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A Method of Determination of the Start and End of Combustion in a Direct Injection Diesel Engine Using the Net Heat Release Rate

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***Abstract*— Biodiesels have been reported to produce higher amounts of NOx and other regulated emissions as opposed to neat diesel. The use of biofuels in the Philippines is mandated by Republic Act 9467. Concurrently, RA 8749 regulates, among other sources, emissions of compression ignition engines. This necessitates further analysis on the use of biodiesel blends in conventional diesel engines in order to check conformance with both laws. With the country recently acquiring a sophisticated engine test facility, users need to be given procedures in order to facilitate their investigations. Studies suggest that the amount of biodiesel emissions are related to ignition delay and combustion duration of diesel engines due to engine system response to the properties of biodiesels. Ignition delay is the duration in crank angle from the start of injection (SOI) of fuel into the engine cylinder until the start of combustion (SOC) of the fuel-air mixture. The combustion duration is the duration in crank angle bounded SOC and end of combustion (EOC). For compression-ignition engines, such as diesel engines, several approaches were developed and utilized in order to pinpoint the crank angle for the SOI, SOC and EOC. Some of these approaches required the use of specialized and dedicated equipment that would be found only in facilities that could afford to acquire them. Other methods estimated SOC using maximum of the 2nd or 3rd order derivatives of recorded in-cylinder pressures. These pressure data may also be utilized together with the corresponding cylinder volumes to generate the net heat release rate (NHRR), which shows the trend of heat transfer to the gases enclosed in the engine cylinder. The start of combustion is then determined at the point where the value of the NHRR is minimum and followed by a rapid increase in value, whereas the EOC is at the crank angle where the NHRR becomes zero prior to the exhaust stroke of the engine. In this study, a method of determining SOI, SOC and EOC was developed using injection line and in-cylinder pressures data recorded from tests of a common rail direct injection diesel engine. This proposed method was then matched against two distinct test criteria for SOC to test its feasibility and results have shown conformance to the two criteria.**

Keywords— common rail direct injection (CRDI) compression-ignition engines, start of injection, start of combustion, ignition delay, end of combustion, net heat release rate

1. INTRODUCTION

Republic Act 9467, also known as the Philippine Biofuels Act of 2006 mandates, for diesel engines, the use of biodiesel blends with blend ratios to be increased from the time of implementation. One of the major concerns regarding the use, especially, of biodiesel blends in conventional compression ignition diesel engines is the production of nitrous oxides (NO_x), one of the exhaust emissions regulated in clean air standards, Republic Act 8749 (The Philippine Clean Air Act of 1999) being one of these. In order to assess conformance to these two laws, studies on coco-methyl esters (CMEs), the chief biodiesel produced in the country, need to be performed on a sustained basis, especially with the limits dictated by RA 8749 being decreased in the future. It is only recent that the country has acquired certification-grade test facilities such as the UP Vehicle Research and Testing Laboratory, thus presenting opportunities to perform these tests in the Philippine context. For aspiring users of the laboratory, the development of methods of analysis derived from existing procedures to facilitate their investigations could be beneficial.

Studies on biodiesels worldwide have shown that there is a general increase in NO_x production from biodiesel use as opposed to neat diesel, as summarized by Lapuerta et al [1]. Nitrous oxides are the result of chemical reactions involving oxygen and nitrogen and there are three mechanisms that lead to the production of NOx [2]:

- Thermal NOx is the product of nitrogen and oxygen during combustion, through the extended Zeldovich mechanism, Equation [1].

$$\begin{aligned} O + N_2 &\rightleftarrows NO + N \\ N + O_2 &\rightleftarrows NO + O \\ N + OH &\rightleftarrows NO + H \end{aligned} \tag{1}$$

- Fuel NOx is brought about by fuels with nitrogen content (e.g., coal). Determination of fuel NOx in biodiesels is excluded because of the absence of nitrogen in their chemical compositions.
- The formation of the third type, prompt (Fenimore) NOx, begins with free radicals of molecular nitrogen in the air combining with fuel in combustion. This is a rapid process and takes place before the thermal NOx process during combustion.

Of these three mechanisms, thermal NOx was seen as the primary opportunity for NOx production in internal combustion compression ignition diesel engines running even on conventional diesel fuel, especially since such engines were designed to operate on fuel-lean mixtures.

Properties of biodiesels (in comparison to those of neat diesel) that were observed to influence diesel engine system response are lower calorific content (which lead to increased fuel delivery to engines), and higher viscosities and densities, which primarily engine affect fuel-injection systems [14]. In turn, effects on fuel injection systems lead to the following engine system responses:

- Injection timings could be advanced because of the higher densities of biodiesel blends. This could lead to increased ignition delay, allowing for longer durations for premix to form and the consequent elevated premix combustion temperatures.
- Combustion duration could be decreased by the resulting elevated in-cylinder temperatures, thus setting the conditions for increased thermal NOx formation.

In compression ignition engines operating on the four-stroke cycle, there are four phases during the combustion stroke, reflected in crank-angle degrees. This begins with the injection delay, which is takes place from the time fuel is injected into the engine cylinder up to the moment of the fuel-air mixture begins to ignite. This is followed by the premixed or rapid combustion phase, where the initial combustion of fuel-air mixture commences due to elevated in-cylinder temperatures brought about by the compression phase. The third phase is the diffusion or mixing-controlled combustion, where the main bulk of the fuel-air mixture is burned due to the high temperatures produced during premix combustion. The rate of combustion in this phase is controlled by the mixing of fuel and air. Late combustion occurs into the expansion stroke and is the final phase of the combustion process [3].

In order to properly define the different phases of combustion processes in compression ignition engines, the crank angles at the start of injection (SOI), start of combustion (SOC) and end of combustion (EOC) need be identified. From these indicators, the ignition delay and the duration of combustion, i.e., the crank angle difference between the EOC and SOC, may be determined. From here, the influence of CME's, in particular, on system response could be better analyzed.

There are various approaches in the determination of SOI, SOC and EOC. Experimental optical-access diesel engines are fitted with mirrors and viewing windows to allow for direct viewing of combustion processes and high-speed photography or laser-light scattering have been employed for determination of combustion duration. SOI could also be determined using a needle-lift sensor, an instrument that is attached to the fuel injector and indicates the timing of its opening. Acquisition of such set-ups may prove expensive for some institutions, however, the UP VRTL being one of these due to financial constraints.

In lieu of needle-lift sensors, an alternative approach suggested by Canacki [4] is to determine the timing when the fuel injection line pressure reaches the injector nozzle opening pressure. This is possible if there is a pressure transducer attached to the injector line to record the pressure during fuel injection. Figure 1 is a diagram of the line pressure readings from 60° BTDC to 180° ATDC recorded on a transducer installed in a common rail direct injection system of a diesel engine.

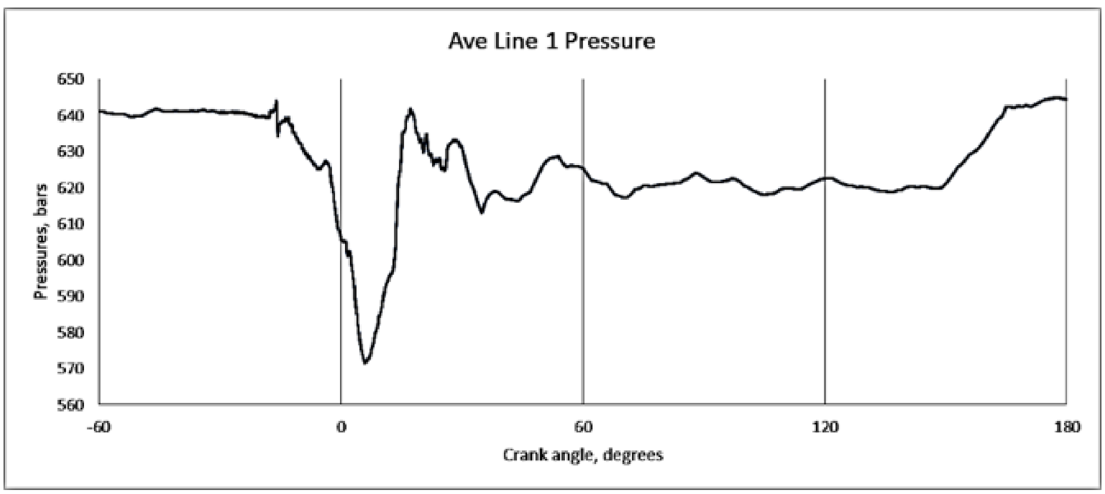


Figure 1. Pressure diagram of injector 1 line generated from test data

1.1 In-Cylinder Pressure

Engines may also be outfitted with dedicated pressure transducers that measure in-cylinder pressures. The data generated by these transducers could be processed and interpreted in order to determine the SOC, EOC and, consequently, the duration of combustion. Figure 2 is a pressure-crank angle curve for the compression and expansion (power) strokes (when both intake and exhaust valves are closed, thus enclosing the gases within the cylinder) generated from experimental data.

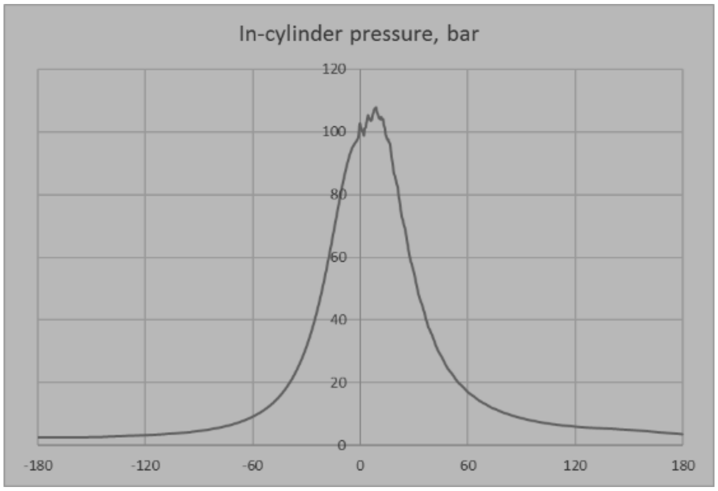


Figure 2. In-cylinder pressure versus crank angle curve from the beginning of the compression stroke to the end of the expansion stroke

In-cylinder pressure increases during the compression stroke. Upon fuel injection, there is a further, rapid increase in pressure as combustion takes place. As the piston moves downward during the expansion stroke, in-cylinder pressure decreases even though combustion may still be taking place.

Assanis et. al. opined that selection of a proper ignition criterion is probably the most controversial issue of ignition study [15]. Several distinct criteria for determining the SOC from the in-cylinder pressure diagram have been proposed and employed. These include, to mention a few, the use of the maximum of the second-order derivative described by Heywood [3] and which used in other related works. In another study, Kratasnik et al [6] claimed the use of the maximum of the third-order derivative of the pressure curve as their criterion. Alkhulaifi and Hamdalla [9] pointed out that the use of the maximum of the second derivative of the in-cylinder pressure curve occurs at a crank angle different from that of the minimum value of the corresponding net heat release rate (to be discussed in the next section), and have opted to use the latter in their study.

1.2 Net Heat Release Rate (NHRR)

A thermodynamic approach to analyzing combustion is through the use of the net heat release rate, NHRR. The heat release rate is used primarily to analyze combustion and yield manifold results depending on established measured parameters. Ferguson and Kirkpatrick [7] define the finite heat release as a differential model of an engine power cycle in which the heat addition is specified as a function of the crank angle. This is derived from the equations of thermodynamics of a closed-mass system and the could be determined using Equation 2 below:

$$\frac{\delta Q}{d\theta} = \frac{\gamma}{\gamma - 1} P(\theta) \frac{dV}{d\theta} + V(\theta) \frac{dP}{d\theta} \tag{2}$$

where:

$\delta Q/d\theta$ = net heat release rate (with respect to crank angle)

γ = the specific heat ratio, determined from in-cylinder pressure and volume data

$P(\theta)$ = measured cylinder pressure as a function of θ
$dP/d\theta$ = the slope of the $P(\theta)$ data
$V(\theta)$ = the in-cylinder volume as a function of θ
$dV/d\theta$ = the crank-angle differential of the in-cylinder volume

The heat release rate may be calculated from Equation 2 using the in-cylinder pressure and volume data for the compression and expansion strokes. There are available software packages to generate the NHRR diagram for the first cylinder of an engine, based on pressure transducer data. A spreadsheet program could also be used to generate this. An example of a computer-generated NHRR diagram of a diesel engine, is shown in Figure 3.

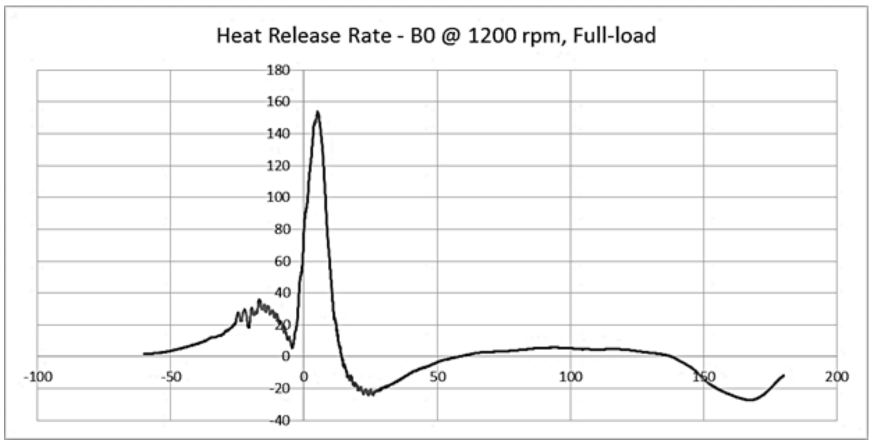


Figure 3. Diagram of net heat release rate (NHRR) of a light duty CRDI diesel engine running at 1200 rpm, generated from test data of in-cylinder pressures and volumes.

The shape of the diagram generated from Equation 2 would depend on the pressure and volume data recorded. It is expected that the in-cylinder volume data would be consistent because of the fixed dimensions of the pistons, connecting rods and cranks. Variations in the shape of the NHRR would thus be influenced by in-cylinder pressure which in turn is brought about by factors affecting combustion due to the engine system response or by the fuel properties, among other possible factors.

Use of the NHRR in analysis of combustion was done in studies, some of which are cited here [10, 11, 12, 13]. In these studies, the SOC was taken to be the point in the NHRR diagram where the slope becomes positive following fuel evaporation. There are instances, though, where the resulting NHRR plot contains noise such that locating the SOC becomes tedious and over-smoothening the curves could lead to inaccuracies. The authors sought to apply an alternative approach in order to facilitate location of the SOI, SOC and EOC using the NHRR.

In this study, the engine used was a 3.0 liter four-cylinder common rail direct injection (CRDI) light duty diesel engine with the engine running on neat diesel. A piezoelectric pressure transducer was installed in the head of the first cylinder to read in-cylinder pressures in bars. Another pressure transducer was installed on the injection line leading to the fuel injector of the first cylinder; readings were likewise in bars. Connections to the solenoid of this injector were also made to record signal voltage. The engine was run under full throttle at 1600, 2000 and 2400 RPM for three trials per speed. Data readings were made for thirty cycles per trial. All data were recorded with respect to crank angle and were post-processed using Concerto software developed by the supplier of the engine test bed. The entire set-up was supplied by AVL.

NOMENCLATURE

CRDI – common rail direct injection
SOI – start of ignition
SOC – start of combustion
EOC – end of combustion
NHRR – net heat release rate
Q – heat transfer, kJ
V – in cylinder volume, cm^3
θ – crank angle, degrees

1.3 Determination of the Start of Injection (SOI)

In order to accurately determine the timing for SOI from the injector line pressure diagram, the voltage signal was used, an example shown in Figure 4. This voltage signal was obtained by attaching leads to the injector solenoid and connecting these to the console leading to the computer used in operating the engine test set-up.

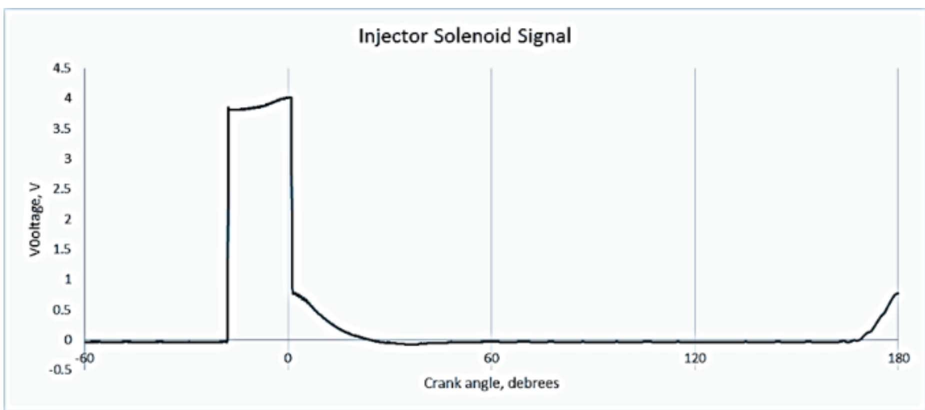


Figure 4. Diagram of solenoid signal voltages generated from test data

Figure 5 shows the superposition of the solenoid signal voltage and the injector line pressure diagrams. It must be emphasized that both diagrams must have the same scale size for the crank angle.

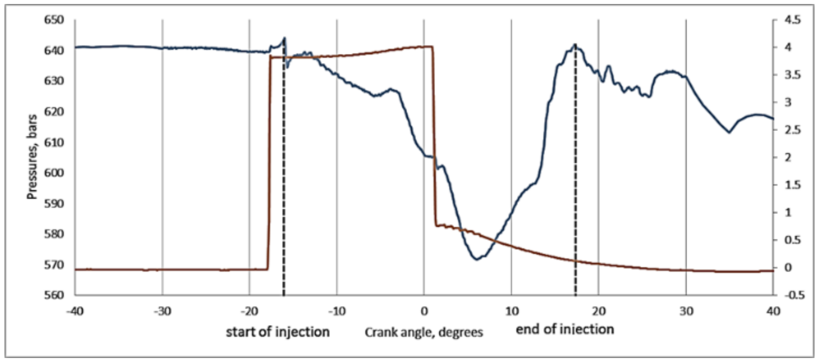


Figure 5. Determination of the crank angles of the start and end of injection by superposition of the injector line 1 pressures and the solenoid signal data

Referring to Figure 5, it could be seen that as the solenoid valve opens, there is a slight pressure build-up in the injection line as the injector needle is being pushed up by the fuel. This is followed by a drop in pressure until the curve reaches a minimum value. At this point, the injector needle begins to close gradually, as seen in the slope of the pressure rise from the minimum value; as the needle closes, fuel is still being injected, albeit at a diminishing rate. The peak pressure after that rise indicates that the injector needle has shut completely and this signifies the end of injection. The crank angle at the end of the injection would be seen to fall outside the range of the crank angles of the solenoid signal. This procedure for this analysis is described by Santos [8].

1.4 Determination of the Start and End of Combustion (SOC and EOC)

Figure 6 contains three diagrams for an engine run at a given speed; these are, in succession, the fuel injection line 1 pressure, the solenoid injection signal and the net heat release rate. The start and end of injection were defined using the method described previously in this paper and these two crank angle positions are highlighted in Figure 6.

As seen in Figure 6, the start of combustion (SOC) is the crank angle at the point of local minimum of the NHRR diagram that is within the interval of the start and end of injection (SOI and EOI, respectively). The positive values in the NHRR diagram before the SOI may be attributed to heating of the enclosed gases due to compression as there was no combustion that took place in that period. Note that the NHRR drops from the first peak coincident with the start of injection. This could be interpreted as prior to combustion; the injected fuel momentarily cooled the in-cylinder gases.

The end of combustion (EOC) was designated to be the crank angle beyond EOI, where the NHRR diagram crosses zero near the end of the expansion stroke at 180° crank angle, based on the premise that heat transfer within the cylinder has ceased because the fuel charge has been completely combusted. If the NHRR values are still positive at the end of the expansion stroke, incomplete combustion would be assumed and the end of combustion would be assigned at 180° crank angle. The combustion duration could then be determined as the difference between the EOC and the SOC, in crank-angle degrees.

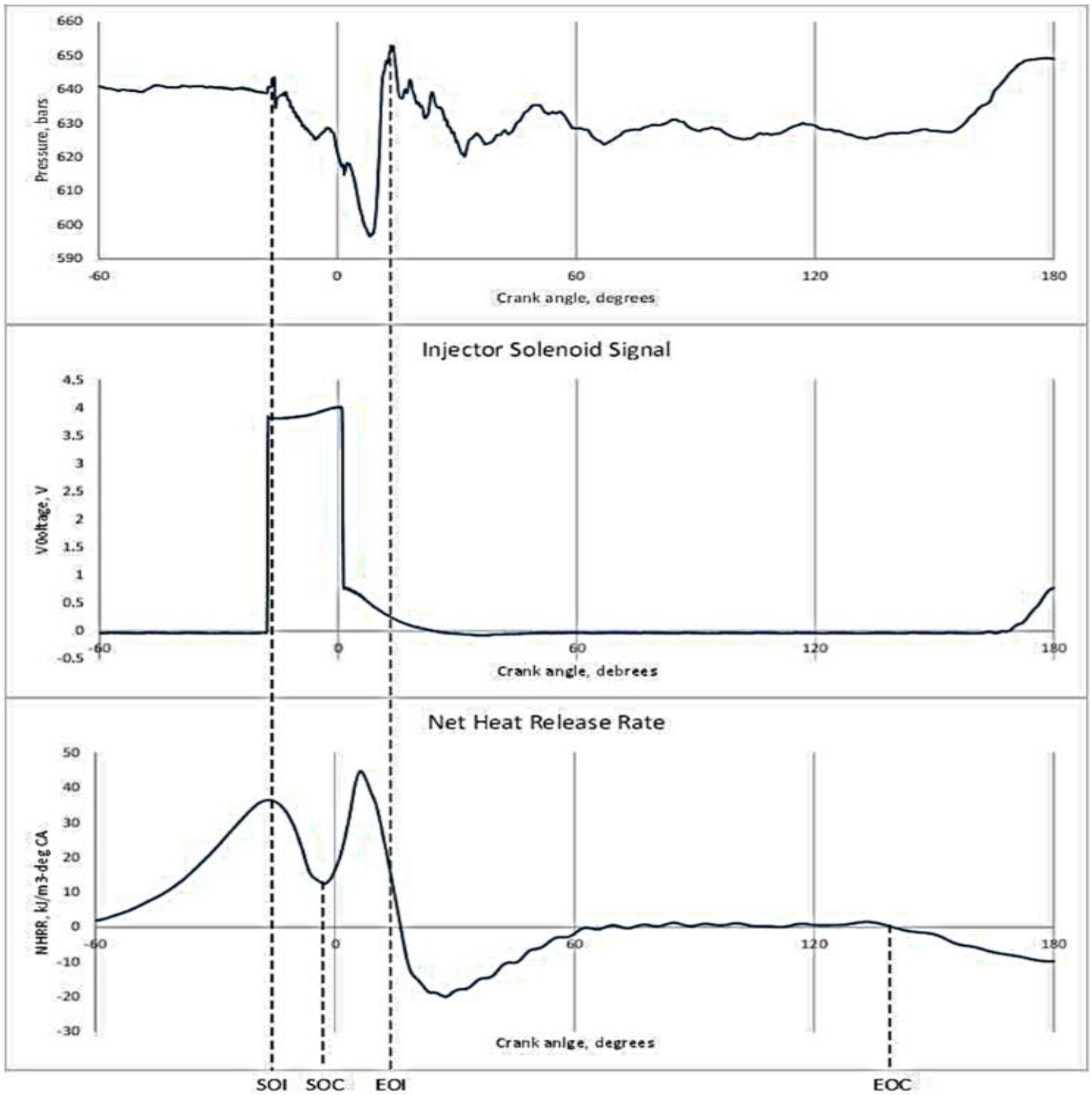


Figure 6. Diagrams of fuel injection line 1, injector solenoid signals and net heat release rate used to determine start and end of combustion in crank-angle degrees

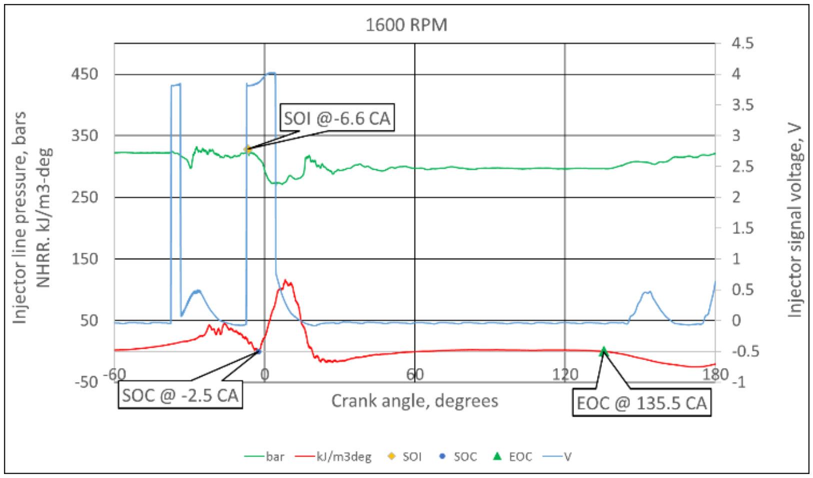
The superimposition of these diagrams were seen to serve as visual guides for locating the necessary parameters from tabulated data recorded during test runs. Figure 7 shows the superimposed diagrams of injector signal voltage, injector line pressure and NHRR for the same engine run at 1600, 2000 and 2400 rpm, all under full-load conditions. On each of these diagrams, the respective crank angles for the SOI, SOC and EOC are indicated. These values were obtained from the respective tabulated data recorded during engine runs and located using the method described above.

Figure 8 shows a comparison of SOC determination using the other criteria of Heywood (the maximum of the 2nd-order derivative of the in-cylinder pressure) [3] and Katrasnik et. al. (the maximum of the 3rd order derivative of the in-cylinder pressure) [6] against the method described above. Because there is noise in both the lines for $d^2P/d\theta^2$ and $d^3P/d\theta^3$, their respective maximum values within the vicinity of the minimum values of NHRR were taken. In Figure 8(a), the difference in crank angle between the abovementioned method and the two other criteria is 0.1 CA degrees. In Figure 8(b), this difference is 0.3 CA degrees whereas in Figure 8(c), the difference is 0.1 CA degrees. Assigning the two criteria to be the standards, the errors in crank angle were seen to be negligible.

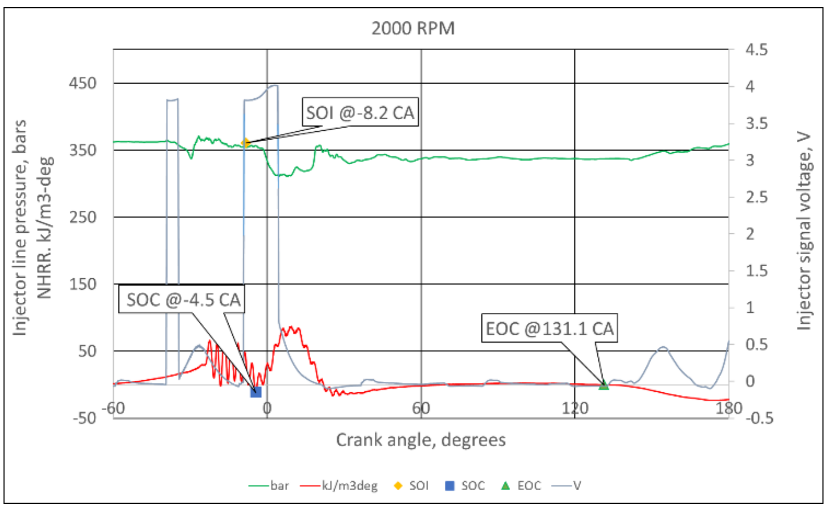
2. CONCLUSION

This work was an attempt to develop a method of determining the crank angles for SOI, SOC and EOC of a properly-equipped CRDI diesel engine, using superimposed diagrams of fuel injector solenoid voltage signals, fuel injector line pressures and the NHRR diagrams and using these as visual guides to locate the said crank angles from tabulations of recorded data. These crank angles were then used to define the phases and durations of combustion, which in turn would be used for analyses of effects of changes in engine operating parameters, fuels and other tests. The method used for determining the SOC was then compared against the criteria described by Heywood [3] and Kratasnik et al [6], respectively, and the differences in crank angles ranged from 0.1to 0.3 crank angle degrees, thus showing agreement among these three methods. It may be concluded that the use of this visual technique on the NHRR plot to determine the different crank angles to define SOI, SOC and EOC in analyzing factors affecting emissions production is feasible.

This study was made on a CRDI engine using available instruments installed on it. In the Philippines, diesel engines using mechanical injectors are still employed and their performance is expected to differ from the more modern types of engines, thus, further work to check the feasibility of this approach on other types of engines need to be made.



(a)



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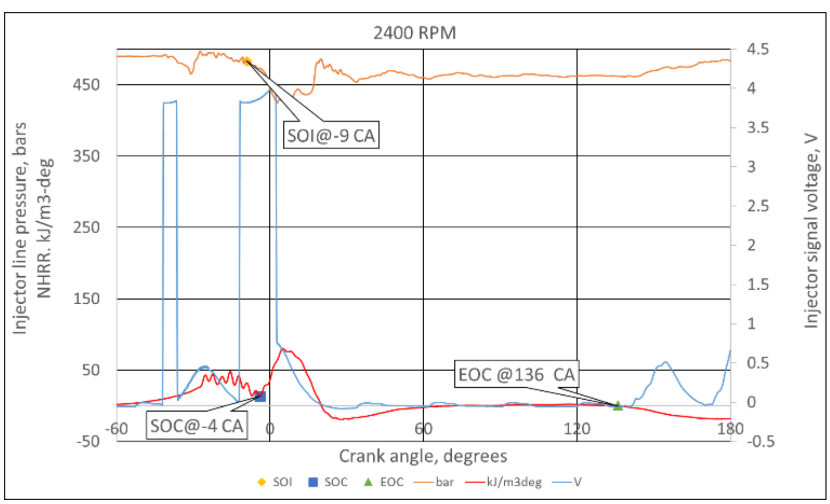
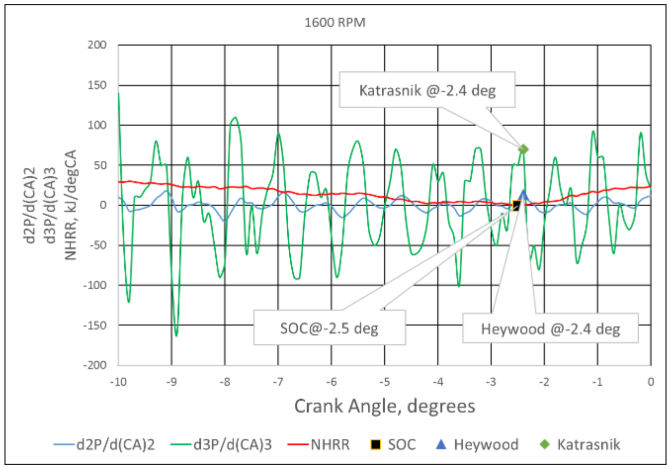


(c)

Figure 7. Superimposed diagrams of injector line pressure, injector solenoid signal voltage and net heat release rate for test engine at full load (a) 1600 rpm, (b) 2000 rpm, (c) 2400 rpm



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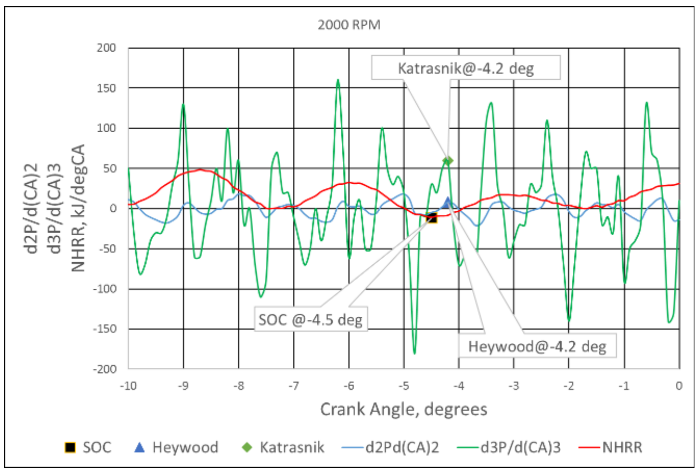

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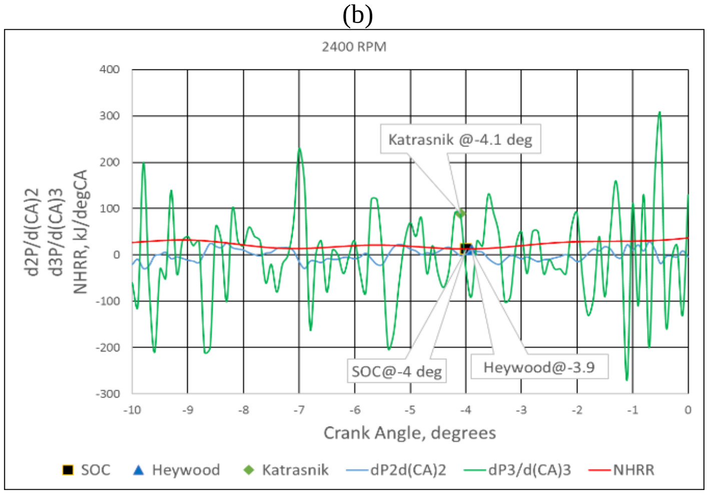

(c)

Figure 8. Comparison of the start-of-combustion (SOC) determined from the net heat release rate (NHRR), the local maximum value of $d^2P/d\theta^2$ and the local maximum value of $d^3P/d\theta^3$ at (a) 1600 RPM, (b) 2000 RPM, (c) 2400 RPM

3. REFERENCES

[1] Lapuerta, M, O. Armas and J. Rodriguez-Fernandez "Effect of biodiesel fuels on diesel engine emissions" Progress in Energy and Combustion Science 34 (2008) 198-223

[2] EPA Technical Bulletin - Nitrogen Oxides (NO_x), Why and How They Are Controlled, United States Environmental Protection Agency Office of Air Quality Planning and Standards, November 1999

[3] Heywood, John B. "Internal Combustion Engine Fundamentals" 1988, McGraw-Hill

[4] Canacki, M, "Combustion characteristics of a turbocharged DI compression ignition engine fueled with petroleum diesel fuels and biodiesel" Bioresource Technology 98 (2007) 1167–1175

[5] Reyes, J. G. T., "The Effects of Varied Coconut Methyl Ester Biodiesel/Diesel Blend Ratios on the Performance and NO_x Emissions of a Multi-Cylinder Common Rail Diesel Engine", doctoral dissertation

[6] Katrasnik, T., F. Trenc and S. R. Opresnik, "A New Criterion to Determine the Start of Combustion in Diesel Engines," Transactions of the ASME, Vol. 128, October 2006

[7] Ferguson, C. R. and A. T. Kirkpatrick "Internal Combustion Engines Applied Thermosciences Second Edition" John Wiley and Sons, USA, 2001

[8] Santos, E. S., "Influence of Different CME-Diesel Blends on the Injection Parameters of a Common-Rail Direct Injection Diesel Engine (Masters Thesis)," University of the Philippines, 2016

[9] Alkhulaifi, K. and M. Hamdalla, "Ignition Delay Correlation for a Direct Injection Diesel Engine Fuelled with Automotive Diesel and Water Diesel Emulsion," World Academy of Science, Engineering and Technology Vol:5 2011-10-25

[10] Pinzi, S, P. Rounce, J. M. Herreros, A. Tsolakis, M. P. Dorado, "The effect of biodiesel fatty acid composition on combustion and diesel engine exhaust emissions," Fuel 104 (2013) 170–182

[11] How H. G., H.H. Masjuki, M.A. Kalam , Y.H. Teoh, "An investigation of the engine performance, emissions and combustion characteristics of coconut biodiesel in a high-pressure common-rail diesel engine," Energy 69 (2014), 749-759

[12] An H., W.M. Yang, S.K. Chou, K.J. Chua, "Combustion and emissions characteristics of diesel engine fueled by biodiesel at partial load conditions," Applied Energy 99 (2012) 363–371

[13] Horn, U., R. Egnell, B. Johansson and O. Andersson, "Detailed Heat Release Analyses With Regard To Combustion of RME and Oxygenated Fuels in an HSDI Diesel Engine," Paper No. 07PFL-353, SAE International 2007

[14] Tat, M.E., J.H. Van Gerpen, P.S. Wang, “Fuel Property Effects on Injection Timing, Ignition Timing and Oxides of Nitrogen Emissions from Biodiesel-Fueled Engines,” Paper Number: 046081, presented at the 2004 ASAE/CSAE Annual International Meeting

[15] Assanis, D.N., Z.S. Filipi, S.B. Fiveland, and M. Syrimis, “A Predictive Ignition Delay Correlation Under Steady-State and Transient Operation of a Direct Injection Diesel Engine,” Transactions of the ASME, Vol. 125, April 2003