

An Improvement on Low Temperature Combustion in Neat Biodiesel Engine Cycles

Ming Zheng, Meiping Wang and Graham T. Reader
University of Windsor

Mwila C. Mulenga and Jimi Tjong
Ford Motor Company of Canada Ltd.

Copyright © 2008 SAE International

ABSTRACT

Extensive empirical work indicates that the exhaust emission and fuel efficiency of modern common-rail diesel engines characterise strong resilience to biodiesel fuels when the engines are operating in conventional high temperature combustion cycles. However, as the engine cycles approach the low temperature combustion (LTC) mode, which could be implemented by the heavy use of exhaust gas recirculation (EGR) or the homogeneous charge compression ignition (HCCI) type of combustion, the engine performance start to differ between the use of conventional and biodiesel fuels. Therefore, a set of fuel injection strategies were compared empirically under independently controlled EGR, intake boost, and exhaust backpressure in order to improve the neat biodiesel engine cycles. For instance, the single pulse injection was applied to commensurate with the heavy EGR-incurred LTC under light loads; and the multi-pulse early injection was applied with the EGR-assisted HCCI under higher loads to facilitate the high homogeneity that is more difficult to generate with a single pulse injection. Converse to the single-shot LTC, the scheduling of the multiple fuel pulses has lesser leverage on the exact timing of combustion that may even occur before the cylinder completes compression, which may cause excessive efficiency reduction and combustion roughness. Moreover, the use of a neat biodiesel fuel may further raise the levels of hydrocarbon and carbon monoxide emissions in LTC cycles because of its higher boiling temperature range. In this research, up to 6 fuel injection pulses per cycle were applied to modulate the fuel mixing history in order to better phase the combustion thus enhance the combustion process.

INTRODUCTION

Methyl or ethyl esters of vegetable oils, waste animal fats and waste restaurant greases (yellow grease), commonly known as biodiesel fuel, have been identified as one of

the future contenders to fulfil the demand gap caused by the depletion of fossil diesel fuels [1-18]. In comparison with conventional diesel fuels, biodiesels are renewable and their combustion-accessible fuel oxygen may promote more complete burning of the fuel. The engine-out emissions of particulate matter (PM), carbon monoxide (CO), and un-burnt hydrocarbons (UHC) in modern four-stroke compression-ignition engines may thus be lower in biodiesel-fuelled engines. However, a slight increase in emissions of nitrogen oxides (NO_x), which could be partially caused by the fuel property incurred combustion-timing variations, has been observed in the use of oxygenated fuels in general [1,4,8-19]. The increased NO_x formation in biodiesel-fuelled engines has also been attributed to the lowered in-cylinder soot levels, thus lower radiation heat transfer, resulting in higher in-cylinder temperatures [4]. Nevertheless, low-temperature combustion (LTC) strategies, such as the homogeneous charge compression ignition (HCCI)-enabling technologies and smokeless diesel combustion, offer a promising solution to simultaneously reduce the in-cylinder formation of NO_x and PM [3-7,20-33].

The conventional diesel high temperature combustion (HTC) process has benefits of high power output and thermal efficiency. Nonetheless, because the HTC is predominantly diffusion-controlled, the flame tends to initialise in and propagate to approximately stoichiometric regions [20-22]. Consequently, the heterogeneous nature of the HTC process presents an inherent NO_x /PM trade-off. Conversely, the use of exhaust gas recirculation (EGR) lowers the flame temperatures due to its dilution, thermal and chemical effects, with the dilution effect being more significant under engine operating conditions [21]. Under steady-state conditions, therefore, the use of EGR at low to medium load conditions may lead to the LTC mode, i.e. EGR-incurred LTC, which is conducive to the in-cylinder simultaneous reduction of NO_x and PM. The LTC mode could also be achieved through HCCI-enabling technologies, such as the use of multi-pulse

early injections, high injection and boost pressures, and EGR, especially at medium to high load conditions [2,3,5-7,25-30].

In recent years, the concerns over the depleting world reserves of fossil fuels, energy security and more stringent emission regulations for harmful pollutants have led to the resolute efforts in searching for renewable alternative fuels and ultra-low emission combustion strategies. Biodiesel fuel, which is identified as a clean alternative fuel, has become commercially available in a number of countries. Because it has characteristics approximately similar to fossil diesel fuel, neat (100%) biodiesel may be directly used in some diesel engines without prior engine modifications. Furthermore, the fuel efficiency of LTC cycles is commonly compromised by high levels of UHC and CO that drain substantial amount of fuel energy from the engine cycle. Nonetheless, the authors have demonstrated that in comparison to conventional diesel fuels, a high Cetane Number (CN) biodiesel may better sustain the combustion in both the retarded start of injection (SOI) and EGR-incurred LTC [2,3] modes. However, the long-term impact of neat biodiesel in modern common-rail injection systems still needs to be identified. Additionally, biodiesel is known to degrade up to four times faster than diesel fuel [13]. The products of biodegrading could have detrimental effects on the injection components especially the high-pressure fuel pump. In the short-term one of the disadvantages of biodiesel is its higher production cost.

The process of LTC, though may produce ultra low emissions of NO_x and soot, typically operates in narrow corridors or isolated islands of specific air-fuel ratios, EGR rates, and engine loads [28,29]. Furthermore, when the engine operating condition varies, the exhaust characterises extensive variations in temperature, pressure, flow rate, oxygen concentration, and combustible contents thus the amount of EGR would have compounded impacts on the variations of intake boost and in-cylinder combustion. The main objective of the work underlying the current research was to identify potential improvements in neat biodiesel LTC cycles. The combustion and emission characteristics of a mixture of neat biodiesel fuels were investigated on a common-rail direct injection (DI) diesel engine, which was configured to have independent control of the EGR and boost and back pressure to achieve the LTC mode. A blend of the fatty acid methyl esters derived from Canola oil, soybean oil, tallow and yellow grease was utilised in the tests. Multi-pulse early-injections were also employed to modulate the homogeneity history of the cylinder charge.

EXPERIMENTAL SET UP

A modern four-cylinder Ford common-rail DI diesel engine coupled to an eddy current dynamometer, with the configuration shown in Table 1, running in single-

cylinder mode was instrumented for the tests as shown in Figure 1 [32]. As described by Han *et al.* [32], the 3 cylinders-to-1-cylinder configuration is a new exploratory 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 low load for stable engine operations. The combustion in Cylinder #1 is then pushed into the LTC cycles by independently controlling the EGR, boost and exhaust back pressures and fuel injection scheduling. An alternative to this strategy could be the use of a motoring dynamometer with the 3 cylinders operating under motoring conditions while the first cylinder is fired during the tests.

Table 1. Geometric characteristics of the test engine.

Engine Type	4-Cylinder, 4-Stroke Ford DuraTorq "Puma"
Displacement	1998cm ³
Bore	86mm
Stroke	86mm
Compression Ratio	18.2:1
Connecting Rod Length	160mm
Combustion System	Direct Injection
Injection System	DELPHI Common-rail (P _{Rail} up to 1600bar)

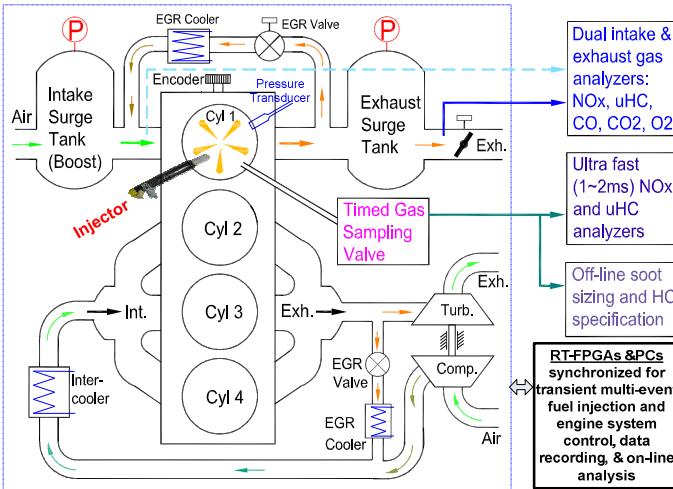


Figure 1. Schematic representation of the test setup with the independent control of intake boost and exhaust backpressure [2].

As reported in previous work [2], the fatty acid methyl esters (FAME) derived from Canola oil, soybean oil, tallow and yellow grease, from biodiesel producers in Canada, were first analysed by an established research institution following the ASTM D6751 standard, a North American standard specification for neat biodiesel fuel designated B100. In addition, ASTM D5291 was applied to obtain the C/H/O ratios and ASTM D4809 for the energy content. Table A-1 in the APPENDIX presents the characteristics of the fuels. The fuels were then mixed according to the approximate volumetric proportions as may be readily procured in Ontario Province of Canada

[1-3]. The final biodiesel fuel blend (hereafter called Biodiesel) was, however, not analysed. Therefore, the fuel characteristics shown in the last column of Table A-1 were estimated from the fraction of the neat B100 fuels UW2-1 to 2-4 on a mass basis as demonstrated in Equations A-1 and A-2 [3].

In order to command the fuel injection precisely, a real-time controller embedded with a field programmable gate array (FPGA) device has been programmed to dynamically control the multiple events of in-cylinder fuel injection via a reconfigurable injector power drive. The 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 the injector power driver to execute the pulse trains, which are programmed to drive the injectors with the suitable voltage and current curves. Up to 8 fuel injection pulses per cylinder per cycle have been applied previously to modulate the homogeneity and the homogeneity history of the high load LTC operations under independently controlled levels of EGR, boost, and intake temperature [25].

As reported previously [25], a dual-bank exhaust analyser system (NO_x , UHC as total hydrocarbons THC, CO, CO_2 , O_2 and soot) was instrumented for the tests; normally one for the exhaust emissions and the other for the intake gas concentrations. Note that PM includes smoke, dry soot, soluble organic fraction (SOF), liquid droplets and other combustion products. Nonetheless, because the primary composition of PM produced in non-premixed internal combustion engines is soot [34,35], the use of a smoke meter provides a qualitative indication of the PM emissions. An in-cylinder gas sampling system is also available for temporal analysis of the NO_x and UHC formation whose results will be reported in the near future. The intake air was supplied from an oil-free dry air compressor thus the NO_x humidity correction was not performed. The engine boost, exhaust backpressure and EGR valve opening were automated with on-line digital control. The engine coolant condition was retained closely with external conditioning systems to minimise the discrepancies of the testing results.

RESULTS AND DISCUSSION

Table 2 summarises the empirical investigations conducted in the present study. Steady-state conditions were investigated at an engine speed of 1500rpm, common-rail pressure (P_{Rail}) of 950bar using the CO_2 -based EGR ratio. Because the tests were performed on a single-cylinder of a multi-cylinder engine, the authors elected to employ the indicated performance so as to exclude the power loss discrepancies of the engine auxiliary equipment. Consequently, the indicated mean effective pressure (IMEP) was employed as an indicator of the load level, as opposed to the conventional torque-

based relative engine load or brake mean effective pressure (BMEP). Based on previous work [7], the following criteria was utilised to categorise the engine load level at the test speed condition: Low Load for $\text{IMEP} \leq 5\text{bar}$, Medium Load for $5 < \text{IMEP} < 8\text{bar}$ and High Load for $\text{IMEP} \geq 9\text{bar}$.

Table 2. Summary of the Biodiesel test points.

Test	Characteristics	Sweep Details
A	SOI Sweep 0% EGR at 5bar IMEP	SOI 350~370°C
B	EGR sweep, SOI 358°C at 5bar IMEP	EGR ratio 0~55%
C	EGR sweep, SOI 353°C at 10bar IMEP	P_{Intake} 1.5~2bar (abs)
D	EGR sweep, SOI 353°C P_{Intake} 1.5bar (abs) 10bar IMEP	SOI advance to improve combustion
E	Early multiple injections at 8bar IMEP	2~6 injections, EGR 20~70%

First, single-shot 5bar IMEP tests were conducted with a commanded-SOI sweep, 0% EGR and an absolute intake pressure of 1.7bar i.e. P_{Intake} 1.7bar (abs). The single-pulse injection was then fixed near piston top dead centre (TDC) and an EGR sweep performed at 5bar IMEP and P_{Intake} 1.7bar (abs). The single-injection SOI sweeps were also conducted at a higher load condition of 10bar IMEP for P_{Intake} 1.5~2.0bar (abs), followed by the Biodiesel early-multiple injection strategies. The results and discussions are presented below.

TEST A: BIODIESEL SOI SWEEP AT LOW LOAD

Figure 2 to Figure 4 present the Biodiesel engine test results for the SOI sweep at low load conditions defined as Test A in Table 2. As the SOI was retarded from 350 to 370°C, the peak cylinder pressures, as shown in Figure 2, decreased because of the combustion taking place during the expansion stroke. The heat-release rates, Figure 3, appeared to be dominated by the lean premixed burning phase where the in-cylinder NO_x formation would be high while the soot, THC and CO would be low especially for the SOI before TDC as shown in Figure 4.

At the SOI of 366°C, the fraction of energy released during the premixed burning phase increased considerably. This SOI, of which combustion occurred during the expansion stroke, resulted in a maximum rate-of-pressure rise $(dP/d\theta)_{\text{Max}}$ of 6bar/°C, maximum premixed-combustion dominated heat-release rate of 0.2/°C and the lowest engine-out soot of 0.035FSN (0.43mg/m^3) for the conditions investigated. Nonetheless, beyond a commanded SOI of 369°C, the soot, CO and THC increased appreciably which was accompanied by a 70% decrease in the IMEP. Noted, before the SOI of 368°C the soot, THC and CO emissions were near-zero while the indicated specific

NO_x was $>4\text{g/kW-hr}$. Therefore, the LTC mode was not fully realised with the SOI strategy at low load and P_{Intake} 1.7bar (abs). For the investigated conditions, the 368°CA could be taken as the furthest energy-efficient SOI retard for the Biodiesel-fuelled common-rail diesel engine.

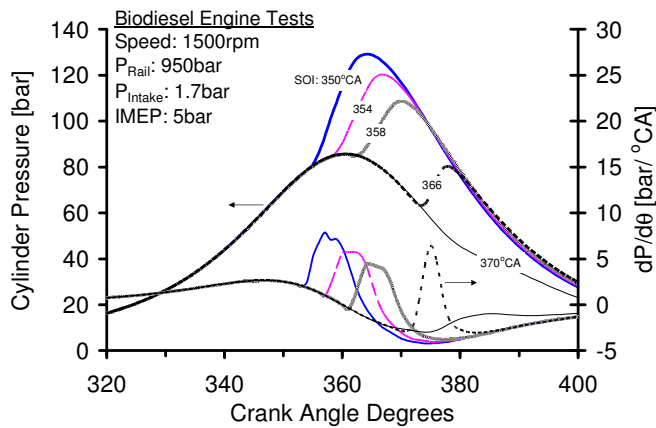


Figure 2. Variation of cylinder pressure and $dP/d\theta$ with SOI at 5bar IMEP.

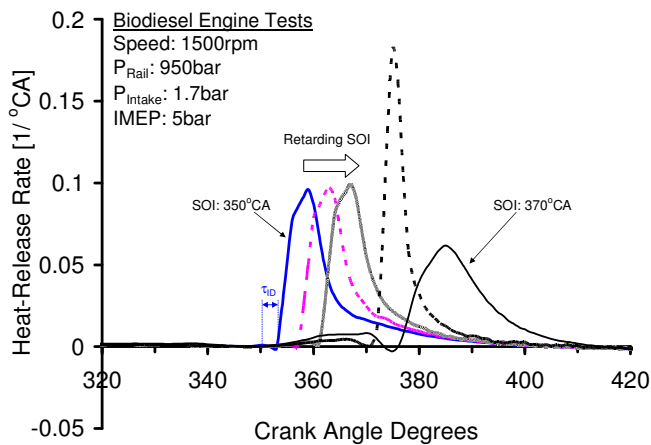


Figure 3. Variation of heat-release rate with SOI at 5bar IMEP.

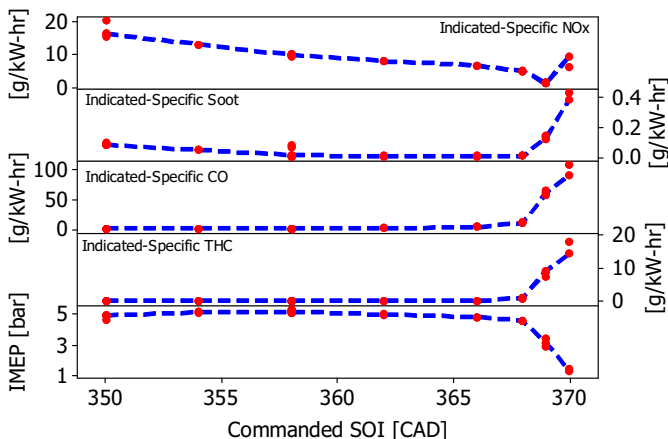


Figure 4. Variation of NO_x , soot, CO and THC with SOI at 5bar IMEP.

TEST B: BIODIESEL EGR SWEEP AT LOW LOAD

Figure 5 to Figure 7 present the Biodiesel test results for the EGR sweep at low load conditions, Test B in Table 2. As the EGR was increased, the peak cylinder pressures (Figure 5) only slightly decreased with no noticeable effect in the $(dP/d\theta)_{\text{Max}}$. The effect of EGR at low load conditions was not apparent because of the limited available CO_2 concentration. Noted, at 55% EGR the intake concentrations of O_2 and CO_2 were 17 and 3%, respectively, resulting in only a slight combustion-phasing retard (Figure 6).

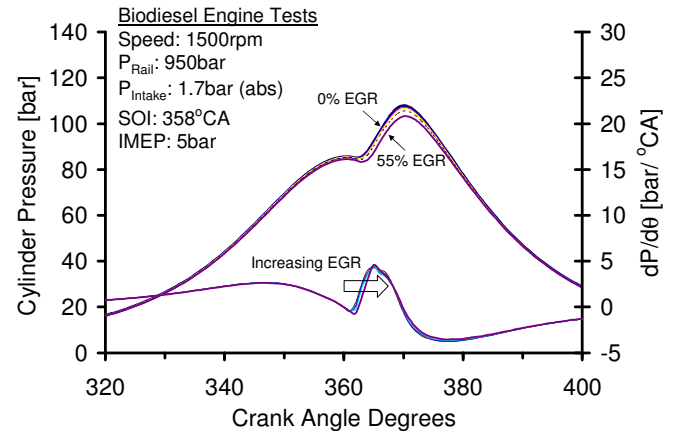


Figure 5. Variation of cylinder pressure and $dP/d\theta$ EGR at 5bar IMEP.

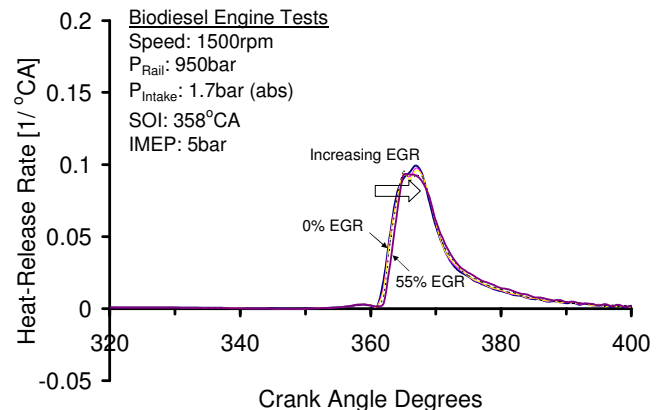


Figure 6. Variation of heat-release rate with EGR at 5bar IMEP.

The engine-out NO_x emissions decreased with increasing EGR but there was only minimal effect on the soot, CO, THC and IMEP (Figure 7). A further increase in the EGR, combined with the SOI adjustment implemented through, for instance, adaptive control schemes [28,29], may provide a potential solution for the energy-efficient Biodiesel LTC in common-rail diesel engines at low load conditions. In a high-loop variable turbocharger (VGT) configuration, the energy delivered to the turbine stage at low loads may not be enough to attain such high boost pressures [5]. Therefore, an intake throttle valve could be employed to increase the