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# Investigation of the Fuel-Air Cycle Phases in a Modern Compression Ignition Engine under Multi-Injection Strategy

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**Abstract:** Special attention is necessary paid for charactering advanced injection strategies including multi-injection techniques in order to improve physical processes (i.e. atomization, evaporation, and mixing) as well as chemical mechanism (i.e. low temperature and high temperature auto-ignition) in compress ignition engines, especially when operating with renewable fuels like biodiesels. This work qualitatively investigates the fuel-air cycle phases in a compression ignition engine equipped with an advanced injection system. The engine used in this study is a modern 4-cylinder targeted-controlled-injection diesel engine, typical of those used in Hyundai Starex CVX vehicles. Single, double, triple, or quadruple injection modes are possible in this engine depending on its load and speed conditions. In addition, both pilot-and post-injection modes can be triggered in several operating conditions. The engine is operated with either fossil diesel or 20:80 blend of a biodiesel derived from palm oil residue with fossil diesel under a wide range of engine speed and load fractions. The outcomes show a capability of multi-injection strategy to shortening the ignition delay which is essentially important at low load fraction and/or low engine speed where the atomization and evaporation conditions are quite poor. The pilot-injection modes enhance the atomization and evaporation by pre-conditioning the combustion chamber prior to the main auto-ignition. Depending on the engine operating condition, the start of main auto-ignition of biodiesel blends could be identical, earlier or later with respect to that of fossil diesel. Since the longer ignition delay observed for the biodiesel blend regardless higher cetane value of biodiesel compared to diesel, this could be attributed to the unequal effect of multi-injection strategy on pre-conditioning the combustion chamber when using different fuel with different physicochemical properties. This important point needs to be noted to control the chamber conditions targeting to improve physical and chemical processes when utilize biodiesels and their blends in auto-ignition engines.

***Keywords:*** *Multiple Injection, Pilot/Post Injection, Biodiesel, In-Cylinder Pressure, Net Heat Release Rate, Ignition Delay*

## 1. Introduction:

Advanced injection schedules involving multiple injections have been utilized for pre-conditioning the combustion chamber prior to auto-ignition, reducing the peak cylinder pressure, phasing heat release rate, and reducing emissions in compression ignition engines [1]. Pre-conditioning the combustion chamber prior to auto-ignition is essential to enhance physical processes such as atomization and evaporation and this is extremely useful when utilizing high viscosity and high surface tension fuels such as biodiesels. Pre-conditioning the combustion chamber also affects chemical processes such as low temperature combustion usually happened before the occurrence of start of main combustion. This work aims to develop a better understanding the effects of multiple injection modes on the fuel-air cycle characteristics of a modern auto-ignition engine operating with biodiesel blends.

One of the target of multi-injection strategy is to pre-conditioning the combustion chamber which enhances the evaporation and the auto-ignition quality as mentioned earlier. Shorter ignition delay and smaller fraction of premixed combustion were observed when utilizing pilot injections [2]. In a comparison of multi-injection and single-injection, Park et. al. [3] observed a similar increasing patent of spray penetration between single and multiple injection while the tip penetration of multi-injection spray increases faster than that of the single counterpart. A higher combustion pressure when using multi-injection was also reported in Park et. al. [3]. In a study in a direct injection diesel engine operating under premixed charge compression ignition (PCCI) modes, Torregrosa et al. [4] suggested a multi-injection strategy for decreasing combustion noise. Two pilot injections at low pressure can help to reduce noise and NOx, post injection at high pressure can help to reduce soot and late post injection at moderate pressure helps to manage exhaust gas temperature which is needed for after-treatment equipment including particle filter and NOx catalyst [2]. Despite advantages of multi-injection strategy, research have been done on compression ignition engines operating with oxygenated fuels such as biodiesels and their blends was limited to single-injection modes.

Biodiesels have been shown as a potential candidate to replace fully or partially fossil fuel to operate compression ignition engines [5]. Main properties of biodiesels are quite close to those of fossil diesel. Biodiesels usually have higher relative density, higher viscosity and surface tension, higher cetane value with respect to fossil diesel [6]. In addition, thanks to higher boiling point, biodiesel is easy to handle. It is quite well agreed in literatures that biodiesels have a shorter ignition delay which is contributable to its higher cetane value, lower particle mass and lower hydrocarbon emission which may be due to the oxygen content in the fuel molecules, while influences of biodiesel blends on NOx and nano-particle size distribution is uncertain. Both increase and decrease in NOx emitted from engines operating with biodiesel blends can be found [7] while reports on nano-particle (around 10 nm in diameter) is contradictory [8]. The contradictory could be due to several reasons including: (1) the biodiesels tested in different studies are derived from different fuel feed stock; (2) deference in the engine technology including injection strategies used; (3) difference in engine operating conditions; and (4) the complexity condition of chemical and physical phenomenon of spray in practical systems like IC engines.

This contribution will investigate the fuel-air cycle characteristics of an advanced engine operating with biodiesel blends under multi-injection strategies. Depending on the operating condition, fuel can be injected into the combustion chamber in one time (single injection) or multi-injection modes (two, three or even four times) in one engine cycle. Observations on the cycle phases especially from the start of injection to low/high temperature combustion and premixed/diffusion combustion at different engine speed and loading conditions will be addressed. A comparison amongst biodiesel blends tested in this study will also be performed.

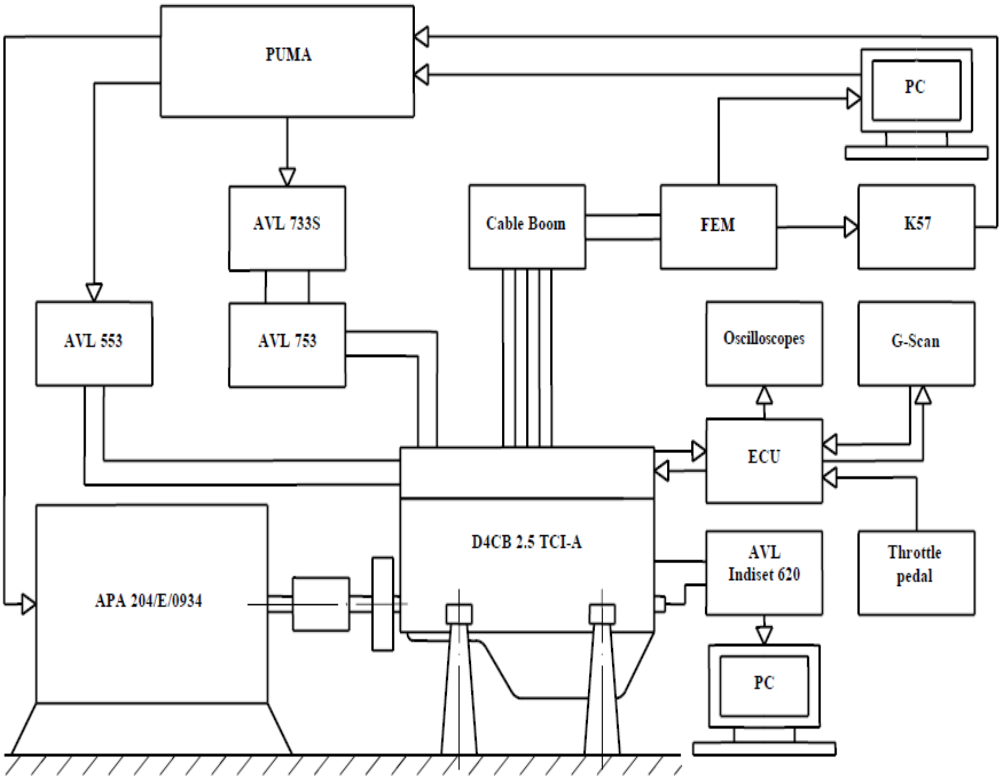



*Figure 1. Schematic of experiment setup*

*(APA 204/E/0934 - Electric dynamometer; AVL 553- Coolant conditioning system; AVL 753 - Fuel conditioning system; AVL 733S - FuelBalance; PUMA - Automation system of instrumentation and testing platform; FEM - Front end module; K57 - The control desk; ECU - Electronic control unit; G-Scan - Diagnostic equipment (OBD-II standard); AVL Indiset 620 - System for measuring in cylinder pressure; PC - Personal Computer of the test bed)*

## 2. Experiment description and fuel properties:

The testing engine is a Hyundai D4CB 2.5 TCI-A diesel engine (4 cylinders in-line; Bore x Stroke: 91 x 96mm, respectively; Compression ratio: 17.6:1; Rate power =120 kW at 3800 rpm; Common-Rail injection). More details about this engine can be found in ref. [9]. The testing system is schematically described in Figure 1.

Fuels used in this study include biodiesel blends B20 (20% of biodiesel and 80% of fossil diesel in volume) along with the fossil diesel, also called B0 in this report. The diesel is a commercial fuel containing 0.05% of sulfur. The biodiesel was derived from residue of a palm cooking oil production process [10, 11]. Selected properties for the B0 and B20 tested here are shown in Table 1.

The testing engine is operated in 4 loading modes including 100% (full load), 75%, 50% and 25% of the full load. At each loading mode, the engine operates under a wide range of engine speed, from 1000 to 3500 rpm with an interval of 500 rpm. In this test, fuel consumed per cycle is measured using the AVL FuelBalance 733S. In-cylinder pressure is recorded using a piezoelectric pressure sensor (AVL QC 33C) [12].

*Table 1. Selected fuel properties*

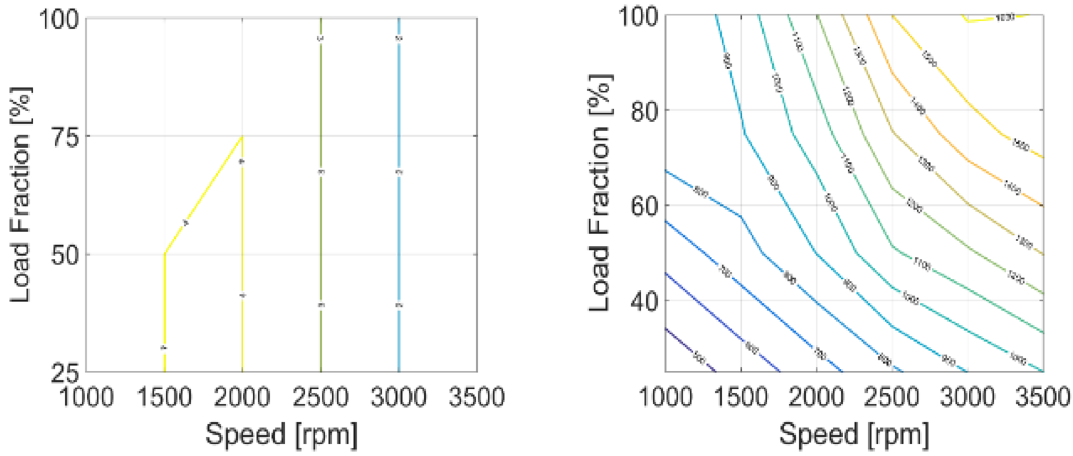
| Fuel | | Testing method | B20 | B0 |
|---|---|---|---|---|
| Oxidation Stability, at 110$^{o}$C | hrs | EN14112 | 24.07 | - |
| Kinematic Viscosity, at 40 $^{o}$C | mm$^2$s | ASTM D445 | 3.38 | 3.14 |
| Rel. density, at 15$^{o}$C | [kg/m$^3$] | ASTM D 1298 | 0.845 | 0.836 |
| Higher Heating values | MJ/kg | - | 43.11 | 45.19 |
| Pour point | $^{o}$C | ASTM D97 | -3 | - |
| Cetane number | - | ASTM D613 | 54.5 | 52.4 |

## 3. Results and Discussion:

### *3.1 Multi-injection strategy*

In this engine, at a specific load and speed condition, a corresponding injection strategy (injection pressure and times of injection) is programmed and managed by an electronic control unit, ECU. Figures 2a and 2b show the maps of times of injection and fuel-rail pressure, respectively.

At a speed condition of 3500 rpm, single-injection is utilised while multi-injection strategy is used with an engine speed lower than 3500 rpm as shown in Figure 2a. Double-injection is used for the whole loading conditions at 3000 rpm while quadruple-injection modes are triggered for medium and low loads at 1500 & 2000 rpm as also shown in Figure 2a.




*a. Times of injection* *b. Fuel-rail pressure [bar]*

*Figure 2: Multi-injection strategy of the tested engine: a. Injection times and b. Fuel-rail pressure*

It is clear from Figure 2b, a lower engine speed and/or lower engine load fraction leads to a lower injection pressure. The lower injection pressure usually leads to the poorer atomization conditions. It should be mentioned that two pilot injections (one main and one post injection) are triggered when quadruple-injection strategy used (25% & 50% of full load at 1500 rpm and 2000 rpm, 75% of full load at 2000 rpm as shown in Figure 2a). The pilot-injection strategy might enhance the atomization as well as evaporation by pre-conditioning the combustion chamber prior to the main injection while the post-injection may help to reduce particle emission by improving particle oxidation which is result from increasing the bulk cylinder temperature and air-fuel mixing with an introduction of a post-combustion event. In the form of this paper, effects of pilot-injection on engine characteristics will be focussed and the influence of post injection will be presented in a separated report.

### *3.2 Influences of pilot-injection on fuel-air cycle at medium and high speed conditions*

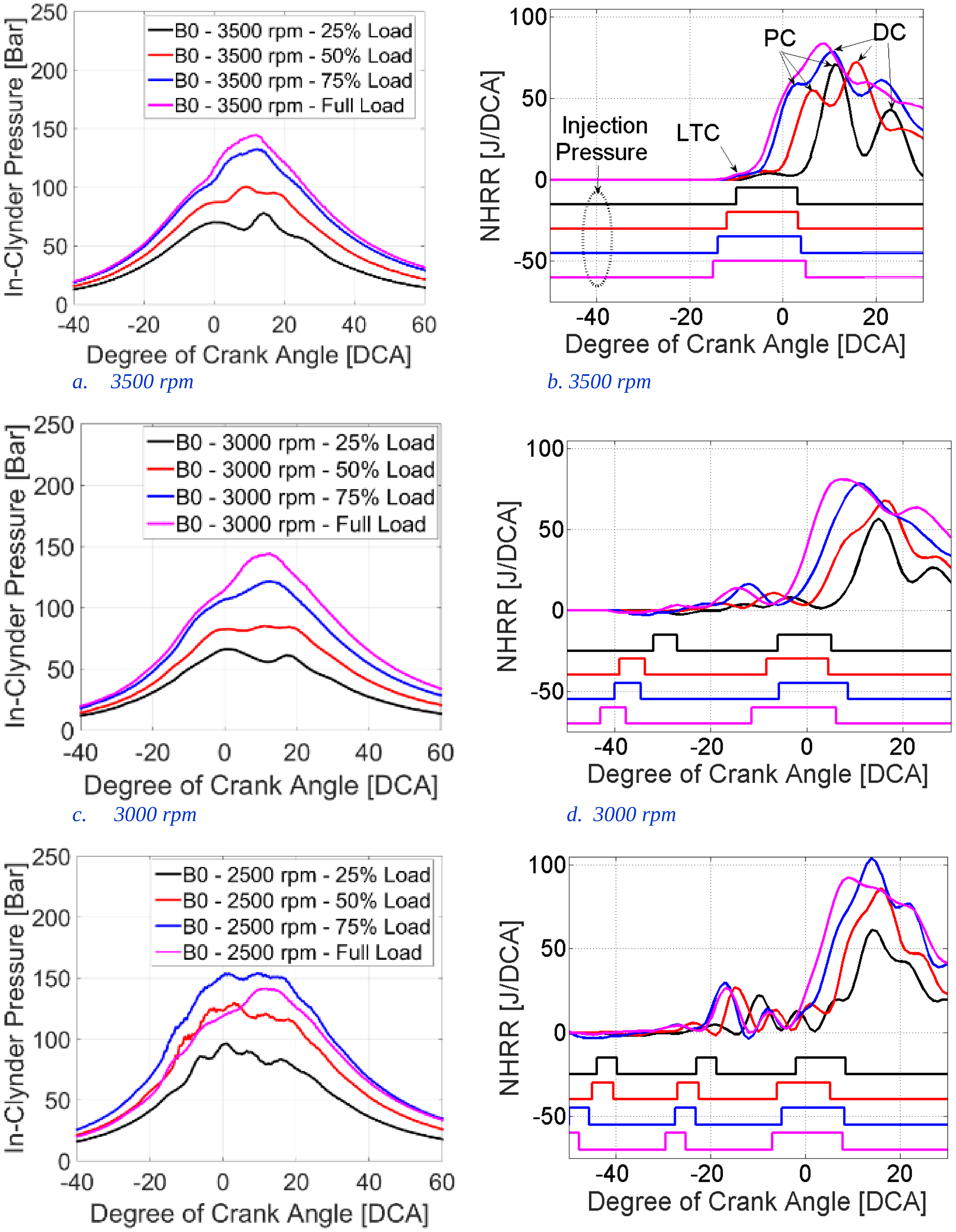
In this section, in-cylinder pressure, net heat release rate (NHRR) along with injection timings of the engine operating with biodiesel blends B0 and B20 will be shown for a whole range of engine loads at medium and high speed conditions (2500, 3000 and 3500 rpm corresponding with single-, double-, and triple-injection modes). Figures 3a to 3f show the in-cylinder pressure (3a, 3c and 3e), NHRR along with fuel-rail pressure (3b, 3d and 3f) for pure diesel fuel named B0 at 3500 rpm (Figures 3a and 3b), 3000 rpm (Figures 3c and 3d) and 2500 rpm (Figures 3d and 3f). The black curve is for 25% of full load with its lowest cylinder pressure and the latest start of combustion as shown in these figures. As noted from Figure 3b for a traditional injection mode (single-injection) utilized at 3500 rpm, the low temperature combustion (LTC), premixed and diffusion combustion (PC and DC, respectively) are quite clearly distinguished. LTC, PC, and DC nomenclatures shown in Figure 3b are used for the local maximum net heat release rate due to low temperature combustion, premixed and diffusion combustion, respectively. The LTC occurs almost directly after the start of injection as evident from Figure 3b. At this high engine speed, the cylinder temperature at start of injection may be already relevant to generate a low temperature combustion mode. A lower load condition also leads to a longer low temperature combustion duration. At 25% of full load, the low temperature combustion duration is almost three times longer than that at full load as shown in Figure 3b.

A pilot combustion event is evident prior to the occurrence of start of main combustion which is attributable to the pilot injection. In this case the LTC is hardly to distinguish. At the same loading fraction, a shorter ignition delay observed at 3000 rpm when compared to that at 3500 rpm. With a lower engine speed, lower fuel injection pressures, and insignificant difference in the main injection timing, a longer ignition delay would be expected at 3000 rpm with respect to that of 3500 rpm. However, as evident from Figure 3d, the ignition delay times at 3000 rpm is shorter than those at 3500 rpm and this can be attributed to the utilization of a pilot injection at 3000 rpm. The short ignition delay times also result in small fractions of PC observed at 3000 rpm (Figure 3b). At 3000 rpm, PC is only clearly shown for 25% of full load as evident from Figure 3d. This influence is clearer when two pilot injections are used even in lower engine speeds such as 2500 rpm and this is evident in Figure 3f.

Figure 3f is an example of a triple-injection mode used at 2500 rpm of engine speed. It shows two local peaks of pilot combustions which may correspond to the two pilot injections. The rate of heat released during the prior combustion duration is also much higher than that at 3000 rpm. Additionally, ignition delays from main injection to the start of the main combustion is much shorter compared to that at double-injection mode shown in Figure 3d. The short ignition delays lead to very small proportion of premixed combustion, which is indistinguishable from Figure 3f.

From the above discussion, the role of pilot injections in pre-conditioning the combustion chamber prior to the start of main combustion is clear. The pilot injections lead to pilot combustions which may enhance the conditions for atomization and evaporation of the fuel spray and this in turn improves auto-ignition quality. This is essential for auto-ignition engines especially when operating at low load and speed conditions in which the low temperature in combustion chamber leads to poor atomization and evaporation. This is resolved by introducing pilot injections to generate pilot combustions or to increase temperature to support those physical processes.

Similar to Figures 3a to 3f, in-cylinder pressure, net heat release rate along with fuel rail pressure signal are shown in Figures 4a to 4f but for biodiesel blend B20 (see Table 1). It can be seen from Figures 4a to 4f, the signals of in-cylinder pressure and rates of heat released are very identical with those of fossil diesel, B0, shown earlier in Figures 3a to 3f. The role of pilot injections in case B20 is similar to that in case B0. This could be attributed to the similarities in physical processes and high temperature auto-ignition characteristics between B0 and B20. It was found in literature [6] at a certain high Weber number, the influence of physical properties (e.g. viscosity and surface tension) amongst different liquids on their atomization characteristics is minimal and therefore the auto-ignition under these conditions may be mainly affected by chemical processes. High temperature ignition delay times, however, are found to be similar between fossil diesel and biodiesels derived from different feedstock [13]. In a sum up, at a certain high fuel injection pressure and a certain high cylinder temperature, where the combustion is dominant by high temperature combustion, the similarity in auto-ignition features observed for B0 and B20 can be understandable. Whether or not this is true at low load and low injection pressure will be examined in the next section.

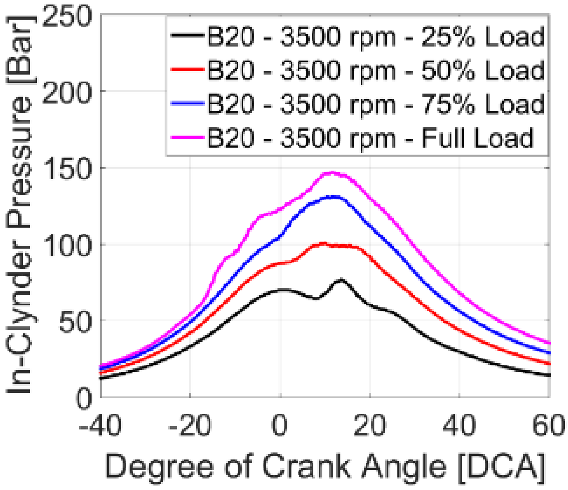



*a. 3500 rpm* *b. 3500 rpm*

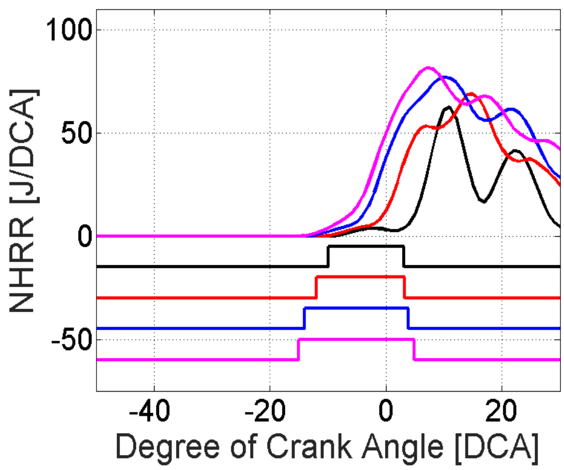
*c. 3000 rpm* *d. 3000 rpm*

*e. 2500 rpm* *f. 2500 rpm*

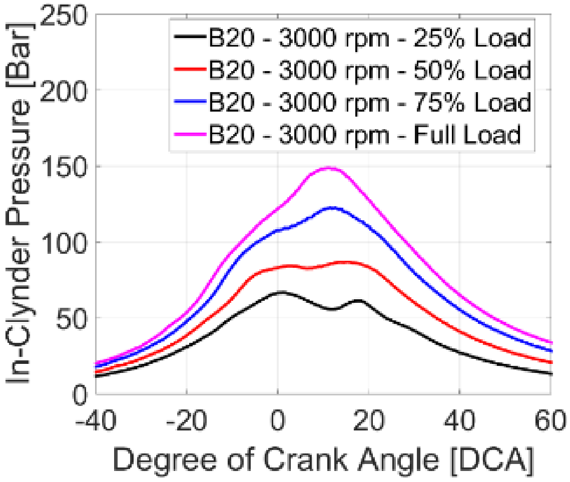
*Figure 3. In-cylinder pressure (a, c, and e) and net heat release rate (b, d, and f) of diesel or B0: bottom to top is for 2500 (e&f), 3000 (c&d), and 3500 rpm (a&b)*



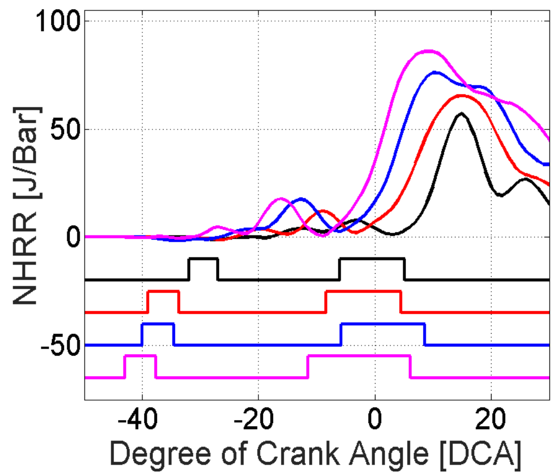

*a. 3500 rpm*



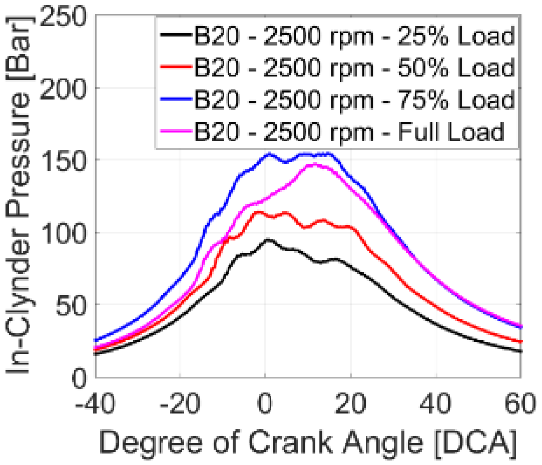

*b. 3500 rpm*



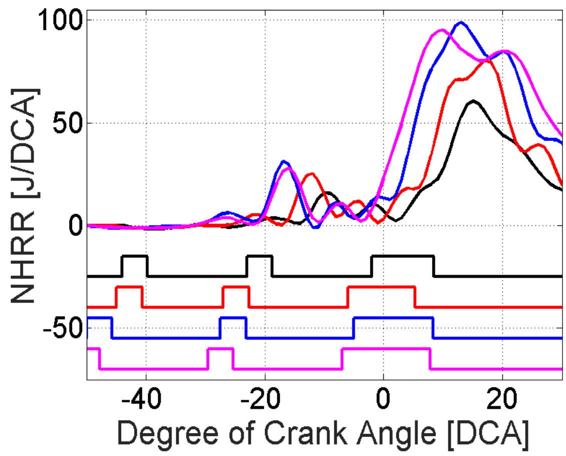

*c. 3000 rpm*




*d. 3000 rpm*




*e. 2500 rpm*

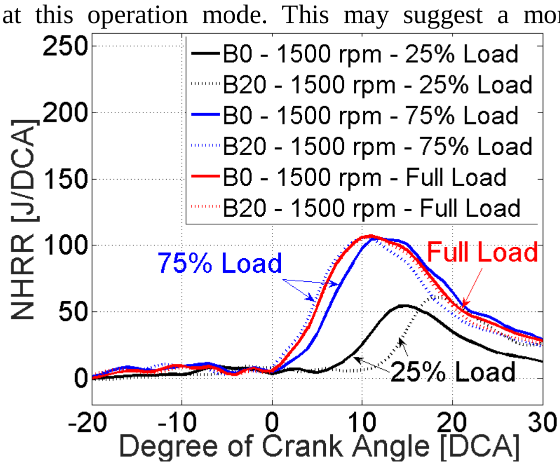



*f. 2500 rpm*

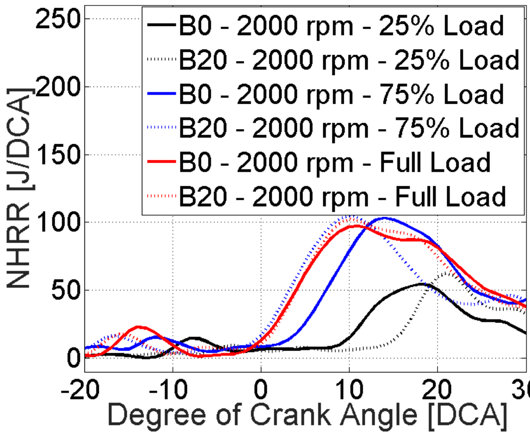
*Figure 4. In-cylinder pressure (left) and net heat release rate (right) of blend B20: bottom to top is for 2500, 3000, and 3500 rpm*

### *3.3 Influences of pilot-injection on fuel-air cycle at low speed conditions*

Figure 5a and 5b shows rates of heat released when using the biodiesel blends at 1500 rpm and 2000 rpm, respectively. At full load, as shown in both Figures 5a and 5b, the rates of heat released of B0 and B20 are almost identical. This could be explained similarly to that shown in previous section for medium and high engine speed. At 75% of full load the start of main combustion of B20 occurs earlier than that of B0 while the occurrence of auto-ignition of B20 is latter than that of B0 at 25% load fraction as evident in both Figure 5a and 5b. The shorter ignition delay of B20 at 75% of full load can be attributed to its higher cetane value while its longer ignition delay at 25% of low load could be due to a poorer atomization quality of B20 with respect to B0 at this operation mode. This may suggest a more effective influence of pilot injections on pre-conditioning of the combustion chamber when using B0 with respect to that when using B20 at those low load and low speed conditions. At low load and low speed, the fuel injection pressure is decreased significantly with respect to that at high load and speed as shown earlier in Figure 2b. At 25% of full load, an injection pressure of approximately 500 bar is used in 1500 rpm while the injection pressure is double at 3500 rpm as clearly shown in Figure 2b. At this condition, a poorer atomization and evaporation of B20 could be the main reason leading to its longer ignition delay. Additionally, the low temperature combustion at this condition could be significant and the LTC characteristics strongly depend on fuel types [13].




*a. 1500 rpm*




*b. 2000 rpm*

*Figure 5. Net heat release rate of B0 and B20 at 25% load; 75% load; and full load: a. 1500 rpm and b. 2000 rpm*

## 4. Conclusion:

Influences of pilot injection strategies on a modern auto-ignition engine operating with biodiesel blends are successfully investigated. The engine is a 4 cylinder targeted-controlled-injection model equipped with an injection system which is manageable to be single, double, triple or quadruple injection modes depending on engine load and speed conditions. Blend B20 is tested in comparison with fossil diesel, B0, at a wide range of engine load and speed conditions. The start of main combustion of biodiesel blends are found either similar, earlier or later with respect to that of fossil diesel and this strongly depends on engine working modes. This could be attributed to the similarity in characteristics of physical and chemical processes amongst the fuel blends under high temperature conditions while this is not the case under at low temperature modes.

**Acknowledgement:**

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