

An Enabling Study of Diesel Low Temperature Combustion via Adaptive Control

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ABSTRACT

Low temperature combustion (LTC), though effective to reduce soot and oxides of nitrogen (NO_x) simultaneously from diesel engines, operates in narrowly close to unstable regions. Adaptive control strategies are developed to expand the stable operations and to improve the fuel efficiency that was commonly compromised by LTC. Engine cycle simulations were performed to better design the combustion control models. The research platform consists of an advanced common-rail diesel engine modified for the intensified single cylinder research and a set of embedded real-time (RT) controllers, field programmable gate array (FPGA) devices, and a synchronized personal computer (PC) control and measurement system. Up to 12 fuel injection pulses per cylinder per cycle have been applied to modulate the homogeneity history of the cylinder charge in hybrid combustion modes in order to improve the phasing and completeness of combustion under independently controlled exhaust gas recirculation, intake boost, and exhaust backpressure.

INTRODUCTION

An LTC cycle can be implemented by the heavy use of exhaust gas recirculation (EGR) or the homogeneous charge compression ignition (HCCI) type of combustion [1,2]. However, the fuel efficiency of the LTC cycles is commonly mired by high levels of hydrocarbon (HC) and carbon monoxide (CO) emissions. More seriously, the scheduling of early fuel delivery in HCCI engines has lesser leverage on the exact timing of auto-ignition that may even occur before the compression stroke completes when a high compression ratio of

conventional diesel cycles is applied, which may cause excessive efficiency reduction and combustion roughness. Moreover, the combustion process becomes less robust and enters into narrower operating regions compared to conventional high temperature combustion (HTC) processes [1,2].

The decreased thermal efficiencies of diesel LTC cycles are attributed to:

- increased un-burnt hydrocarbon (UHC) and CO emissions;
- off-phasing of the combustion event;
- split combustion events;
- fuel condensation leading to oil dilution.

Even though diesel engines are overall lean-burn systems, the classical heterogeneous nature of the high-temperature combustion (HTC) process presents numerous challenges in the emission reduction of oxides of nitrogen (NO_x) and particulate matter (PM). In such diesel engines, the flames tend to initialize in and propagate towards regions where the air-to-fuel ratios are near-stoichiometric [1-9].

The use of EGR has been effective in reducing the in-cylinder NO_x formation mainly because the dilution, thermal and chemical effects of EGR lower the flame temperature and oxygen concentration of the working fluid [9]. However, a further reduction of NO_x by applying more aggressive EGR usually increases the PM formation because of the predominant diffusion-controlled combustion where the lack of oxygen would lead to soot formation on the locally fuel-rich reaction zones, especially at high loads. Nonetheless, low-

temperature combustion strategies applied to compression ignition engines, such as HCCI or smokeless diesel combustion, promise simultaneous reductions of NO_x and PM [9-28].

Adaptive control strategies based on cylinder pressure and heat release characteristics are implemented to stabilize and enable the low-temperature combustion from mid to high loads especially when high levels of boost and EGR are applied.

EMPIRICAL APPROACHES AND PHASING
CONTROL MODEL

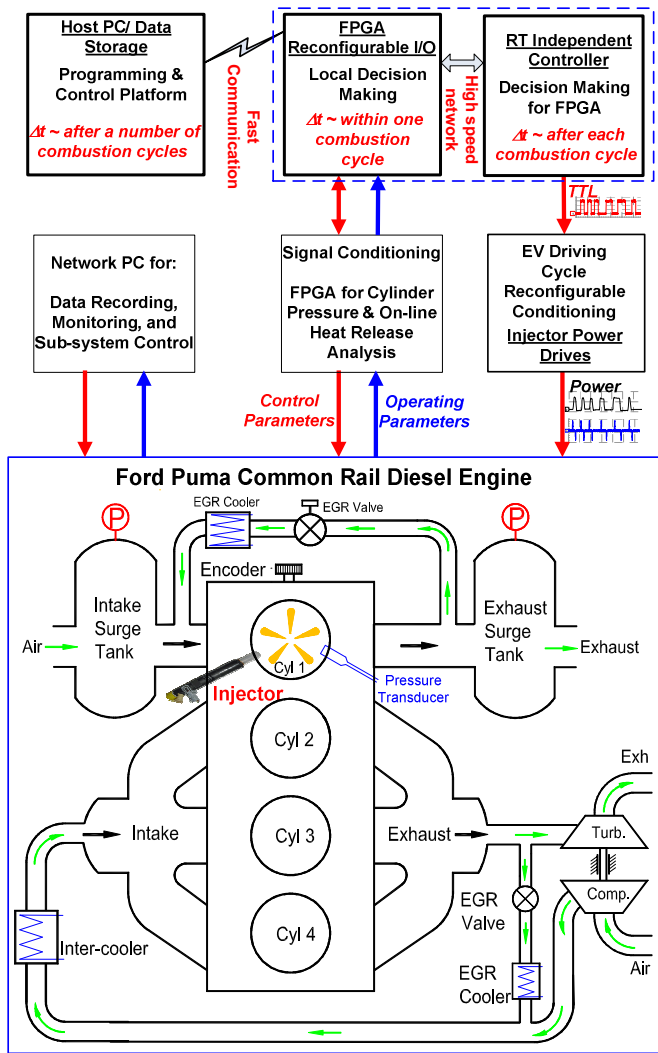


Figure 1. Schematic representation of the test setup with independent control on intake boost and exhaust backpressure at the University of Windsor

A modern 4-cylinder Ford Puma common-rail diesel engine (Table 1), running in a single-cylinder mode of a 3-to-1 cylinder configuration was instrumented for the tests shown in Figure 1 [1]. As described by Han *et al.* [22], the 3-to-1 cylinder configuration is an appropriate exploration strategy that enables the investigation of unstable combustion regimes with a non-motoring dynamometer. The 3 cylinders are operated in the

conventional HTC mode at a low load for the stable engine operation. The combustion process in Cylinder 1 could be then pushed into the LTC cycles by independently controlled EGR, intake boost and exhaust back pressures, and fuel injection pressure and scheduling.

A dual-bank exhaust analyzer system (NO_x, HC, CO, CO₂, O₂, and soot) has been used in the tests; normally one for the exhaust emissions and the other for intake gas concentrations. The intake air is supplied from an oil-free dry air compressor. The engine boost, exhaust backpressure, and EGR valve opening are precisely controlled with a set of PC-based network system. The engine coolant and lubricant conditions are retained closely with external conditioning systems to minimize the discrepancies of the testing results. [1,2]

Table 1. Geometric characteristics of the test engine.

Engine Type	4 Cylinder, 4 Stroke Ford DuraTorq "Puma"
Displacement [cm ³]	1998
Bore [mm]	86
Stroke [mm]	86
Compression Ratio (r _c)	18.2:1
Combustion System	Direct Injection
Injection System	Common-rail (up to P _{rail} ~ 1600bar)

In order to command the fuel injection strategies precisely, 3 sets of real-time controllers embedded with FPGA devices have been programmed to dynamically control the following:

- the common-rail pressure;
- the events of in-cylinder fuel injection;
- the optimized control of the combustion characteristics: CA50 fixing; Indicated Mean Effective Pressure (IMEP) topping-up; and peak dp/dθ curbing.

The fuel injection control FPGA generates the desired transistor-transistor logic (TTL) pulse patterns corresponding to the on-fly updated injection schedule. This TTL output signal is amplified using a reconfigurable injector power driver to execute the pulse trains, which are programmed to drive the injectors with the suitable voltage and current profiles.

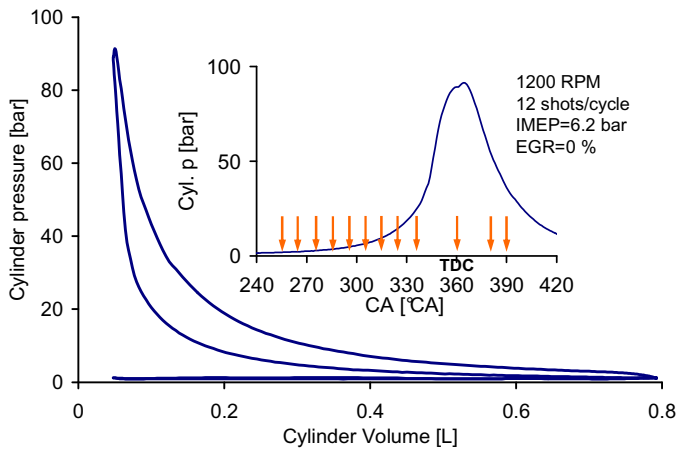


Figure 2. Test result of 12 injection pulses per cylinder per cycle (0% EGR)

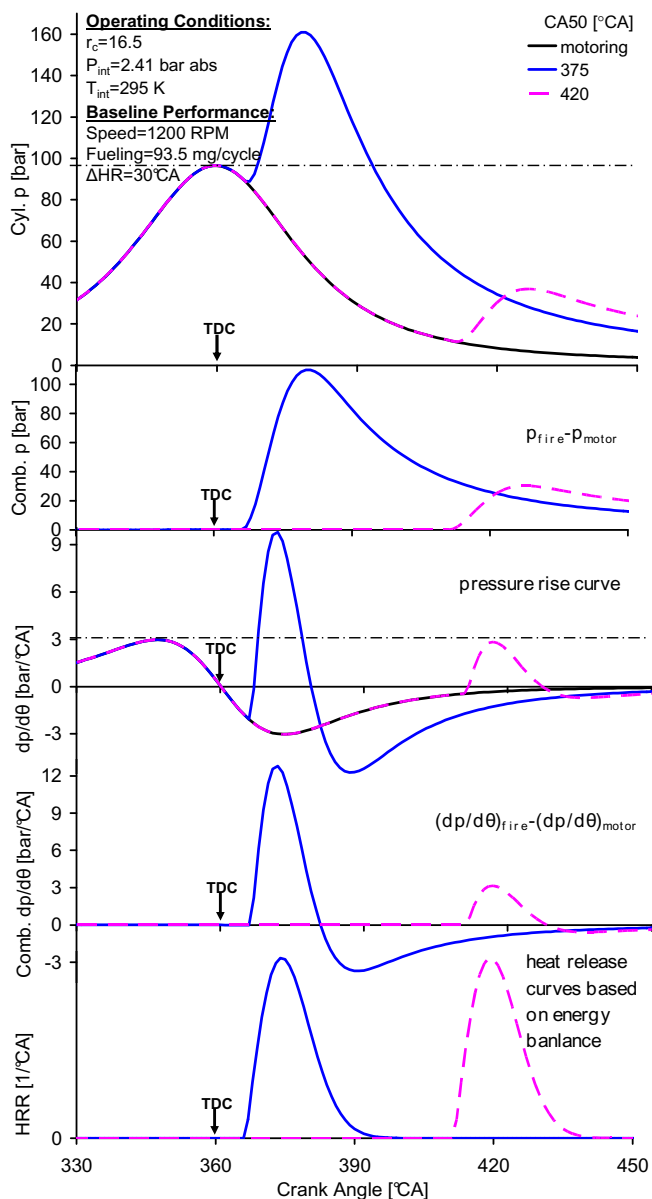


Figure 3: LTC enabling analytical method based on the simulated heat release pattern diagnostics

Up to 12 fuel injection pulses per cylinder per cycle have been applied to modulate the homogeneity and the homogeneity history of the relatively higher load LTC operations under independently controlled levels of EGR, boost, and intake temperature. The cylinder pressure traces and p-V diagram for 12 injection tests is shown in Figure 2. In this case, the improvement in the homogeneity of the cylinder charge relies on the scheduling of the fuel injection events instead of on the EGR modulation (zero EGR). The model-based control requires the online diagnostics of the combustion characteristics such as the maximum cylinder pressure, p_{max} , maximum cylinder pressure rise rate, $(dp/d\theta)_{max}$, and the combustion phasing represented by the crank angle position of the 50% heat-released (CA50).

Figure 3 demonstrates the relationship among the cylinder pressure, $dp/d\theta$ and the heat release curves for conventional or late combustion events via the engine cycle simulation [1,2]. When the combustion process completes close to the start of expansion stroke, the crank angles of p_{max} and $(dp/d\theta)_{max}$ are readily identifiable on the cylinder pressure and pressure rise curves respectively. However, the identification becomes difficult in postponed combustion events, since the pressure rise $(dp/d\theta)$ curve indicates that the hump produced by the combustion process may fall lower than the hump produced by the motoring compression. Even in these cases, the timing of the combustion can be identified by comparing the pressure rise curves of motoring and firing. In addition, the resulted subtraction curve between firing and motoring $dp/d\theta$ traces also strongly resembles to the actual curve of heat release rate [1] (Figure 3), which method is therefore, defined as *the motoring based combustion event identification*.

Adaptive control algorithms were developed to comprehend the impacts of engine operating parameters that include EGR, boost, engine speed, and compression ratio on the above *motoring based combustion timing identification*. A set of FPGA-RT programs were produced to optimize the control. In one of the tested approaches, the baseline motoring $dp/d\theta$ data sets have been saved to the FPGA memory that enables the method of the motoring based combustion event identification irrespective of very late combustion events.

It was found that the motoring curves produced from the engine cycle simulation were fairly accurate to model the effects of compression ratio, boost, and EGR. However, in order to obtain baseline motoring pressure traces precisely, a variety of engine running conditions including boost, engine speed, EGR, and compression ratio variations have been investigated experimentally (Figure 4-Figure 7).

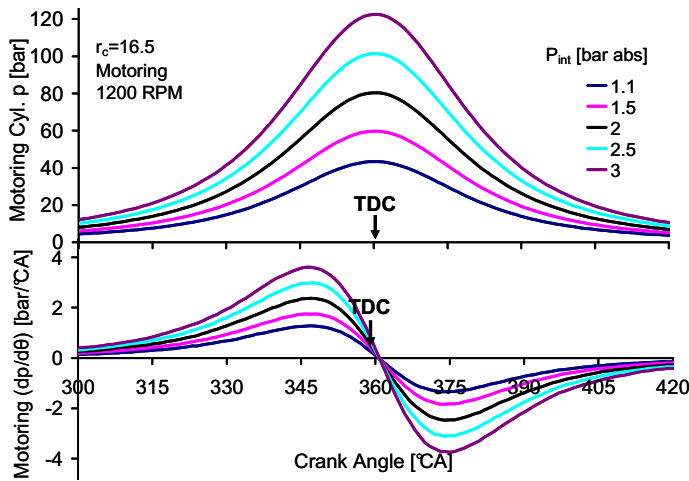


Figure 4. Measured motoring pressure and $dp/d\theta$ at various boost levels

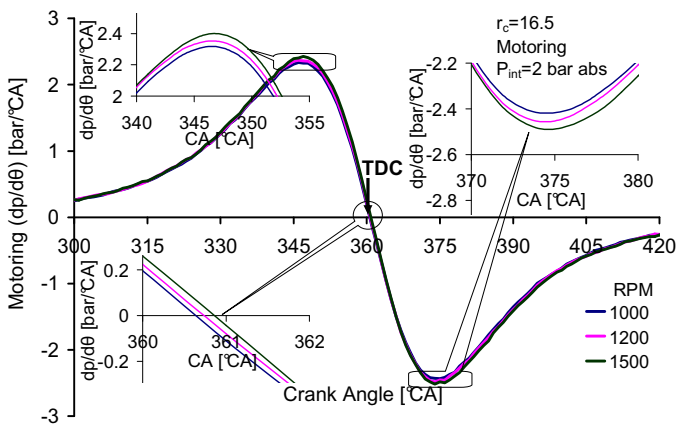


Figure 5. Measured motoring $dp/d\theta$ at various engine speeds

With the same hardware configurations, it is obvious that the boost has the strongest effects on the cylinder pressure and pressure rise patterns (Figure 4). The engine speed and EGR level only have slight impacts on the pressure rise curves within the limited speed variations and low load operations, as shown in Figure 5 and Figure 6. The cylinder compression ratio has also shown strong impacts (Figure 7). Though a post-TDC combustion event is favorable in lowering the $(dp/d\theta)_{\max}$ in practice, because of its proximity or concurrent occurrence with the maximum pressure falling rate produced by motoring expansion. Conversely, a pre-TDC combustion event is unfavorable in containing the $(dp/d\theta)_{\max}$ because of the motoring hump prior to TDC.

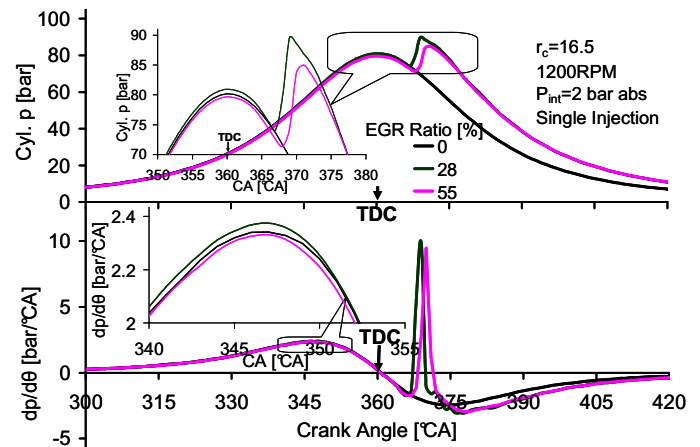


Figure 6. Measured cylinder pressure and $dp/d\theta$ at various EGR levels

Based on the above experimental results and analyses, correlations between the engine operating parameters and the motoring pressure characteristics are established. The various maximum cylinder pressure and pressure rise values can be stipulated from the baseline conditions of zero boost, fixed compression ratio, zero EGR, and low engine speed as summarized in Equation 1. Thus, the entire pressure rise curves during motoring can be predicted, which will be used in the online evaluation of the combustion characteristics.

$$z = [a \cdot (p_{\text{int}}) + b] \cdot [c \cdot (r_c) + d] \quad (1)$$

In Equation 1, the unit of intake pressure p_{int} is *bar* in absolute pressure. The values of a , b , c , and d are rendered from the engine cycle simulations [30] in order to formulate the control model (Table 2). The standard deviations of the experimental data under typical laboratory coolant temperature of 80°C are also shown in Table 2.

With the combustion diagnostic model improved, it is necessary to quantitatively investigate the controllability of the combustion phasing via sweeping the timing control of a single-shot fuel injection event. Figure 8 shows the relationship between the commanded start of injection (SOI) and the resultant combustion phasing (the median heat-release timing, CA50). This control sensitivity of fuel injection to combustion is so represented by defining a heat release phasing control factor k :

$$k = \frac{\Delta \text{CA}_{50}}{\Delta \text{SOI}} \quad (2)$$

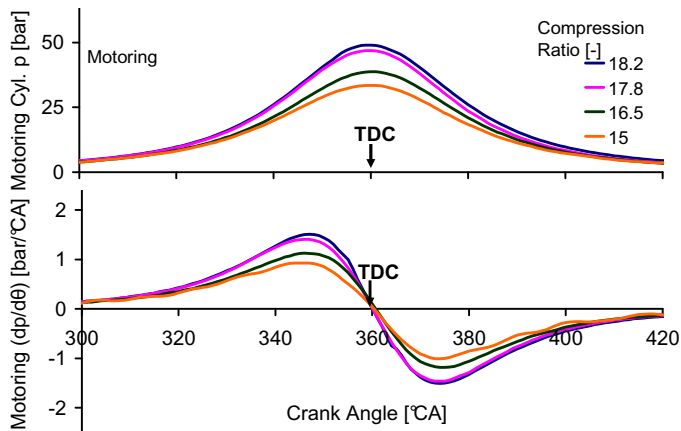


Figure 7. Measured motoring pressure and $dp/d\theta$ for different engines with various compression ratios

Table 2. Engine geometric characteristics

Z		Values	$\sigma_{\text{experimental}}$
p_{max}	a	41.2	0.4
	b	-2.4	
	c	0.08	2.4
	d	-0.3	
$(dp/d\theta)_{\text{max}}$	a	1.3	0.03
	b	-0.09	
	c	0.1	0.07
	d	-0.8	

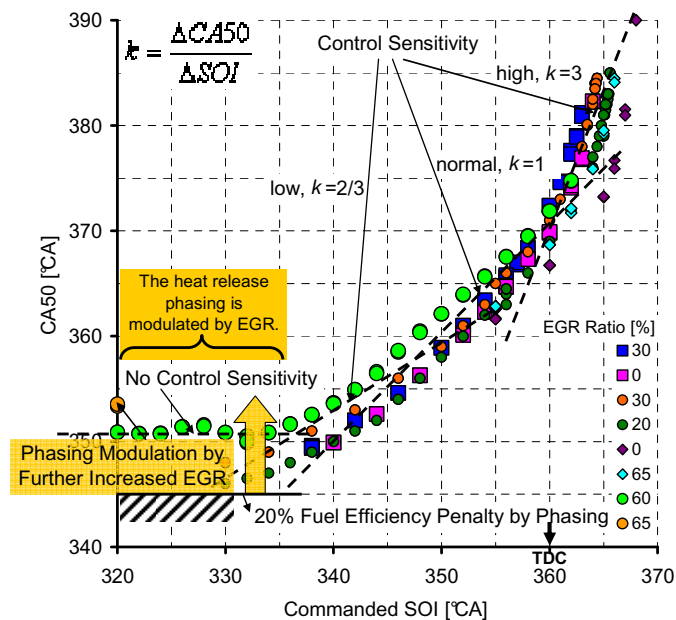


Figure 8: The relationship between the commanded SOI and the measured combustion phasing

From Figure 8, with an earlier commanded injection timing (e.g. slightly before TDC) the retarding of 1°CA in injection timing corresponds to approximately 1°CA postponing of CA50. However, this parity relationship departs to higher ratios for post TDC fuel injections and, conversely, may diminish for excessively early injections.

For instance, when the start of fuel injection occurs from the crank angle 362°CA to 365°CA , 3°CA variations in the commanded injection timing cause a 10°CA shift in the CA50. Since the control sensitivity on combustion phasing varies extensively across the SOI modulation range, adaptive control parameters needs to be adjusted accordingly.

On the other hand, if the SOI is too early (e.g. from 320°CA to 335°CA), the commanded SOI loses the control on the combustion phasing. Thereupon, resorts must be sought from the other engine operating parameters that include the levels of EGR, air fuel ratio (AFR), boost, and homogeneity etc. For instance, in order to obtain a combustion phasing of 353°CA when the SOI is very early at 320°CA , increasing EGR ratio from 60% to 65% is more effective than postponing the SOI by 20°CA in Figure 8.

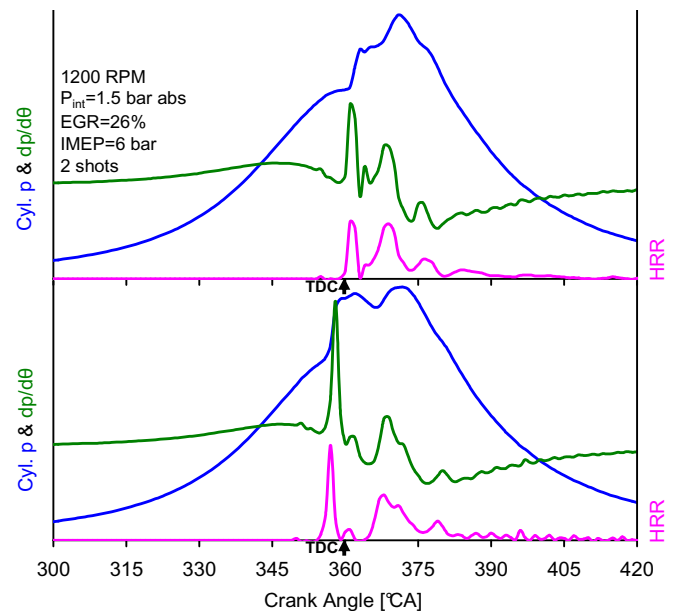


Figure 9. Experimental heat release, cylinder pressure and $dp/d\theta$ curves of the joint and split combustion events

The mixed combustion modes in modern diesel engines impose immense challenges to the adaptive control, owing to the versatile capabilities of the digitally controlled multi-events of the common-rail fuel injection systems. For instance, a variety of heat release shapes such as split combustion events can be readily produced to study the heat release pattern effects on the combustion efficiency and exhaust emissions. In the upper graph of Figure 9, when two injection pulses are such scheduled that one at 5°CA prior to TDC and the other at 2°CA after TDC, the analysis of the cylinder pressure trace produces a heat release curve with double humps. With a prolonged dwell between these two injection pulses, the analysis of the cylinder pressure