

# The Effects of EGR and Injection Timing on the Engine Combustion and Emission Performances Fueled by Butanol-Diesel Blends

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## ABSTRACT

The combustion and emission characteristics of a diesel engine running on butanol-diesel blends were investigated in this study. The blending ratio of n-butanol to diesel was varied from 0 to 40 vol% using an increment of 10 vol%, and each blend was tested on a 2.7 L V6 common rail direct injection diesel engine equipped with an EGR system. The test was carried out under two engine loads at a constant engine speed, using various combinations of EGR ratios and injection timings. Test results indicate that n-butanol addition to engine fuel is able to substantially decrease soot emission from raw exhaust gas, while the change in NO<sub>x</sub> emissions varies depending on the n-butanol content and engine operating conditions. Increasing EGR ratio and retarding injection timing are effective approaches to reduce NO<sub>x</sub> emissions from combustion of n-butanol-diesel blends. But the engine control strategies need to be optimized in order to achieve low levels of both soot and NO<sub>x</sub> emissions, as well as a reasonable fuel economy.

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## 1. INTRODUCTION

Butanol has recently drawn much research attention as an alternative fuel that has the potential of being utilized in internal combustion engines. The main advantages of n-butanol compared to other alcohols include its higher energy density, good intersolubility with diesel, proper viscosity for high pressure pumping systems, less ignition problems, and easy distribution through existing pipelines. Therefore, butanol is considered a promising candidate for mixing with diesel used in CI engines. [1,2,3,4,5,6,7,8]

There are a number of researches studying performance and emissions of diesel engines running on n-butanol and its blends. Rakopoulos et al. [1] tested n-butanol-diesel blends (8%, 16%, 24% by volume) on DI naturally aspirated diesel engine. It is reported a significant reduction of smoke density and a slight reduction of NO<sub>x</sub> and CO were achieved with n-butanol addition at the expense of slightly higher HC emission and fuel consumption. Yao et al. [2] fueled a heavy

duty direct injection engine in their laboratory with n-butanol-diesel blends (0%, 5%, 10%, and 15%) using different injection strategies. The heat release analysis illustrated that blends with higher n-butanol content gave more premixed combustion at same operating conditions, explaining the reason why soot emissions were seen a significant decrease with more n-butanol addition. As to injection strategies, effects of pilot and post injections on combustion and emission characteristics were found the same on n-butanol-diesel blends as they were on pure diesel. It was reported that soot could be further reduced with early pilot injection, but CO was increased as a penalty; and post injection was effective in bringing down soot and CO simultaneously. Liu and Lee [3] studied the spray and combustion characteristics of neat n-butanol in a constant volume chamber that is capable of providing stable ambient temperature and oxygen concentration conditions, simulating the in-cylinder operation of diesel engines. It was found that lower oxygen concentration (corresponding to higher EGR

rate in diesel engine) led to extended ignition delay, but auto-ignition timing was barely affected when oxygen concentration was between 16% and 10.5% at 800-1000 K ambient temperature. Total soot mass was reported to be higher at lower oxygen concentration, but when ambient temperature was as low as 800 K no soot was detected because the resulting low combustion temperature and mixing conditions avoided soot formation region.

The application of n-butanol is still at its infant stage compared with diesel or even other alcohol such as ethanol, thus it entails an in-depth understanding of how n-butanol can affect the combustion and emission characteristics of IC engines before it can be more widely applied as an engine fuel. This work aims at investigating the influence of n-butanol addition to diesel fuel on the combustion performance, and emission characteristics of a conventional diesel engine. As an oxygenated fuel, n-butanol has a great potential for reducing carbon monoxide (CO) and soot emissions from diesel engines. At the same time, engine control strategies can be optimized for the use of butanol-diesel blends to achieve an acceptable level of nitrogen oxides (NOx) as well as good fuel economy. For this stake, experimental study has been carried out to test the mixtures of n-butanol and diesel on a common rail direct injection diesel engine under a variety of operating conditions and control strategies. Results from these tests are analyzed and compared to offer better insight on the effect of n-butanol content on diesel engine combustion and emissions, as well as on selecting proper control strategies for diesel engines fueled with n-butanol-diesel blends.

## 2. EXPERIMENTAL APPARATUS AND METHODS

The internal combustion engine used in this study is a Ford Lion V6 direct injection diesel engine with specifications listed in [Table 1](#). It has maximum power of 195 hp with production calibration. This engine is equipped with a common rail fuel injection system and a high pressure water cooled exhaust gas recirculation (EGR) system. The engine was set up on an engine test bench and was connected to an eddy-current dynamometer. The variable geometry turbocharger originally installed on the engine was disabled. For proper functioning of the high pressure loop EGR system, a flow restriction valve was installed on the exhaust pipe to provide sufficient back pressure. A Labview program was locally developed for monitoring and measuring relevant properties of intake air, fuel, oil, cooling water, as well as in-cylinder pressure traces which was acquired by the pressure transducer (Model AVL GH13P) installed inside one of the six cylinders in the place of its glow plug. Based on the in-cylinder pressure, the apparent heat release can be calculated as following by the first thermodynamic law assuming equilibrium during combustion:

$$\frac{dQ_n}{d\phi} = \frac{\gamma}{\gamma - 1} p \frac{dV}{d\phi} + \frac{1}{\gamma - 1} V \frac{dp}{d\phi}$$

where  $\gamma$  is specific heat ratio,  $c_p/c_v$ .

A programmable electronic control module (ECM) was applied, through which a variety of engine operating parameters, including number of injections, injection timings, fuel rail pressure, EGR valve position, etc., can be monitored and adjusted using the software coupled with the engine ECM-ETAS INCA. By default, the ECM operates according to its original specifications by Ford. The common rail fuel injection system is capable of delivering a maximum of 6 separate injections per cylinder per cycle and providing an injection pressure of 220 bar to 1650 bar. Up to two pilot injections, two main injections, and two post injections can be triggered each cycle, though by default ECM settings only one pilot injection and one main injection are utilized, the interval between which is fixed. The EGR valve position can be adjusted through INCA from fully close (no EGR) to fully open (heavy EGR). The EGR fraction is defined as the ratio between the mass flow of recirculated exhausts and the total mass flow entering the engine through the intake. In this work, the EGR rate was calculated in the same way as in Ref [2]. The formula is as follows:

$$\text{EGR\%} = \text{CO}_{2\text{intake}}/\text{CO}_{2\text{exhaust}} \times 100\%$$

Gaseous emissions including O<sub>2</sub>, CO<sub>2</sub>, HC and CO concentrations are measured directly by Horiba MEXA-554JU exhaust gas analyzer on the raw exhaust gas from the engine without going through any after treatment system. Ice baths were installed in the sampling lines to condense the water vapor, and compressed air line dryers (McMaster item #4958K34) were installed to filter out the condensed water before the sample entered the analyzer. In this sense, all water vapor is considered to be removed from the sample, and the results are considered to be dry-basis measurements. For measurement of NOx emissions, a Horiba MEXA-720NOx non-sampling type analyzer is used. The measurement range of this device is from 0 to 3000 ppm NOx concentration, with  $\pm 30$  ppm accuracy for the 0-1000 ppm range,  $\pm 3\%$  accuracy for the 1000-2000 ppm range, and  $\pm 5\%$  accuracy for the 2000-3000 ppm range. According to the manufacturer, the measurement is wet-basis, therefore no correction for the water content of the exhaust is required.

Soot measurement is performed using a standard filter paper method. Samples of raw exhaust gas are drawn through a 7/8" round filter paper using -vacuum pump. The filter paper discs are cut from rectangular strips of filter paper supplied by Grainger Industrial Supply (#6T167) and the filter holder is taken from a Bacharach True-Spot smoke meter adapted to the new setup. Condensed water or oil are removed from the sampling line by a line filter installed after the vacuum pump. After sample collection, the filter blackening is to be measured with a digital scanner. The paper blackening (PB) is defined as:



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$$PB=(100-R_R)/10$$

where

$$R_R=R_p/R_f \times 100\%$$

$R_p$ : reflectometer value of sample

$R_f$ : reflectometer value of the unblackened paper

$R_R$ : relative brightness of the sample  
(relative radiance factor)

A flow meter is used to monitor the sampling flow rate which is controlled by a needle valve on the inlet of the vacuum pump. Based on the expected soot content, the flow rate and sampling duration are selected to achieve an effective sampling length of 405 mm. With the sampled volume at 298 K and 1 bar, the paper blackening value can be considered as the filter smoke number (FSN). More details can be found in Ref [9].

For measurement of steady-state fuel consumptions, a small sampling tank made of PVC pipe was constructed and integrated in the fuel supply system, on which three liquid level sensors (Honeywell LLE102101) with repeatability of  $\pm 1$  mm were installed to detect the presence of fuel at different levels in the sampling tank, outputting a logic high voltage in air and a logic low voltage in liquid. Different measuring volumes can be chosen by means of selecting two of the three sensors to use. In this way, the volume contained between the two sensors is known, allowing a volumetric measurement of net fuel flow to the engine. The pipe volume between the two sensors furthest apart is 159.4 ml, rendering roughly 60-100s elapsed time of the measurement. A timer is started as the fuel drops below the upper sensor and stopped as it drops below the lower sensor. Mass flow rate then can be calculated based on the specific gravity of tested fuel.

## 2.1. FUEL PROPERTY

Butanol is a four carbon alcohol that assumes a straight-chain or branched structure, of which the location of hydroxyl group (-OH) determines its different isomers. Though the physical properties of butanol isomers vary depending on their different structures, their major applications appear to be similar. Among the butanol isomers, normal butanol (expressed as n- butanol or 1-butanol), which has a straight chain structure with the -OH at a terminal carbon, is most commonly used and it receives much research attention because biomass based butanol usually assumes this structure. The baseline diesel fuel used is the U.S. ultra low sulfur diesel obtained through a local fuel supplier (Illini FS). This ultra low sulfur diesel is straight diesel No. 2 without any additives. The n-butanol used in this study is analytical grade normal butanol with 99.9% purity. Blends of butanol and diesel were made by volumetric ratios of 1:9, 2:8, 3:7, and 4:6, corresponding to 10%, 20%, 30%, and 40% of n-

butanol content denoted as B10, B20, B30, and B40 respectively. The properties for both base line fuel and n-butanol are listed in [Table 2](#).

## 2.3. TEST CONDITIONS

[Table 3](#) summarizes the test matrix of this study. The engine was held at 1000 RPM throughout the study, while the fueling rate was fixed to obtain 3 bar bmep and 5 bar bmep considered as light load and medium load respectively as the initial conditions. For each load, EGR ratio was gradually adjusted from zero to the point of combustion deterioration (observed by an abrupt increase in CO emission), and the main injection timing was modified at zero, moderate, and high EGR levels. Modification of main injection timings followed this manner: the ECM default setting at the operating speed and load was used as a reference, and the main injection timing was advanced or retarded as far as 6 crank angle degrees earlier or later than the default timing, using a 2-crank-angle-degree step. Meanwhile, the pilot injection was kept initiated about 18 CA before the SOI regardless of the SOI. These test conditions were performed for all test fuels. The ECM default injection timings are denoted as "0", while other timings are indicated as crank angle degrees relative to the default.

## 3. RESULTS AND DISCUSSION

### 3.1. COMBUSTION CHARACTERISTICS

The in-cylinder pressure and the corresponding apparent heat release at 3 bmep load for different butanol/diesel blends are shown in [Figure 1](#) and [2](#). At this point, no EGR was applied and the engine default injection was used. The fuels with different blending ratio of n-butanol are seen minimal difference for the main injection though pure diesel and B10 showed a little higher in-cylinder pressure after pilot injection. A clear peak can be seen for the pure diesel heat release curve for pilot injection while a much flatter peak was seen for the blends especially with higher n-butanol content, suggesting the pilot combustion could be incomplete for pure n-butanol blends, most likely due to the high auto-ignition temperature of the n-butanol. It is interesting to notice that the appreciable difference in pilot injection hardly affected the main injection, which is most likely due to the low overall in-cylinder temperature at the onset of SOI at the low load condition, thus the impact of the pilot injection is negligible at this condition. At higher load condition, however, more differences were seen among different blends as illustrated in [Figure 3](#) and [Figure 4](#). Though the pilot injection showed similar behavior as in the light load condition, a slight auto-ignition delay and a faster slope in the rate of heat release indicative of more premixed combustion is observed for the high n-butanol content blends. This finding is consistent with the work in Ref[6]. Longer ignition delay as well as the lower ambient temperature environment resulted from pilot injection provided the high n-butanol content blends more air/fuel mixing timing, which led to more premixed burn.



Then both EGR and modified injection strategy were applied at the medium load condition and the apparent heat release are shown in [Figure 5-6](#). Limited by the length of the text, a comparison is only made between pure diesel and B10. Retard injection for pure diesel, in general, resulted in more premixed burn as illustrated by the increase of the heat release peak which can be explained by the fact that both ambient temperature and pressure decrease rapidly after top dead center. Such trend for n-butanol blends, however, was less evident at no EGR condition and even a reverse trend was observed at heavy EGR condition as the heat release peak slightly decreased with the retard injection. This implies that the impact of injection timing on fuel/mixing for n-butanol blends is much less significant than pure diesel. The premixed combustion phase is reduced with retard injection because of a shorter ignition delay and the occurrence of diffusive combustion. The impact of injection timing will be further discussed in the next section.

## 3.2. INJECTION STRATEGY EFFECT

To study the impact of injection timing for different fuels on BSFC, NOx and soot emissions, the start of injection was modified from -6 CA to +6 CA relative to the engine original default injection timing with an increment of 2 CA. Again, we didn't apply the EGR at this point. The BSFC increased substantially with retard injection at low load condition especially for high n-butanol blends within the testing injection timing range. At each injection point, the n-butanol blends exhibits higher BSFC than pure diesel due to its lower heating value. At medium load, the increase of BSFC resulted from injection timing became moderate so as the difference between the n-butanol blends and pure diesel. This indicates that at low load condition, applying retard injection on n-butanol blends may result in dramatic penalty on BSFC though it might benefit the emission control. Therefore it is not suggested to use aggressive retard injection strategy on n-butanol blends from the BSFC viewpoint.

As for the NOx emission, SOI before TDC will result in much higher NOx emission for all fuels at both low and medium conditions. This is expected as injection during compression stroke can lead to higher in-cylinder pressure and consequently higher temperature. NOx generation is extremely sensitive to the adiabatic flame temperature [6], therefore retard injection yielded significant NOx reduction. It is also interesting to notice that with higher n-butanol content in the blends, the NOx emission increased tremendously for advanced injection timing at both low and medium conditions. The NOx emission for B40 is consistently higher even than pure diesel when SOI is initiated before the default timing. Better air/fuel mixing due to the joint effect of higher resistance to auto ignition and higher volatility of n-butanol blends resulted in more premixed burn and consequently a higher NOx emission. This is in agreement with the combustion characteristics shown in the previous section. In contrast, the impact of injection timing on NOx emission became almost negligible

if using retard injection timing and the NOx emission levels for n-butanol blends were all about cut in half. Therefore, retard injection will be very beneficial in NOx control especially for the higher n-butanol blends. Regarding soot emission, the injection timing effect is less perceivable if no EGR is taken into account. It is more straightforward to see the reduction of soot by adding n-butanol since n-butanol has higher oxygen content which helps soot oxidation. The benefits of soot emission control by using diesel alcohol blends have been detailed in a number of previous studies. [2,3,4]

## 3.3. SOOT-NOX AND BSFC-NOX TRADE OFF

Though it is important to study a individual parameter of the engine fueled by a certain fuel, simultaneous control of multiple emissions and engine performance is important from a more application focused standpoint. The trade-offs of soot-NOx and BSFC-NOx for B0, B10, and B30 under medium load conditions are demonstrated in [Figure 10](#) and [Figure 11](#). While the injection timings utilized are not specifically illustrated in the legends, the brake specific NOx emissions can be used as a reference to differentiate injection timings under same EGR ratios. Higher NOx emissions, shown by points more to the right side, typically indicate earlier injection timings. The goal of the engine control strategy is to converge all the points towards the bottom left as much as possible on the trade-off plots.

Previous studies have shown the potential of simultaneous reduction of both soot and NOx emission by using heavy EGR and modified injection strategy, [10,11] which often referred as low temperature combustion concept. By introducing heavy EGR, the intake air will be diluted to achieve a low in-cylinder temperature and adiabatic flame temperature thus lead to the suppression of both NOx and soot generation. The observation on [Fig 10a](#) for pure diesel confirmed this concept as noticed by the very bottom triangle mark which is conducted under 26% EGR and most retard injection condition. This point falls on FSN about 0.6 and brake specific NOx about 0.35 g/kWh.

It is now interesting to see how n-butanol content can affect the NOx-soot trade off and by looking at [Fig 10b](#) and [10c](#). Apparently with the increase of the butanol content, the same triangle mark are pushed further towards the left bottom corner. For B30 in particular, this triangle mark falls on FSN about 0.35 and brake specific NOx about 0.32 g/kWh compared with FSN of 0.62 and brake specific NOx of 0.24 g/kWh for B10. It should be notice that the optimal point for B10 considering the trade-off is with 18% EGR, with a much lowered FSN of about 0.45 at the expense of a higher brake specific NOx of about 0.7 g/kWh, yet still higher than B30 in both category. This approves that same LTC strategy can be applied on n-butanol diesel blends and the emission control will be further benefited with the increase of n-butanol content.

As for the BSFC-NO<sub>x</sub> trade off, retard injection in general brings all the point towards upper left for all fuels under all EGR conditions indicating retard injection could reduce NO<sub>x</sub> emission at the expense of increasing the BSFC. It can be found that more substantial increase in BSFC is resulted from retard injection under heavy EGR condition compared with light EGR condition. Meanwhile when heavy EGR is applied, default or slight retard injection timing did not impose much difference on the BSFC-NO<sub>x</sub> trade off indicating heavy EGR with slight retard injection timing strategy can achieve a milder combustion with benefits on soot and NO<sub>x</sub> without significant penalties in fuel specific consumption

#### 4. CONCLUSION

The combustion and emission characteristics of a diesel engine running on n-butanol-diesel blends were investigated in this study. The blending ratio of n-butanol to diesel was varied from 0 to 40 vol% using an increment of 10 vol%, and each blend was tested on a 2.7 L V6 common rail direction injection diesel engine equipped with an EGR system. The test was carried out under 3 bmep and 5 bmep at a constant engine speed of 1000 RPM, using various combinations of EGR ratios and injection timings. The findings of the study can be summarized as following:

1. N-butanol addition to engine fuel is able to improve the fuel/air mixing due to the longer ignition delay and low ambient temperature resulted from the pilot injection. Therefore more premix burn is observed for n-butanol blends especially at medium load.

2. Retard injection without EGR will lead to substantial and moderate increase in BSFC at low load and medium load respectively. The same injection strategy, however can significantly reduce NO<sub>x</sub> emission especially for higher n-butanol blends. The impact of injection timing on soot emission is not apparent if no EGR is taken into account.

3. N-butanol addition substantially decrease soot emission from raw exhaust gas under all occasions. Heavy EGR ratio and retarding injection timing, often referred as low temperature combustion strategy, are also effective approaches to simultaneous reduce NO<sub>x</sub> and soot emissions from combustion of n-butanol-diesel blends. Higher n-butanol ratio can further benefit the soot control in the sacrifice of higher BSFC. It can be concluded that the engine control strategies should be optimized in order to achieve low levels of both soot and NO<sub>x</sub> emissions, as well as a reasonable fuel economy.

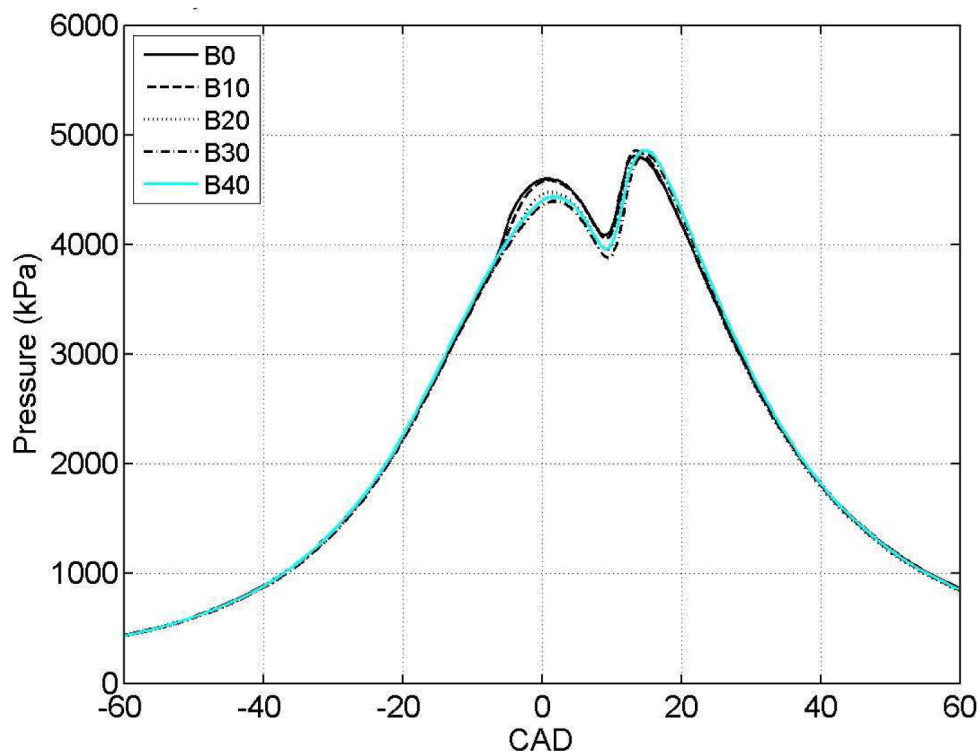


Figure 1. In-cylinder pressure for B0 through B40 with zero EGR and default injection timing at 3 bmep

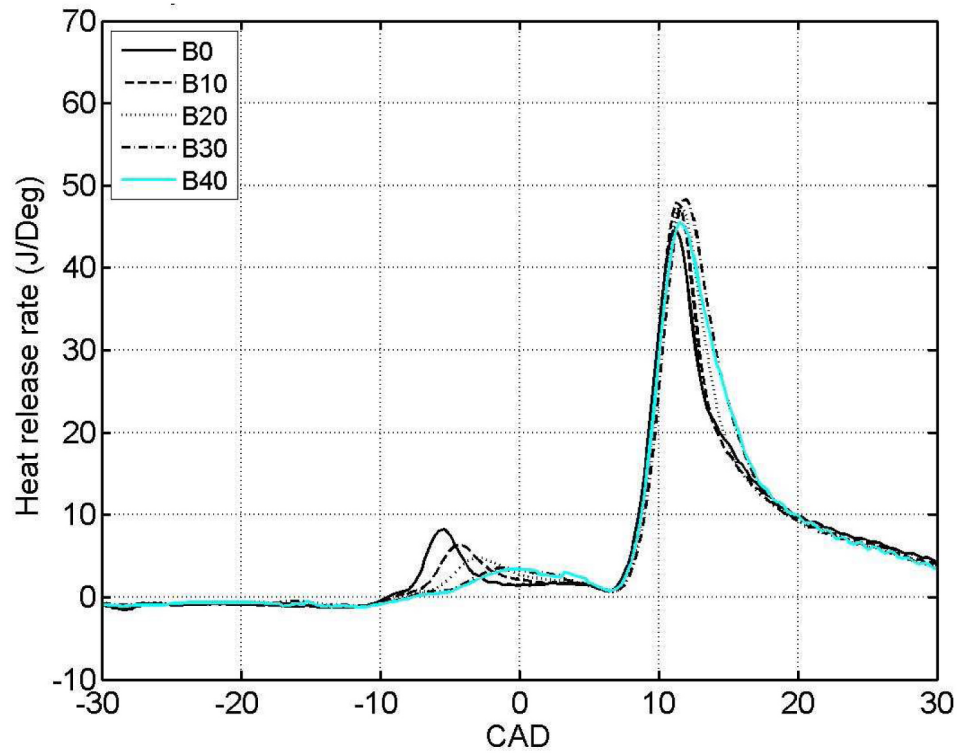


Figure 2. Apparent heat release rate for B0 through B40 with zero EGR and default injection timing at 3 bmep

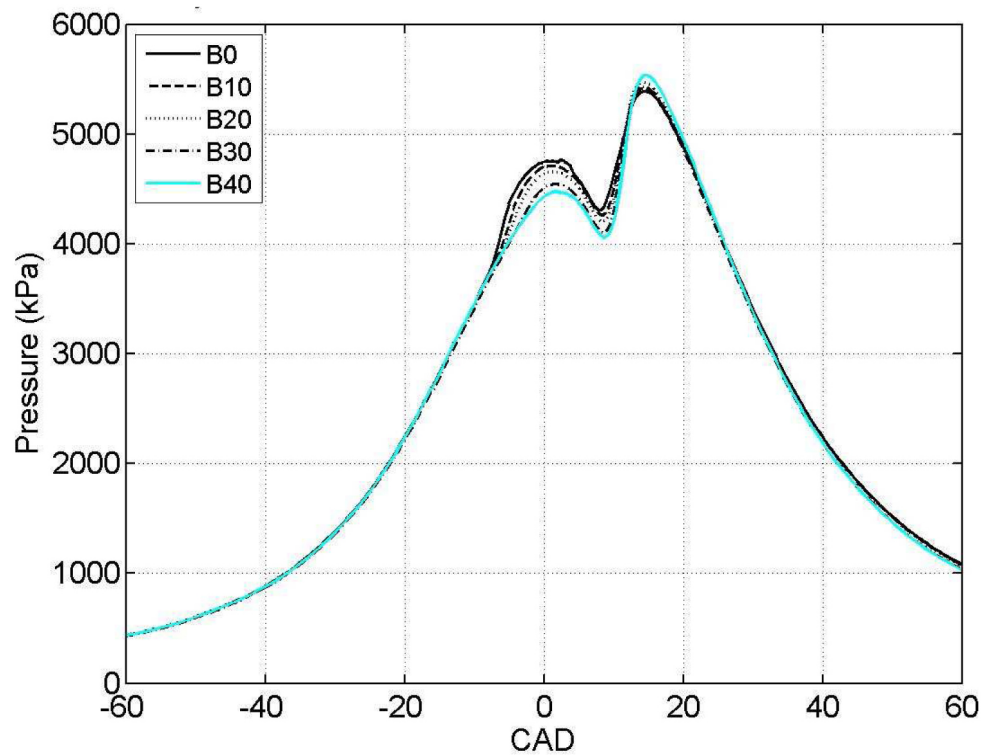


Figure 3. In-cylinder pressure for B0 through B40 with zero EGR and default injection timing at 5 bmep