in problematic engine starting regardless of fuel level. In an effort to produce robust engine starting at lower CRs the engine was motored first. This allowed for strong starting performance coupled with high load fueling levels. For both CRs, IMEP_g and exhaust CO₂% increased as fueling level increased. However, while in-cylinder CO₂% exceeded exhaust CO₂% for moderate ϕ , this trend was reversed as fueling was reduced. Exhaust CO% was minimal except for stoichiometric fueling at CR18. Peak NO_x production occurred at CR18 and $\phi = 0.55$. Exhaust UHCs were maximized for higher fueling cases but dropped quickly after start. Similarly, ignition delay increased with ϕ but decreased during warm-up. As a result, burn duration was shortest with higher fueling and tended to decrease a few seconds after start. In-cylinder UHC started high (5000 – 15000 ppm) but decreased steadily during warm-up and dropped by one or two orders of magnitude during the exhaust phase. Finally, soot emissions were relatively independent of CR and increased with fueling level.

BACKGROUND & INTRODUCTION

Over the past decade a number of excellent studies have evaluated common rail diesel characteristics on engine startup performance [1-4]. Cold temperature limits and fuel injection strategies (variations on multiple shots) have shown promising startup performance benefits. The effect of fuel rail pressure variations has been investigated - clearly another important area in engine startability. Modeling efforts have also been

pursued to help understand the important physical factors in diesel engine startup performance [5, 6]. Cold start combustion instabilities and their important coupling to injection timing have been investigated [7].

What is not evident from the published literature is cycle-resolved emissions behavior during startup. The instruments to do this are relatively new and specialized. In addition, the startup performance of “pure” compression ignition engines, unaided by glow plugs, warrants further study. Also, basic data and knowledge of the startup performance of diesel engines with mechanical fuel injection is scarce. While modern diesels have rapidly been adapted to common rail injection, developing a more thorough understanding of “legacy” diesel engines is still important. Many legacy engines are still in use (with many decades of service life). Furthermore, military vehicles primarily employ conventional mechanical injection. As the nature of diesel fuel will continue to evolve, understanding the impact of fuel on legacy diesel engines is also important so that engine startup performance does not suffer.

In order to further understand diesel startup performance, knowledge and data of the in-cylinder diesel environment is essential. However, diesel in-cylinder species data are fairly modest principally due to the nature of heterogeneous diesel combustion. One seminal study thirty years ago used in-cylinder sampling to characterize particulate and NO_x species formation throughout the diesel combustion process [8]. Similar approaches using fast sampling valves [9-12] coupled to the combustion chamber have shown the progression of soot development and oxidation during the combustion event, with significant late combustion oxidation occurring. These approaches can work during steady-state engine operation but would be time consuming during engine startup since a cylinder dump event occurs for each sample. Thus, this work seeks to use

not only fast cycle resolved emission analyzers in the exhaust port but also in the combustion chamber during diesel engine startup. To the authors' knowledge, no published in-cylinder sampling results exist during diesel engine startup.

In a previous paper [13] the authors performed a detailed study of conventional diesel engine starting at CR18. Since many diesel engines (notably military diesels) have lower CRs, this follow-on study investigated diesel engine starting performance at a CR of 16 using an alternative approach of motoring the engine first in order to achieve acceptable engine starting.

The objective of this work is thus to characterize cycle-by-cycle mechanical compression ignition cold start performance (unaided by glow plugs) and emissions (UHC, CO, CO₂, NO_x and soot) principally as a function of fueling and Compression Ratio (CR). Conventional starts at CR 18 will be compared to motored starting at a lower CR of 16 where conventional starting was shown to be problematic. Additionally fast in-cylinder sampling results will be presented to further elucidate fuel preparation and emissions formation mechanisms.

EXPERIMENTAL APPARATUS

The engine used in this study is a standard single-cylinder Cooperative Fuels Research (CFR) diesel test engine. Under stabilized steady-state engine operation the engine speed is fixed with a motoring/absorbing dynamometer at 900 RPM. For this study the dynamometer was used as the starter motor. This engine allows variable compression ratio, injection timing, and injection amount. Table 1 lists the basic specifications of this engine. A Kistler™ 6125B pressure transducer was mounted in the engine head. A line diagram of the engine configuration is shown in Figure 1. Data, including fast emissions sampling, were all collected with a National Instruments™ LabView data acquisition system sampling at a rate of 50 kHz. With the crank angle sensor (on the very large 80 kg flywheel) sampled at this rate, maximum CAD uncertainty and IMEP_g uncertainty were determined to be 0.1 degree and 0.1 bar respectively.

Table 1: Engine Characteristics

Type	Indirect-injection diesel, pancake-style chamber, in-line cam-driven pump
Bore	82.6 mm
Stroke	114 mm
Speed	900 RPM steady-state
R _v	16 and 18
Coolant	water reflux, 100 °C
Intake Air	Lab ambient, 20 °C +/- 1 °C
Fuel	Diesel #2

The fuel pump used by the CFR Diesel engine is a conventional rack ("barrel and plunger") type for the adjustment of fuel flow rate (e.g. engine load). The spill port opening occurs at the end of injection period. A vernier coupling connects the fuel pump to the cam shaft for the adjustment of injection timing. The injector opening specification pressure is 1500 +/-50 psi. The CFR diesel injector is of the "pintle-nozzle" type and a CFR pintle position sensor is used to determine injector opening and closing points. This pintle position sensor was verified using a Kistler high pressure diesel line pressure sensor, discussed later. In this paper the injected fuel-air equivalence ratio (ϕ) is calculated from the measured emissions and Laminar Flow Element (LFE – Meriam Instruments™) air-flow measurements during stabilized engine operation.

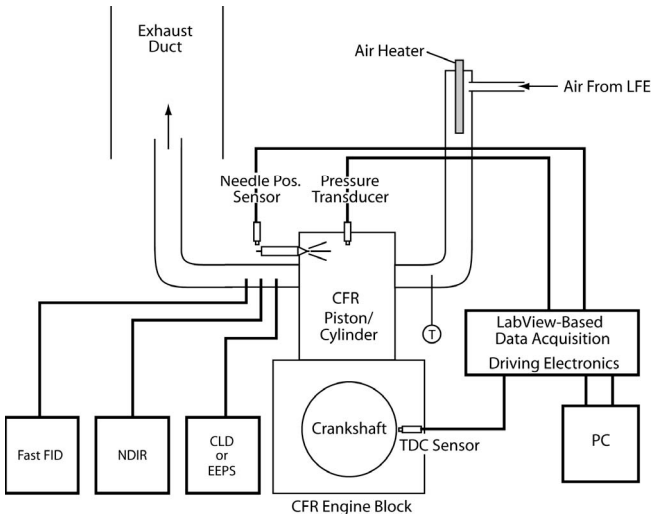


Figure 1: Schematic of diesel CFR engine and experimental setup.

The fuel used in this study was standard commercial diesel (#2). Detailed fuel analysis was performed and is included in the Appendix.

Three different Cambustion™ fast emission analyzers (down to ten millisecond response time) were used in the CFR engine exhaust near the exhaust valve. A Cambustion™ Fast Flame Ionization Detector (FFID Unit: HFR500), Non-Dispersive Infra-Red (NDIR Unit: NDIR500) Fast CO and CO₂ detector, and Chemiluminescent detector (CLD Unit: CLD500) were used as the principle diagnostics. Each Cambustion™ Unit has two sample heads, one for the in-cylinder measurement and one for the exhaust measurement. While the FFID and CLD units are sampled continuously, the NDIR unit alternates measuring CO₂ and then CO continuously throughout the engine cycle. The Cambustion™ exhaust probes were located in the exhaust manifold with the NO_x probe the closest at just a few centimeters from CFR cylinder head, next approximately ten centimeters downstream was the NDIR and then similarly the FFID. The FFID and NDIR

in-cylinder sample probes were located in a sample plug located in the CFR cylinder head, 90 degrees around the bore from the horizontally positioned fuel injector.

Calibration of all three Cambustion™ units was performed before each engine start with the Cambustion™ calibration sampling probe attachments. These attachments allow in-situ calibration for the exhaust probes by flooding the sample probe inlets with calibration gases. Bottled zero and calibration gases were used, and are specified in the appendix. The in-cylinder sample probes were calibrated outside the engine before engine startup.

An additional fast soot diagnostic was used to sample from the engine's exhaust pipe, the TSI Fast Soot Analyzer: Model 3090 Engine Exhaust Particle Sizer (EEPS). This unit samples simultaneously 16 Channels per decade of size for a total of 32 channels (two decades) between 5.6 and 560 nm at 10 Hz. A TSI EEPS analog output was input to the LabView system for phasing of the separately collected EEPS data.

Figure 2 shows a few characteristic startup engine cycles with some of the key measured signals, including the fast exhaust port diagnostics. Each of these displayed signals will be discussed next. Not shown are the engine position signals and CO raw data (only an issue for very rich and lean startup conditions, to be discussed later). The three combustion signals are shown exactly as they were collected, not adjusted for instrument response time and exhaust transport delays (which were accounted for in the data analysis).

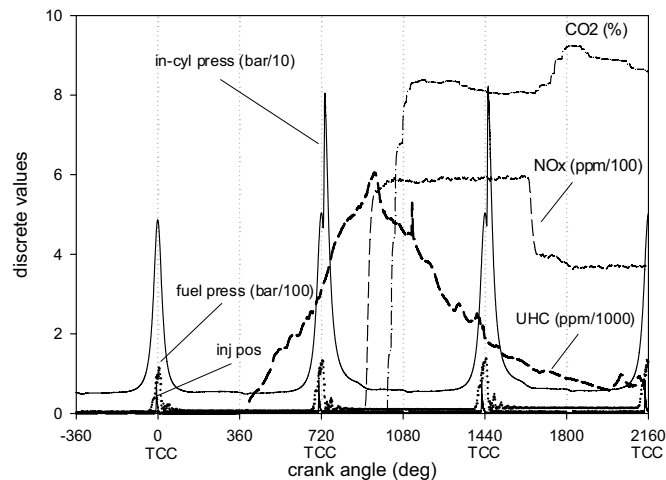


Figure 2: Representative engine cycles with simultaneous raw-scaled exhaust diagnostic signals.

Cylinder Pressure: The Kistler in-cylinder transducer shows the first cycle with fuel injection, but without combustion.

UHC: UHC emissions show up after the first cycle to receive fuel (but not burn) – this signal steadily rises

even after the exhaust stroke ends, suggesting that liquid fuel was transported into the exhaust and was steadily vaporizing during the next engine cycle. Next, then two engine cycles with combustion are seen.

NO_x: NO_x emissions first rise after the exhaust valve opens on the first combustive cycle since this probe is closest to the exhaust valve. The signal is characteristically stable both during and after the exhaust event.

CO₂: CO₂ exhibits a fairly stable plateau during exhaust, but lags NO_x slightly due to probe position being mounted slightly further downstream.

Since the NO_x and CO₂ signals were always approximately stable for each engine cycle, these signals were averaged during each cycle's exhaust stroke and will be displayed as the average value for each cycle in the forthcoming figures. The FFID UHC signal, which was often significant for one or more cycles before combustion began, was also simply averaged (time/transport adjusted). An exhaust blowdown-displacement model was not used to mass-weight this signal since for the non-combusting cycles there is not a blowdown phase.

The injector position sensor and fuel line (Kistler) pressure sensor are shown below each compression/expansion in-cylinder pressure event (the scale was kept small to enhance overall figure clarity). At first, the fuel line pressure (dotted line) rises, but a distinct change occurs in the pressure rise corresponding to the opening of the injector, shown with the injector position sensor. The line pressure then continues to rise and remains high during the injection event, after which it falls due to the opening of the mechanical injection pump spill port.

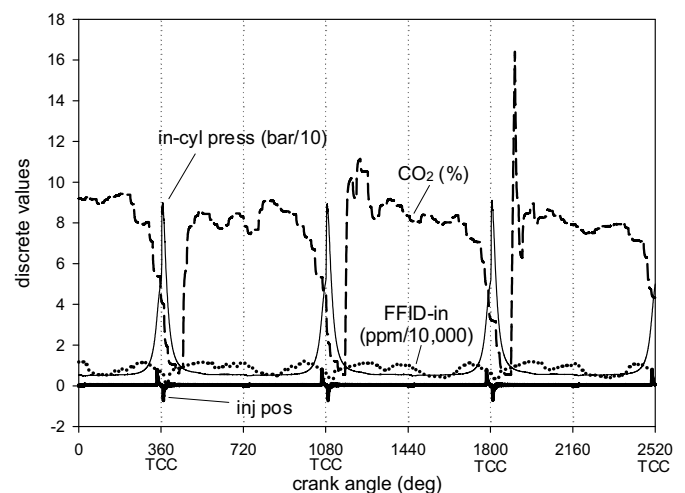


Figure 3: Representative engine cycles with simultaneous in-cylinder (raw-scaled) diagnostic signals.

Characteristic in-cylinder signals are next shown with in-cylinder pressure data in Figure 3. The time cycle sequence was chosen approximately three seconds

after start since it shows three types of in-cylinder CO₂ characteristic behaviors. The in-cylinder CO₂ signal rises after combustion has begun coupled with the transport and sensor delays (not adjusted for in this figure). This results in the appearance of the CO₂ signal rise near the end of the expansion stroke. It should be emphasized that the in-cylinder CO₂ measurement is a local combustion chamber measurement offset from the anticipated main diffusion flame zone. The exhaust CO₂ measurement is significantly different, and is expected to be homogenous due to expansion and exhaust stroke mixing.

The first CO₂-in signal event shows a fairly consistent burned gas plateau suggesting that the burned gas composition is fairly consistent during the combustion event, perhaps a longer diffusion burning period. The signal then falls off between combustion events due to the intake stroke drawing in fresh cylinder air thus diluting the in-cylinder CO₂ measurement. The second CO₂-in event in the figure shows an approximate 2% peak in CO₂ at the start of combustion followed by a fairly constant plateau. This may be an engine cycle with a greater pre-mixed burn (richer) early combustion phase. The third event shows a sharp rise followed by a stable combustion plateau. A short rich early pre-mixed combustion phase may be the result. It was anticipated that the in-cylinder signals would be challenging to interpret due to the stratified nature of diesel combustion. Future work will seek to connect combustion heat release characteristics with this in-cylinder data. For this paper, a simple averaging of the CO₂-in signal (coupled with standard deviation results as will be discussed later) during the combustion event is presented.

EXPERIMENTAL DETAILS

Test Matrix

Table 2 shows the test points selected for this study. Two compression ratios, 16 and 18, were explored for a wide range of fueling values. In order to obtain reliable starts at CR16, fuel was introduced after the engine was brought up to idle speed (900 RPM) as will be discussed later. Starts at CR18 were conventional. Due to higher post-compression in-cylinder pressure and temperature, a much wider range of fueling values was possible with CR18. For stabilized motoring, in-cylinder pressure/temperature at top center was 49 bar/940K and 42.5/920K bar for CR18 and CR16 respectively.

Table 2: Test Matrix

Fuel-air equivalence ratio (Φ)	CR16 (motoring starts)	CR18
1.0		x
0.9	x	
0.825	x	
0.7	x	x
0.625	x	
0.55		x
0.5		
0.4		x
0.3		x

CR18 Conventional Starting:

Fuel injection quantity and injection advance settings were set with a stabilized running engine the day prior to the start. Then the fuel bypass at the injector was used to stop the engine after which ten seconds of motoring was performed in order to ensure that the cylinder was free of residual fuel. The engine always came to rest on the compression stroke of the engine. For the following day's start this 'zeroeth' cycle was not counted in the 'cycles since cranking begins' metric. The first complete engine cycle beginning with it's associated intake stroke will be characterized in this work as Cycle 1 for the conventional engine starting.

The dynamometer was used as the starter motor for this study. The cranking-startup sequence was as follows:

- Data acquisition initiated.
- Commenced cranking with the fuel bypass closed.
- After approximately six seconds of data collection, the Combustion units were immediately switched to 'purge' mode, which allows compressed air to keep exhaust from entering the sample heads, and thus keep excessive deposits from forming.
- At five minutes after start, the Combustion units were switched from purge to sample after which a steady-state file was collected for all of the data.

Dozens of initial tests at various operating conditions showed that a higher compression ratio (18 instead of 16) produced more robust starts. Additionally, injection timing settings (details given shortly) advanced beyond best torque timing were employed in order to achieve robust engine starting. A previous paper [13] has discussed these results which show that beyond a minimum advance little is gained by over-advancing injection timing.