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A NEW TECHNIQUE TO ENABLE DIESEL ENGINES TO AUTONOMOUSLY OPERATE ON DIFFERENT MILITARY FUELS

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SUMMARY

Autonomous operation of diesel engines using different military fuels faces many challenges. Engines should be able to use Jet Propellant-8 (JP-8) fuel, as well as alternate and renewable fuels intended to replace petroleum-derived jet or diesel fuels. These fuels can have wide ranges of physical and chemical properties. In addition, diesel engines that power military ground vehicles are originally manufactured for commercial applications which are equipped with additional after treatment devices needed to the meet emission standards. Such devices are not needed in military vehicles. However, commercial engines and after treatment devices are calibrated as one system to meet the emission targets, causing some penalty in fuel economy and peak power. These engines should be recalibrated to produce the highest power density and the best fuel economy required in military vehicles. Furthermore, commercial engines are optimized to operate on ULSD (Ultra Low Sulfur Diesel) fuel, which has narrow specifications. This is not the case in military engines which should be able to operate on JP-8 and other approved alternate fuels which have wide ranges of Cetane Numbers (CN), density, and volatility. It should be noted that all these challenges are related to the combustion process. This paper presents a new technique developed to sense and control the combustion process for different fuels. This technique is based on the ionization in hydrocarbon-air flames. The measured ion current is analyzed in detail to determine the autoignition and combustion characteristic of the fuel used in the engine. This is followed by the development of a control strategy to phase the combustion process of different fuels in order to achieve the targets of improved fuel economy, high power density and reduced soot emissions in military vehicles.

MOTIVATION

Military ground vehicles are powered by diesel engines which are originally produced for use in commercial vehicles. Meanwhile, the production targets of commercial vehicles do not meet the needs of military vehicles. For example, the peak power and fuel economy in a commercial vehicle can be compromised in order to meet some emission standards. In military vehicles, high power density and best fuel economy are among the highest priorities in the operation of the diesel engine. In addition, commercial vehicles use conventional fuels such as ULSD fuel which have narrow specifications. This is not the case for military vehicles which are required, according to the Single Fuel Policy, to use kerosene-based, aviation-grade (jet) fuel (JP-8, JP-5, Jet A-1 with military additives). These aviation fuels have a wide range of properties, particularly as related to the cetane number (CN) which can vary from 25 to 65. Furthermore, military vehicles should be able to operate on synthetic or renewable fuels that are approved drop-ins to replace JP-8. Therefore, there is a need to modify the commercial diesel engines to meet the military needs of high power density and best fuel economy while operating on allowed jet and diesel fuels which have a wide range of physical and chemical properties.

Modifications of commercial engines for military applications include removal of the after treatment devices and the elimination of the EGR and its cooling system. In addition, the ECU (Engine Control Unit) should be reprogrammed for high power density and best fuel economy. Use of an in-cylinder combustion sensor that produces a feedback signal to the ECU would allow for further optimization of this conversion process.

IN-CYLINDER COMBUSTION SENSORS

Two types of in-cylinder combustion sensors have been under research and development: the gas pressure transducer and the ion current sensor. In this paper, the ion current sensor has been chosen, because it produces a signal which carries basic information about the autoignition and combustion properties of the fuel and the composition of the cylinder gases. This is in addition to its low cost and easy installation in the cylinder head. The glow plug or the fuel injector can be used as an ion current sensor [10].

SOURCES OF THE ION CURRENT

Extensive investigations on hydrocarbon-air flames reported that ionization is produced by chemical reactions and thermal effects.

Chemi-Ionization

Chemi-ionization in hydrocarbon-air flames is initiated, mainly by a reaction of the CH radical with the oxygen atom and C_2H_2 , followed by reactions between CHO^+ and CH_2, H_2O and NO, according to the following [1-6]:

$$CH + O \Leftrightarrow CHO^+ + e^- \quad \text{.............(1)}$$

$$CH + C_2H_2 \Leftrightarrow C_3H_3^{\;+} + e^- \quad \text{.............(2)}$$

$$CHO^+ + CH_2 \Leftrightarrow CH_3^{\;+} + CO \quad \text{.............(3)}$$

$$CHO^+ + H_2O \Leftrightarrow H_3O^+ + CO \quad \text{.............(4)}$$

$$CHO^+ + NO \Leftrightarrow NO^+ + CHO \quad \text{......... (5)}$$

Thermal-Ionization

At high temperatures a molecule with a low ionization potential such as NO can be ionized [7] according to:

$$NO \Leftrightarrow NO^+ + e^- \quad \text{.............(6)}$$

Equations (1) to (6) represent ionization in the combustion products of a mixture a hydrocarbon and air at equivalence ratios close to unity. This is not the case in diesel combustion where the charge is heterogeneous and contains areas where the mixture is rich. A recent study by Estefanous [9] showed that heavy hydrocarbons contribute to ionization in fuel rich mixtures. In diesel engines the charge quality can vary from very lean to very rich. The study concluded that the ionization in diesel engines is due to combustion product of rich mixtures such as $C_7H_5^+$, $C_9H_7^+$, $C_{13}H_9^+$, in addition to reactions (1) to (6).

EXPERIMENTAL SETUP

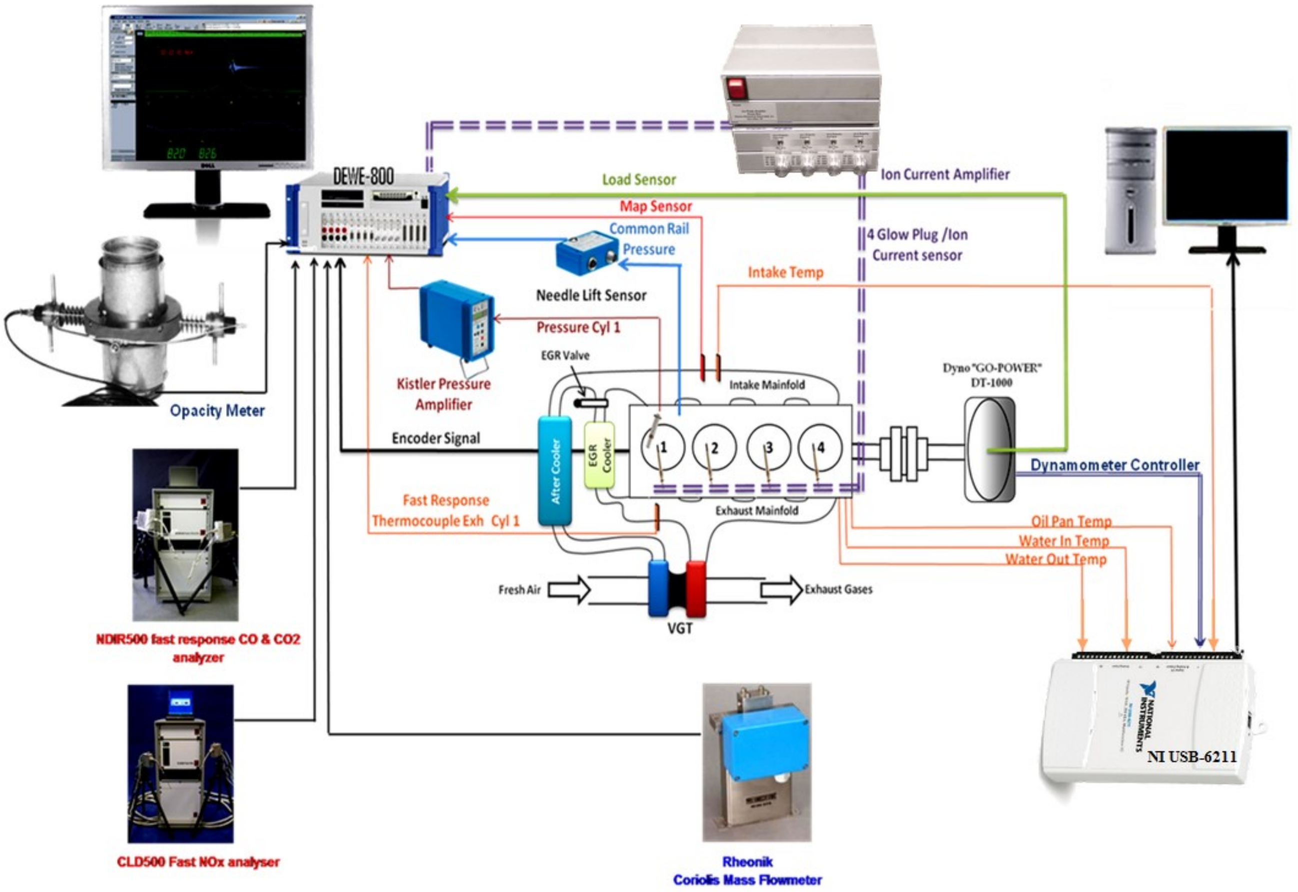

Figure 1. . Layout of the experimental setup [11].

Figure (1) shows the engine, instrumentation and data acquisition system. The engine is loaded using a hydraulic dynamometer. A load cell is installed between the engine crank shaft and the hydraulic dynamometer to measure the instantaneous torque developed by the engine. The positions of the crankshaft and engine speed are determined by an optical encoder, with a resolution of 0.25 CAD, fitted to the front of the engine. Each of the four cylinders is fitted with a glow plug which was modified to act as ion sensing probe in addition to its original function of heating the cylinder gases. Cylinder number 1 is fitted with a Kistler piezo gas pressure transducer, an injector fitted with a needle lift sensor, a Kistler resistive sensor mounted on the high pressure line, as near as possible to its

Injector and a fast response thermocouple in its exhaust manifold. A fuel measuring system based on a Coriolis mass flow meter was used to measure the fuel mass flow rate. Several high speed and low speed response thermocouples are installed on the engine to monitor different temperatures including the intake, the exhaust, cooling water and oil sump. A Dewe-800 combustion analyzer was used to record the signals based on the crank angle degrees.

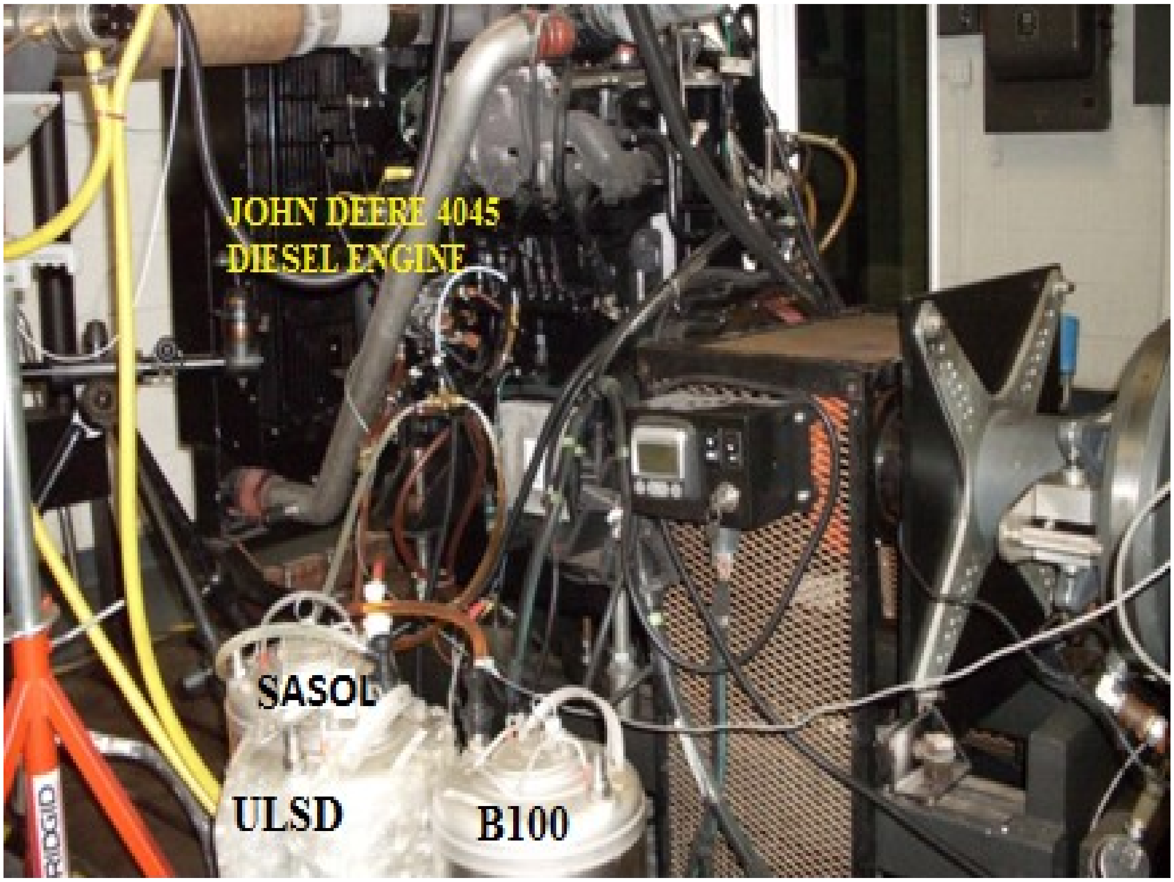

Figure 2. John Deere 4045 diesel turbocharged diesel engine, connected to a hydraulic dynamometer and three fuel tanks for ULSD, SASOL IPK and Biodiesel.

Engine

The engine is a 4-cylinder, 16-valve, diameter of 106 mm, stroke of 127mm and compression ratio of 17:1, equipped with a variable geometry turbocharger (VGT) and a common rail injection system. Figure (2) is photograph of the experimental setup, showing the engine and three fuel tanks for ULSD, low-ignition quality SASOL IPK and 100% Biodiesel (B100). Note, this paper does not include results for Biodiesel as it is not approved for use in military vehicles.

Ion Current Electric Circuit

Figure 3 shows the ion current electric circuit that consists of a glow plug, a 100 V source and a 50 ohm resistor. The tip of the glow plug acts as an ionization sensor. The whole plug is insulated from the engine ground to form one electrode. The rest of the engine acts as the other electrode [8].

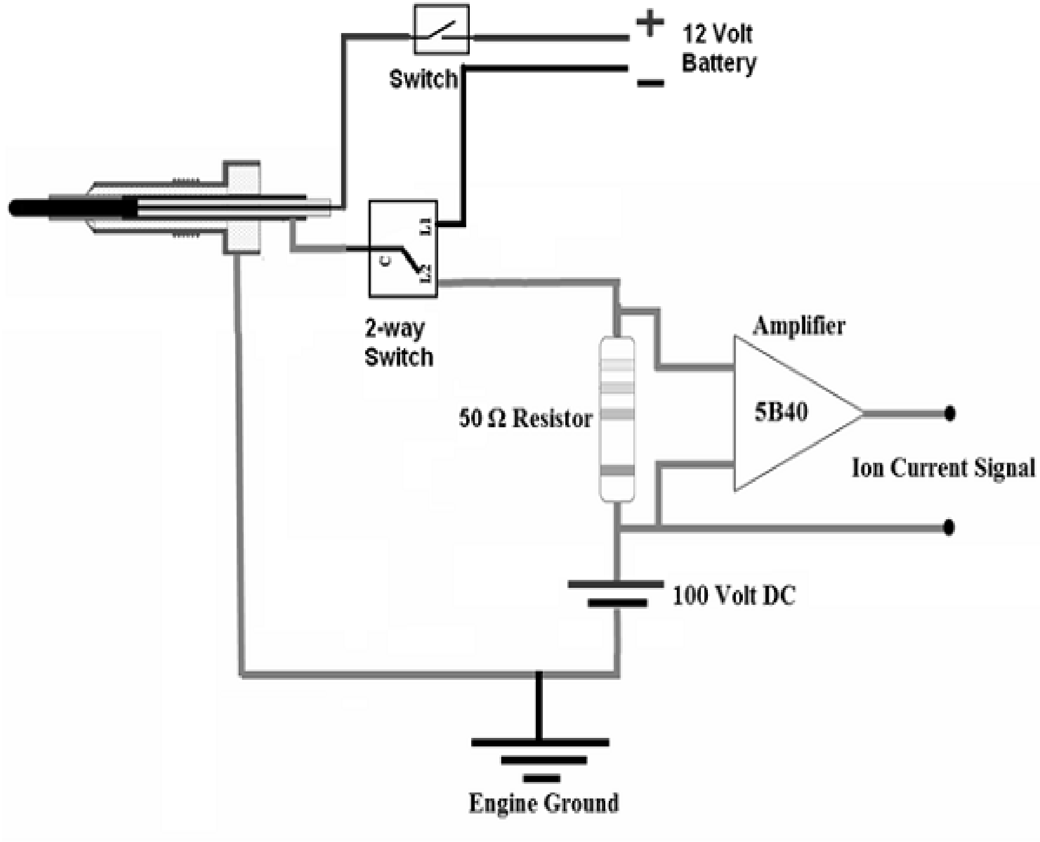

Figure 3. Ion current electric circuit and glow plug activation circuit.

Figure 4. A glow plug modified to act as an ion current sensor in addition to its original function to work as a glow plug.

Figure 4 shows an ion current sensor made in our labs from two glow plugs. The voltage across the resistor is measured, amplified and recorded as an indicator of the ion current. The ion current circuit is coupled with a glow plug activation circuit which is electronically controlled to burn off any accumulated soot deposits on the sensor.

CHARACTERISTICS OF THE ION CURRENT SIGNAL

Figure 5 shows sample traces for the cylinder gas pressure, rate of heat release (RHR), ion current, rate of change of the ion current and needle lift (N.L). The needle lift indicates the start of injection (SOI). The cylinder pressure indicates the start of combustion, peak cylinder gas pressure and its location (LPP). The ion current signal and its rate of change indicate the start of ion current (SIC), the peak of the ion current produced by the premixed combustion (I_1) and its location (i_1). I_1 is mainly produced by H_3O^+ according to reactions 1, 2 and 3. The peak of the ion current due to the mixing and diffusion controlled combustion amplitude is (I_2) and its location (i_2). (I_2) is mainly produced by (a) the ionized heavy hydrocarbons, including soot precursors and soot particles formed during the diffusion and mixing controlled combustion fraction [9] and (b) chemi-ionized and thermally ionized NO [9]. The locations of I_1 and I_2 relative to TDC are other parameters used in the analysis.

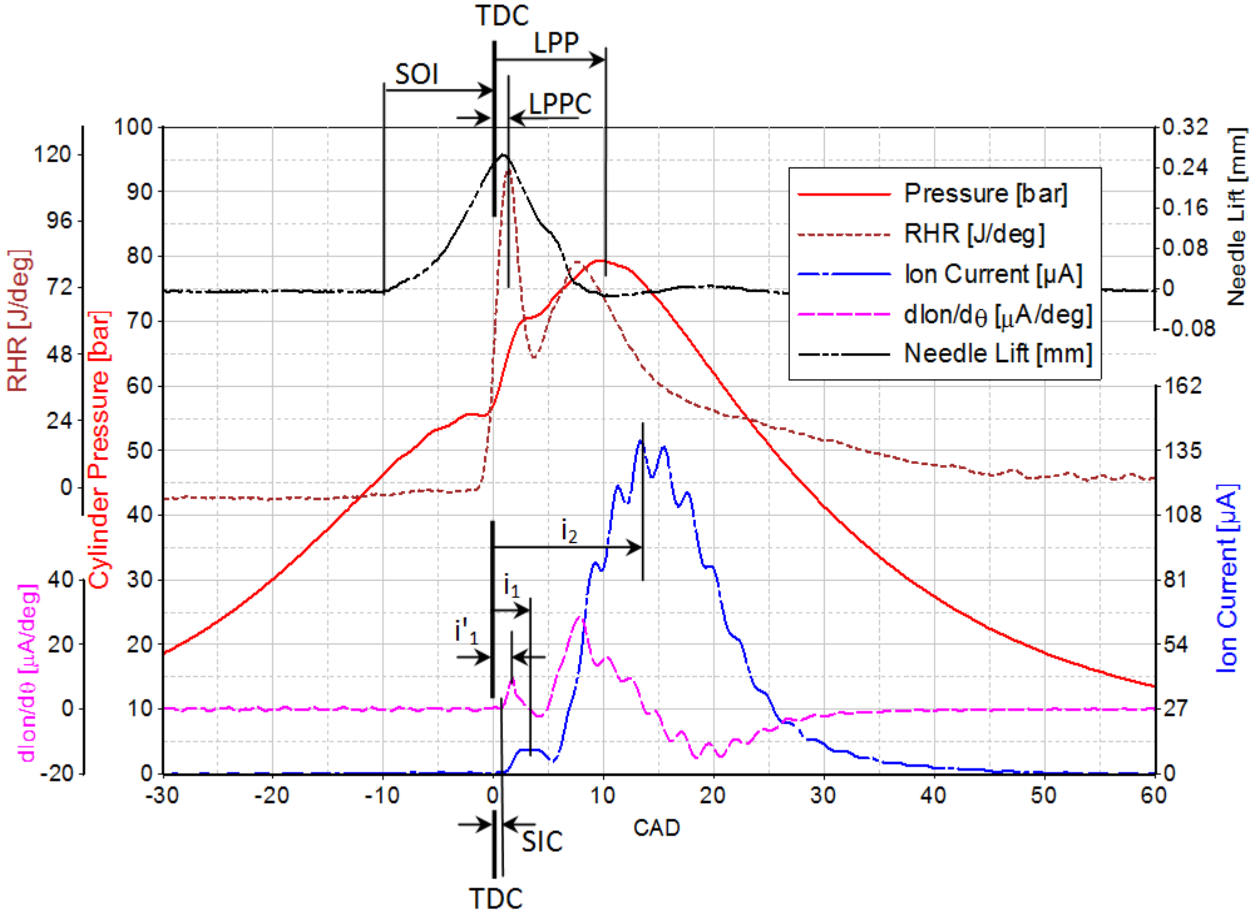

Figure 5. Cylinder gas pressure, needle lift, RHR, ion current traces in a diesel engine [IMEP=8 bar, Const. Speed=1800RPM, SOI=10° bTDC, Inj. Press=900bar] [11].

The RHR is calculated from the pressure signal and indicates the peak of the premixed combustion amplitude and its location (LPPC). These parameters are used in the technique presented in this paper to determine the autoignition and combustion characteristics of the supplied fuels. The ion current is used as a feedback signal into an open WSU-ECU to adjust different engine operating parameters in real time and properly phase the combustion process of the fuel supplied to the engine [11].

COMBUSTION PHASE CONTROL

Figure 6 shows three sets of traces for the needle lift, cylinder gas pressure and ion current, while the engine was controlled by the production ECU. One set is for the engine operation using ULSD. Another set is for the operation of the engine using the low CN SASOL IPK fuel. The third set is for a mixture of the two fuels formed during the flushing period.

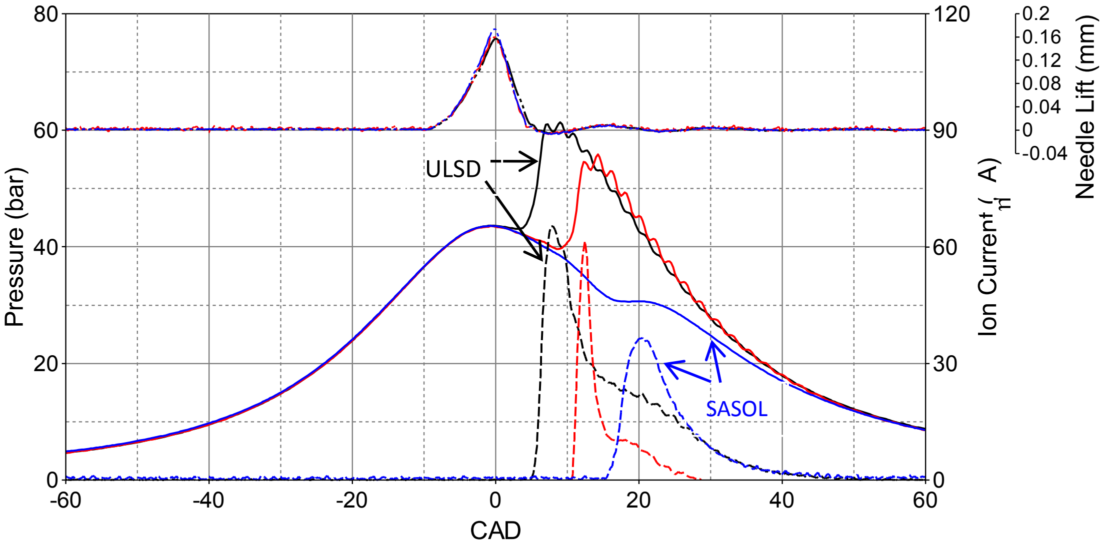

Figure 6. Traces for needle lift, cylinder pressure, and ion current when John Deere engine used USLD, mixture of (ULSD and SASOL IPK), and SASOL IPK, under the control of the production ECU.

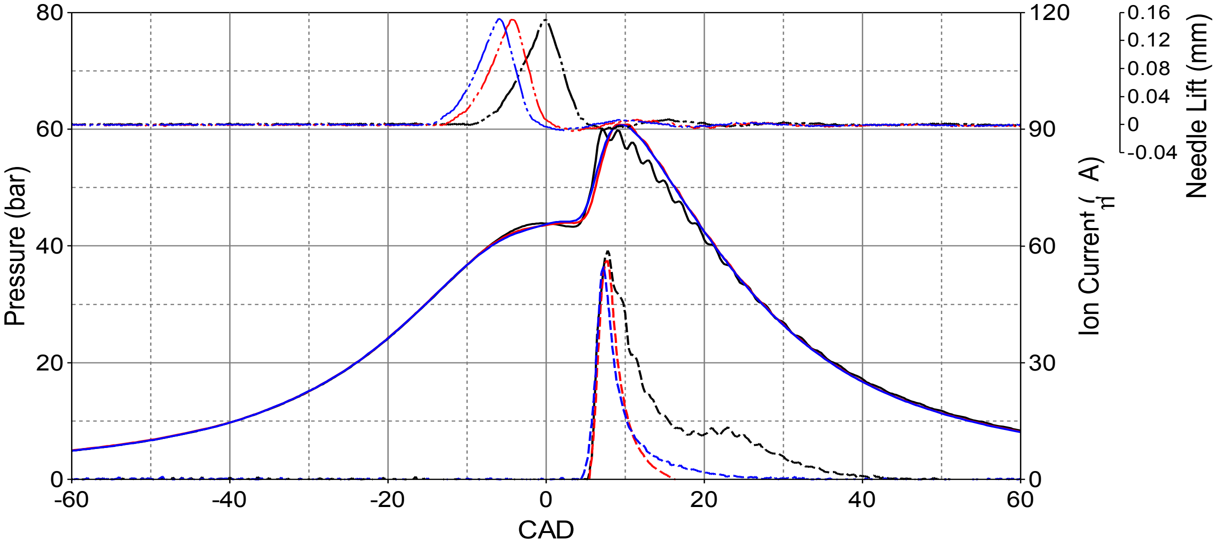

Figure 7. Traces for needle lift, cylinder pressure, and ion current when John Deere engine used USLD, mixture of (ULSD and SASOL IPK), and SASOL IPK, under the control of WSU ECU fed by the ion current signal**.**

It should be noted that the start of injection, as can be seen in the needle lift traces, was the same for the three fuels. This caused the start of combustion of SASOL IPK to occur much later than ULSD in the expansion stroke.

Figure 7 shows the same traces when the engine control was shifted from the production ECU to WSU ECU. WSU ECU is fed by the ion current signal to keep the same combustion phasing for all the fuels, in real time, irrespective of the variations in their physical and chemical properties. Combustion phasing was kept the same by controlling the start of injection, as depicted

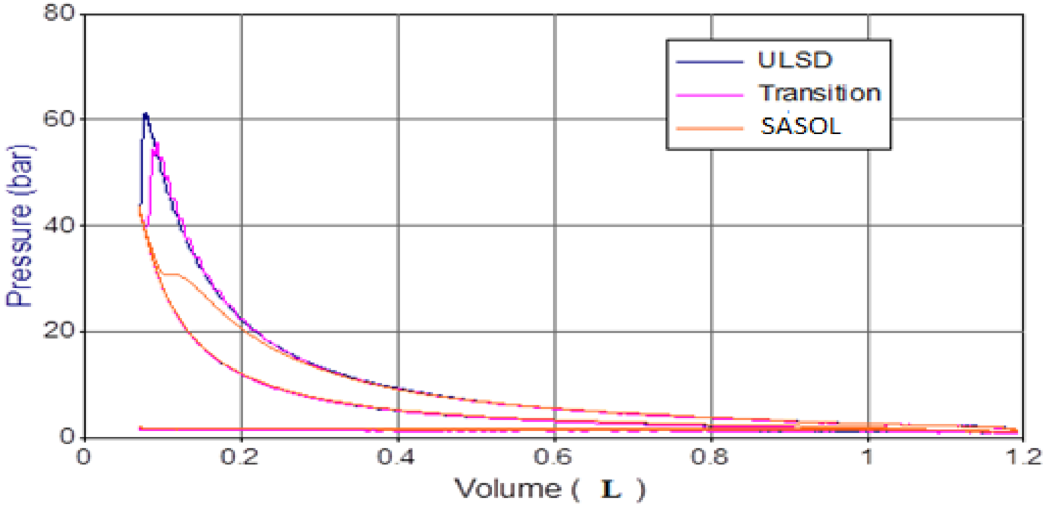

Figure 8. P-V diagrams when John Deere engine used USLD, mixture of (ULSD and SASOL IPK), and SASOL IPK, under the control of the production ECU.

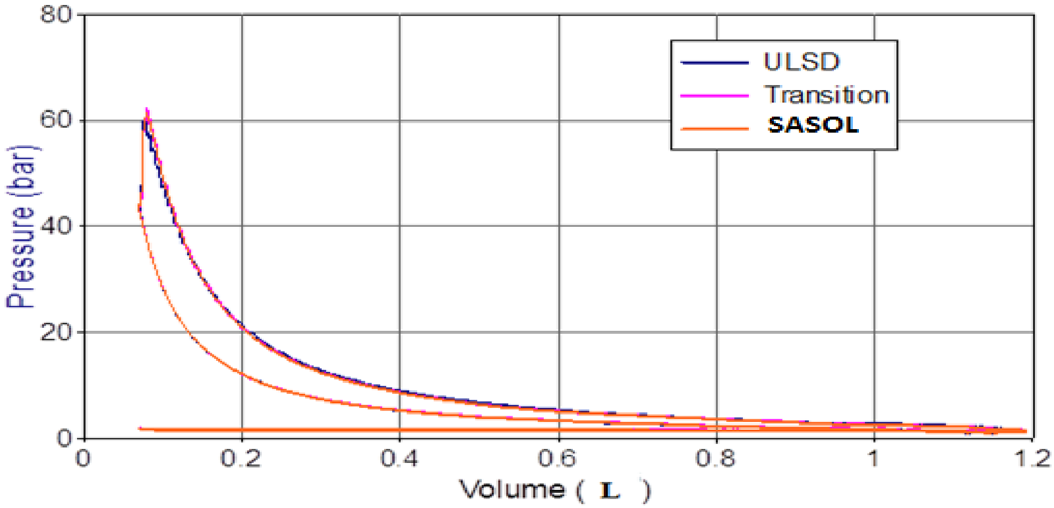

Figure 8. P-V diagrams when John Deere engine used USLD, mixture of (ULSD and SASOL IPK), and SASOL IPK, under the control of WSU ECU.

by the needle lift traces for the two fuels. Start of injection for SASOL was eight CAD earlier than the start of injection for ULSD.

Effect of using SASOL on engine power output

The effect on indicated power output can be determined from the area enclosed in the P-V diagram. Figure 7 shows the P-V diagrams measured when the engine used ULSD, a mixture of ULSD and SASOL IPK, and 100% SASOL IPK fuels under the control of the production ECU. The loss in the useful work done by the gases on the piston during the expansion stroke is clear when the fuel was changed from ULSD to SASOL IPK. This loss was caused by the long ignition delay of SASOL IPK compared to ULSD. The loss in power was 25%.

Figure 9 shows the P-V diagrams measured when the engine was operating at the same conditions of Fig. 7, except for the use of WSU ECU instead of the production ECU to control the engine. It is clear that the losses in power observed in Figure 8 were eliminated and the engine gained its power using SASOL IPK fuel.

AUTONOMOUS OPERATION OF JOHN DEERE DIESEL ENGINE ON ULSD AND SASOL IPK

The autonomous operation of John Deere engine on ULSD of 45.3 CN, SASOL IPK of 31CN and 100% Biodiesel was demonstrated in the Lab at WSU under different steady state speeds and loads and under transient operating conditions. The specifications of these fuels are given in Table1 in the appendix. In this paper, a sample of the traces is given for one case, when the fuel supply to the engine was changed back and forth from a good ignition quality ULSD to a low ignition quality SASOL IPK. A comparison was made between the engine operation under the control of the production ECU and under the control of WSU ECU. WSU ECU had a feedback signal developed by a new analytical technique of the ion current signal.

Figure 9 shows traces for the peak cylinder gas pressure, SIC, LPPC, indicated mean effective pressure (IMEP), and SOI. It shows the variations in these parameters during 1900 consecutive cycles (3800 revolution in 152 second) during which the engine was supplied with a good ignition quality (ULSD) fuel of 47 CN and a poor ignition quality SASOL IPK fuel of 31 CN. It should be noted that SASOL IPK takes a longer time to auto-ignite compared to ULSD.

Figure 9 has two main sections. In the first section (first 870 cycles) the engine was under the control of its production ECU. In the second section (cycles 871 to 1900), the engine control was switched from the production ECU to WSU ECU. The following paragraphs compare the engine operation in these two sections under the control of the two ECUs.

Figure 9 indicates a steady engine operation in the first period (P_1) of 340 cycles when ULSD fuel was used. The cylinder gas peak pressure reached 67 bar. The SIC and LPPC were both at 4.5° CAD (crank angle degrees). The indicated mean effective pressure (IMEP) was 3.85 bar and the start of injection (SOI) was at -7° CAD. In the second period (P_2), from cycle 341 to cycle 465, the fuel supply was changed from ULSD to SASOL IPK. The figure shows that the engine production ECU did not change the SOI and the peak cylinder gas

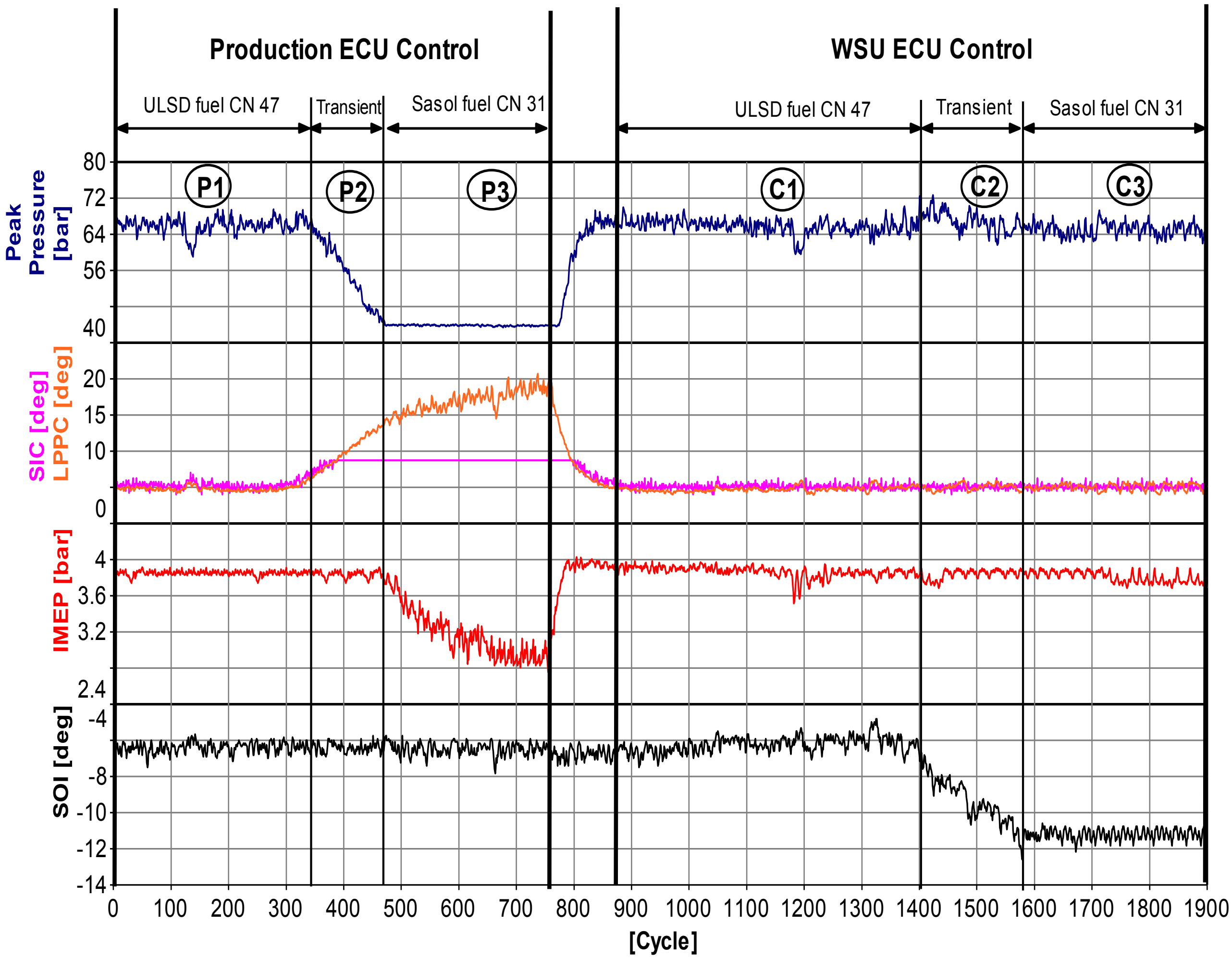

Figure 9. Effect of changing the fuel from ULSD to SASOL IPK on the operation of John Deere engine while under the control of the production ECU and WSU ECU.

pressure dropped during period P2 and reached a value lower than 44 bar, which is the cylinder gas compression pressure without combustion. The peak pressure recorded for the cycles during period P2 was the compression pressure. But, how low the peak gas pressure was in these cycles cannot be obtained from Fig. 9. Figure 6 shows that for SASL the peak cylinder gas pressure was 30 bar, while the compression pressure was 44 bar. The drop in the peak gas pressure is caused by the late combustion of the fuel in the expansion stroke. The late start of combustion is clear from the SIC and LPPC traces. In the third period,(P_3), from cycle 465 to cycle 760, the production ECU did not change the SOI and caused a drop in the IMEP from 3.85 to 2.90 bar, or a 25% drop in power. At cycle 760, the fuel was changed back to ULSD fuel, where the combustion started earlier and the engine gained power and IMEP was restored back to 3.85Bar. At cycle 870, WSU ECU started to control the engine.

Engine operation under the control of WSU ECU

During period (C_1), the engine was under the control of WSU ECU using ULSD. The values for the peak gas pressure, SIC, LPPC, SOI and IMEP were equal to those under the production ECU as explained earlier. At cycle 1400, the fuel was changed from ULSD to SASOL IPK, during period (C_2). The transition to Sasol IPK fuel was complete in cycle 1570. It should be noted that during the transition period (C_2), WSU ECU advanced the SOI from -7° to -11.5° CAD to compensate for the longer ignition delay of SASOL IPK fuel. The advancement of combustion process is clear in SIC and LPPC traces. The peak pressure remained at 67 bar under the command of WSU-ECU, while it dropped to 44 bar under the command of the production ECU. Furthermore, the IMEP under WSU ECU remained at 3.85 bar while it dropped to 2.9 bar under the production ECU. Therefore, engine power was maintained in spite of the switch to a fuel with different combustion characteristics.

CONCLUSIONS

These conclusions are based on an experimental investigation on a John Deere 4045, 4-cylinder, turbocharged diesel engine equipped with a common rail injection system and solenoid operated injectors. The engine was equipped with an open ECU referred to as WSU ECU, in addition to the production ECU. An ion current sensor, constructed from two glow plugs, was installed in the cylinder head of each cylinder. The ion current signal was processed using a new technique and fed into WSU ECU to control the engine for autonomous operation on SASOL IPK, a low ignition quality kerosene-based jet fuel of 31 CN, and ULSD fuel of 45 CN.

1. Changing the fuel from ULSD to SASOL IPK, with the engine controlled by the production ECU caused a 25% drop in engine power, under the operating conditions specified in this investigation.
2. The ion current signal carries basic information about the autoignition and combustion characteristics of the fuel, and has been successfully processed and used as a feedback signal to an open WSU ECU to control the combustion phasing of different fuels.
3. The autonomous operation of John Deere diesel engine on military fuels which have a wide range of physical and chemical properties has been demonstrated on tests conducted using ULSD of 45 CN and SASOL IPK of 31 CN.

RECOMMENDATIONS

1. Extend the investigation to engines equipped with other types of fuel injection systems such as the Unit Injector and HEUI systems
2. Investigate the use of the ion current signal for the feedback control of diesel engines under different injection strategies, such as pilot and split injections.
3. Investigate the use of ion current to predict several engine performance and emissions parameters for use in engine feedback control and for on board diagnostics.

NOMENCLATURE

CAD: Crank Angle Degree
CN: Cetane Number
ECU: Engine Control Unit
EGR: Exhaust Gas Recirculation
IMEP: Indicated Mean Effective Pressure
i_x: Location of Ion Current Peak number x.
I_x: Ion current Peak number x
kg: Kilogram
LPP: Location of the Peak Gas Pressure
LPPC: Location of the Peak of RHR due to Premixed Combustion
MJ: Mega Joule
NL: Needle Lift
NO: Nitric Oxide
P: Gas pressure
RHR: Rate of Heat Release
SIC: Start of Ion Current
SOI: Start of Injection
TDC: Top Dead Center
ULSD: Ultra Low Sulfur Diesel
V: Volume of Gas
VGT: Variable Geometry Turbocharger
WSU: Wayne State University
θ: Crank Angle

APPENDIX

Table 1: Fuel specifications

	ULSD	SASOL IPK	B100
Density Kg/m3	836.5	754.3	830
Cetane Number	45.3	31	47.5
Flash Point (^{o}C)	64	53	157
Heating Value (MJ/kg)	41.2	43.3	35.98

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