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Investigation of Cylinder Deactivation (CDA) Application On a Naturally Aspirated Engine

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Abstract: Increasing oil prices and emission legislation have forced automotive company to investigate new methods and technologies to reduce the harmful effect produced from the motor vehicle, particularly CO_2 (Carbon-Dioxide). A lot of studies and research have been put into in order to achieve a zero emission vehicle with the usage of electricity rather than fossil fuel, but the challenge to cost and environmental effect makes an IC engine is still being the predominant power plant for automobile in this century. One of the popular techniques among engine manufacturers to have a better engine efficiency is cylinder deactivation. Cylinder deactivation is a promising method to reduce the fuel consumption and emission by forced the engine to operate at higher load. However, the higher combustion pressure and extreme temperature at firing cylinders will result in higher NOx composition. This paper will investigate further the engine performance, fuel economy and emission by using one-dimensional (1-D) simulation tool. A standard 1.6 litre naturally aspirated four in-line cylinders, port fuel injection engine is modelled and correlated to the measured test data. The model is then simulated with cylinder deactivation mode by deactivating the intake and exhaust valves at cylinders no 2 and no 3 as well as fuel injection at various engine speeds at part load conditions to show improvements in fuel consumption, $CO_{2\ \mathrm{emissions}}$, pumping losses and effects on CO and NOx emission. This correlated model is then used to investigate the application of EGR in order to reduce the emission level. Also, the effects on in-cylinder combustion as well as pumping losses are presented. The study shows that the application of EGR is very significant for engine with CDA mechanism to ensure the overall engine fuel consumption and emissions are reduced simultaneously.

Keywords: Cylinder deactivation, CDA, pumping losses, 1-D simulation, EGR

1. Introduction

The exhaustion of fossil fuels such as petrol and diesel and the stringent emission legislation has forced automotive engine manufacturers to investigate the new advanced method and technologies to reduce the harmful effect from the

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engine as much as possible to meet the regulation. Recent engine's key technologies such as gasoline direct injection, optimized intake and exhaust timing, exhaust gas recirculation, and bundled with extreme downsizing engines are promising methods in reducing fuel usage by improving their thermal efficiencies [1-7]. Generally, engines operate more efficient at higher loads due to the less throttling effect. However, most of the actual engine operating region in most drive cycles is plotted at part load conditions. The throttle valve must be nearly close to control the amount of air inducted into the combustion chamber. Smaller throttle valve opening will cause high pumping losses, which decrease the engine efficiencies and thus end up with a fuel penalty. As a countermeasure to reduce the pumping losses, the throttle valve opening is required to be wider of respective engine conditions. Better matching of real engine load with optimum engine load can be obtained by applying cylinder deactivation [2-3].

Cylinder deactivation (CDA) operates by deactivating half of the total cylinders, which requires the remaining firing cylinder to operate at a higher load than usual to provide a similar overall power required of the normal operation. Hence, in order to supply the required work with only half the total cylinders, each cylinder needs more air and fuel than it would with all cylinder firing [8]. Therefore, the intake manifold pressure must be higher (less throttled), significantly reducing the engine's pumping work [9-12]. In cylinder deactivation mode, the intake and exhaust valves of the unfired cylinders are kept shut to ensure no air is induced and extracted from the combustion chamber. As a result, the enclosed air at the respective cylinders works like a pneumatic spring that periodically compresses the same volume without overall pumping work [10]. Cylinder deactivation creates an effective variable displacement engine, where the engine provides the optimum power based on demand with the fuel economy benefits without sacrificing the overall actual power [10-11]. One of the drawbacks of CDA application is the NOx emission level. High combustion temperature, which is more than 2800 F at the firing cylinders, will result in higher nitrogen oxide (NOx) formation.

The thermal reaction of oxygen and nitrogen at elevated temperatures during the combustion process will produce nitrogen dioxide (NO2) and nitrogen-monoxide (NO). One of the most popular techniques to reduce this effect is exhaust gas recirculation (EGR). EGR is a known technique to reduce NOx emissions. Many studies have been conducted on the effect of EGR, but most of them have focused on the compression ignition (IC) engines [13-20]. Increasing of EGR rate from 0% to 5% can significantly reduce the NOx formation up to 50% [16-18]. Hence, it is very important to investigate further this CDA technique, principle and the interaction between parameters that directly contribute to the engine performance. A one-dimensional (1D) engine simulation is used to infiltrate the thermodynamics behavior of this engine. A complete engine model of 1.6 liters natural aspirated, spark ignition (SI), port-fuel injection (PFI) four-cylinder engine is constructed based on actual physical dimensions. This model is used as a baseline for CDA application. This paper presents the model construction, correlation with actual on bench testing and thermodynamic analysis for normal and CDA modes. As for optimization, the effect of EGR to suppress the NOx formation will be exploited and discussed.

2. Methodology

2.1 Model Construction

This study has applied steps to create one complete engine model as illustrated in Fig. 1.

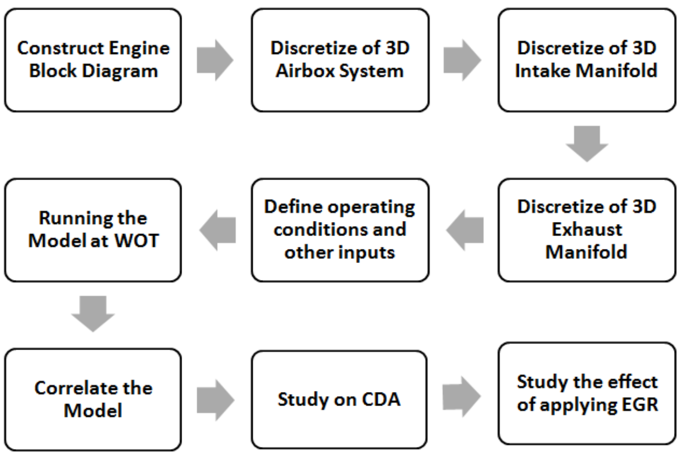

Fig. 1 - Steps of engine model construction

A complete engine model has been built from the intake system until the exhaust tailpipe. This ensures the engine model represents the actual engine setup in the test bench. The engine subsystems, intake system and exhaust system were modeled precisely by considering all the bending effects and surface roughness. The actual 3-D CAD model of the subsystems were converted into 1-D block diagram and meshed in GT-Power. The flow model involves the solution of Navier-Stroke equations, namely the conservation of continuity, momentum, and energy equations. A predictive combustion model 'SI-Turbulence' was applied in this study due to its suitability for better predicting part load engine operation, spark timing effect, cylinder knocking, combustion chamber design, and spark plug gap [12]. In order to improve the model's predictive accuracy, the FMEP model used in this model is based on the actual friction data on the bench. The constructed model has then simulated at an engine speed of 1000 to 6400 rpm (with 500 rpm interval) at wide open conditions. The results of engine performances have been plotted and compared with actual testing data.

2.2 Model Correlation

The results of engine performances have been measured on the engine dynamometer test. The tests were carried out at full load and at selected part-load conditions. The engine was run at Wide Open Throttle (WOT) for full load condition with an engine speed of 1000 to 4000 rpm. For part load conditions, the engine was tested at 1 to 4 bar Brake Mean Effective Pressure (BMEP) from 1000 to 4000 rpm only. The upper engine speed is limited to 4000 rpm does not describe the mechanical limit of the engine during CDA mode, but it represents the reasonable limit for the most common part-load operation during the actual urban drive cycle in Malaysia [13,21-23].

The accuracy of the engine model has been verified by correlating the result of intake manifold air pressure and exhaust manifold backpressure up to 4000 rpm at full load conditions. In the engine modeling, the best practice is to ensure that the differences between measured and simulated data are less than 2% for the intake manifold pressure and 5% for the exhaust manifold pressure [11]. The model predicts less than 4% difference in critical parameters that represent the engine performances based on the simulated results. As illustrated in Figure 3, the results indicate that the simulation and actual testing show an excellent agreement.

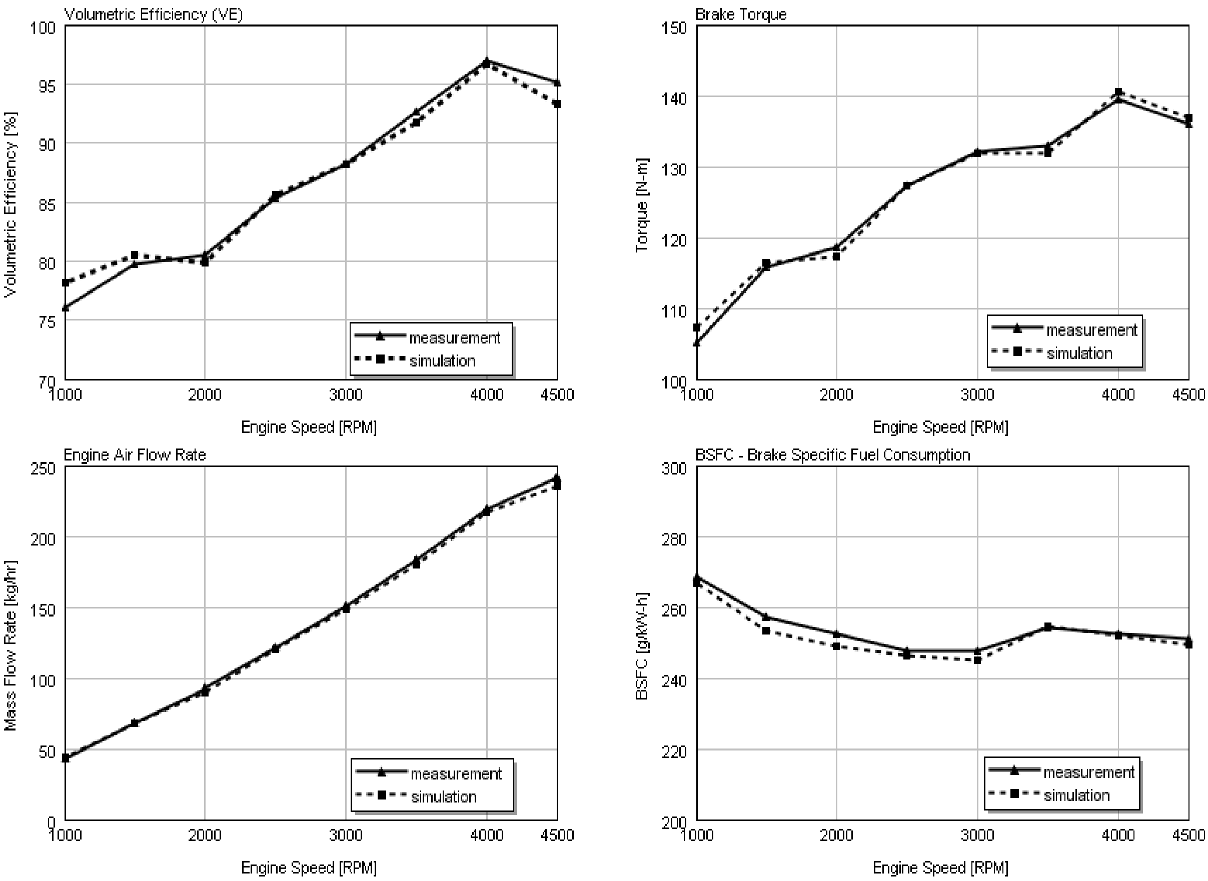

Fig. 3 - Comparison between measured and simulated results at full load operations

The second step is to correlate the simulation and measurement data at part load conditions. Most engine operating conditions during the conventional and actual drive cycle fall in this region. The allowable percentage difference between both cases is below 5%. As described in Figure 4, the engine model predicts excellent correlations with the bench test and is ready for further development.

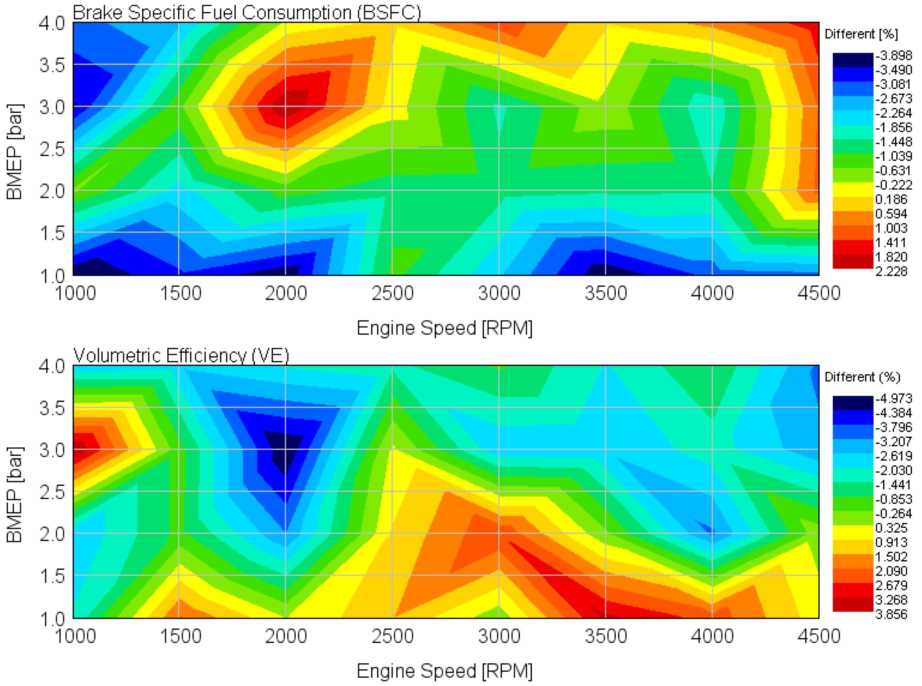

Fig. 4 - Percentage different between simulation and measurement data

3. Results and Discussion

3.1 Part Load Engine Operation with CDA

The constructed engine model then undergoes multiple series of tests to identify the significant difference in performance by operating only half of the cylinders at part load conditions. The cylinder deactivation mechanism was set up by deactivating half of the cylinders, keeping the intake and exhaust valves shut, and zero fuel injection. The combustion model for deactivated cylinders was ignored, and the fuel-to-air ratio was set to zero. The air-fuel ratio (AFR) at the firing cylinders was set up at a stoichiometric value, 14.7, the best mixture for the part-load operations. Figure 5 compares the cylinder pressure traces of cylinder 1, for normal 4-cylinder operation and 2-cylinder operation at 2 bar BMEP at 2000 engine rpm.

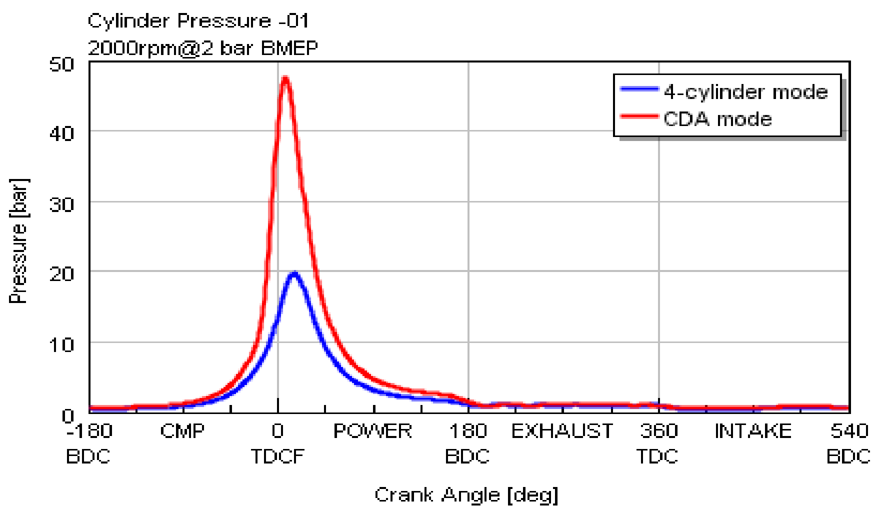

Fig. 5 - Predicted combustion pressure for normal 4-cylinder mode and CDA mode operations at 2000 rpm@2bar BMEP

Deactivation of half-cylinder requires the remaining active cylinders to operate at higher Indicated Mean Effective Pressure (IMEP) to provide the same overall Brake Mean Effective Pressure (BMEP) [19-20]. In order to supply sufficient work with only half the cylinders, each cylinder requires extra air and fuel than it would during normal operation. Therefore, the throttle opening for CDA mode is much higher, contributing to less pumping work produced.

Figure 6 shows the pumping work, a plot of cylinder pressure versus normalized cylinder volume at firing cylinder (cylinder 1) during this both conditions at the point of interest operation.

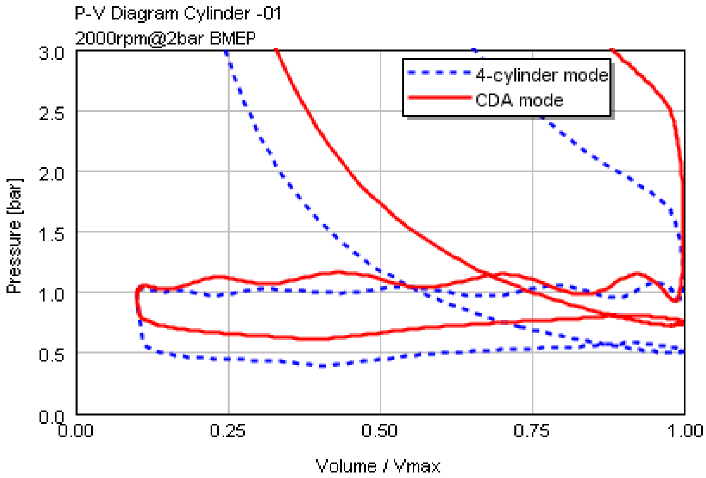

Fig. 6 - Log P-V for cylinder 1 during normal 4-cylinder mode and CDA mode at 2000 rpm, 2 bar BMEP

On the other hand, the unfired cylinder pressure shows the constant value all over the cycle, as illustrated in Figure 7. This is because the unfired cylinder acts like a pneumatic spring and keeps compressing and expanding the same air.

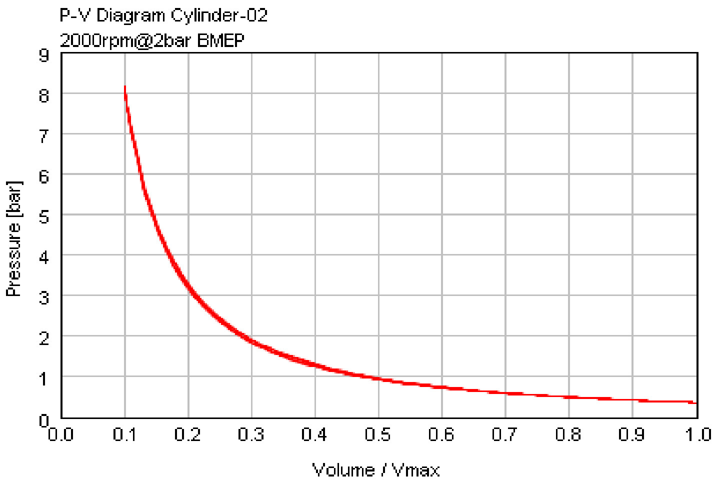

Fig. 7 - Predicted cylinder pressure of an unfired cylinder at 2000 rpm, 2 bar BMEP

Figure 8 shows the fuel consumption benefits derived from the simulated CDA model. It can be seen that the CDA operation gives a significant improvement across the engine speed from 1000 rpm to 4500 rpm at BMEP below 4 bar. Negative test results indicate fuel savings in CDA mode. It is noticeable that CDA generates considerable advantages in fuel consumption at lower engine loads, up to 26% at 1bar BMEP and 2500 rpm. Even at higher loads operations (<4 bar), the optimal combustion timing still can be achieved. This is proved by improvement of fuel consumption all over the ranges.

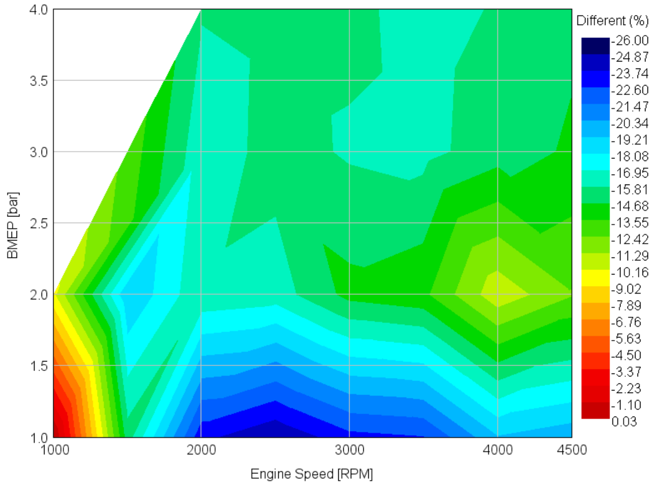

Fig. 8 - BSFC benefits contour

Figure 9 shows the pumping mean effective pressure (PMEP) comparison between normal 4-cylinder and CDA modes. A significant reduction can directly contribute to the pumping work savings due to the less throttling effect. The contour map shows an improvement of up to 76% at low engine speed during low load operations. Meanwhile, it also can be concluded that the pumping work is absolutely reduced by operating the engine in CDA mode.

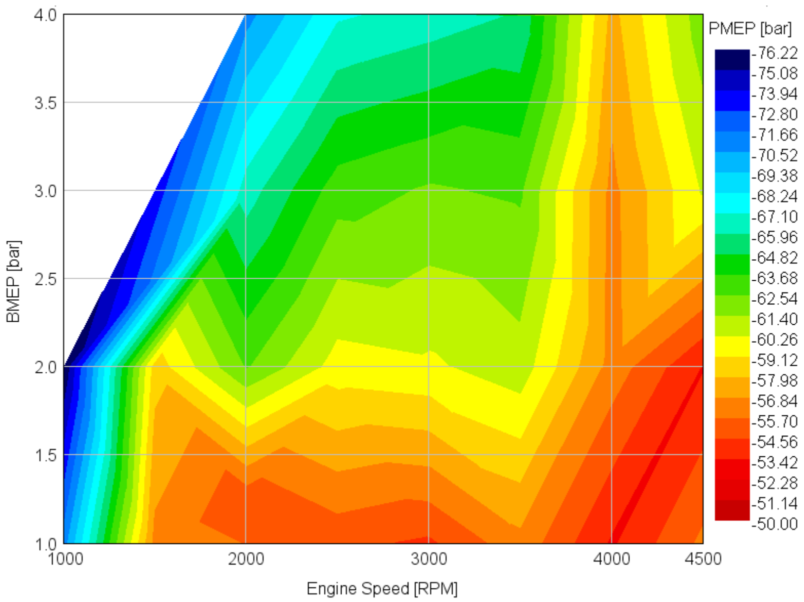

Fig. 9 - PMEP contour

Several studies have proved that the high temperature in the firing cylinders in CDA mode tends to provoke higher NOx output [18-19]. The amount of NOx emission is very sensitive to combustion temperatures. Generally, NOx emissions do not form in great amount until the combustion temperature reach 2800 F. Once this threshold is conceded, any further rise in temperatures will boost the rate of NOx formation.

However, this phenomenon can be reduced by introducing the EGR system. This study has studied the effect of external EGR with various ratios on NOx formation. The effect of EGR on cylinder pressure indicated specific fuel consumption, and also NO_x emissions in a rational range of EGR from 0% to 15% have been investigated. Figure 10 shows the effect of EGR on the average cylinder pressure at selected part-load operations. The presence of EGR significantly reduced the cylinder pressure by 10% for every increment of 5% EGR.

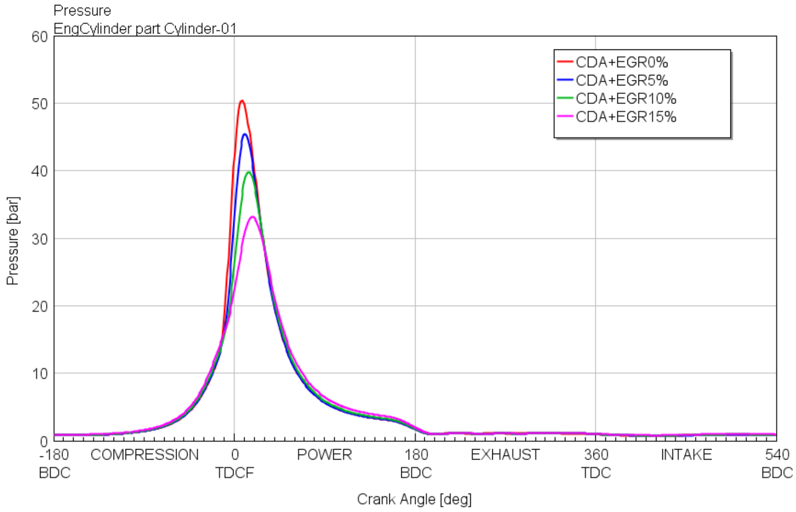

Fig. 10 - In-cylinder pressure diagram for different percentage of EGR at 2000rpm@3bar BMEP

The EGR replaces some of the inlet air and reduces the in-cylinder trapped oxygen by increasing the re-circulated gas. The lack of oxygen will slow down the combustion rate, leading to lower in-cylinder pressure. The effect of EGR is almost similar to the addition of excess air, which can dilute the unburned mixture, thereby reducing the peak cylinder temperatures and NO formation rate, as depicted in Figure 11. Since the burned gas dilutes the unburned mixture, the absolute temperature reached after combustion varies inversely with the burned gas mass fraction. However, EGR also significantly reduced the combustion rate, leading to unstable combustion. As depicted in Figure 12, the combustion becomes slower with increasing EGR percentages.

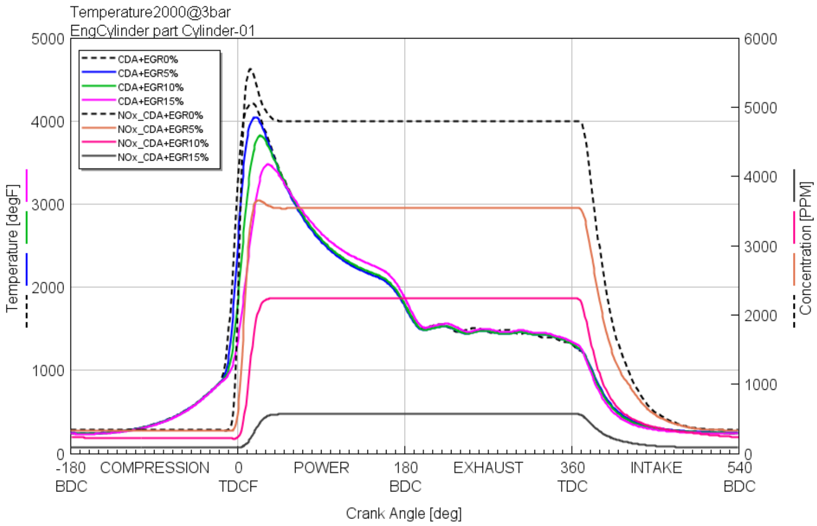

Fig. 11 - In-cylinder combustion temperature and NO_x formation for different percentage of EGR at 2000rpm@3bar BMEP

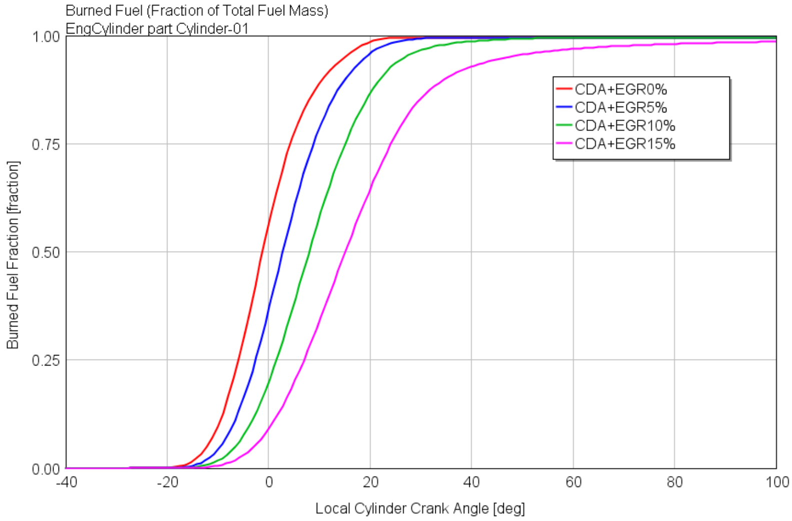

Fig. 12 - Burned fuel fraction for different percentages of EGR at 2000rpm@3bar BMEP

From the fuel consumption perspective, introducing an EGR could reduce the amount of fuel usage while maintaining the same engine brake specific output. This circulation gas reduced heat loss through the walls because the combustion gas temperature decreased significantly. In connection to that, the combustion becomes more efficient, allowing more of the fuel's chemical energy to be converted to useful energy. In Figure 13, it was found that the improvement in terms of BSFC up to X% with every increment of Y% EGR. This will boost up the capability of CDA engine in promoting higher thermal efficiency.

3.2 Future Outlook

Some studies have proved that vehicles regularly travel at idle, low speed, medium speed, and mild acceleration, particularly for urban driving, contributing to the highest weight on the overall vehicle fuel economy. Understanding the engine behavior and characteristics during part load operation will help strategize the CDA application through the drive cycle. A previous study has been made that indicates that the recommended range for fuel consumption improvement falls below 4 bar BMEP between 1500 rpm to 2500 rpm [15] based on the actual drive cycle in Malaysia, as illustrated in Figure 13. The case study of the constructed engine model in this paper needs to be explored wider to cover all the common engine operating regions. The actual improvement in the vehicle fuel economy can be obtained through over the actual drive cycle. The difference in fuel usage between normal 4-cylinder mode and CDA mode under the same engine condition is the most valuable in concluding the system's effectiveness.

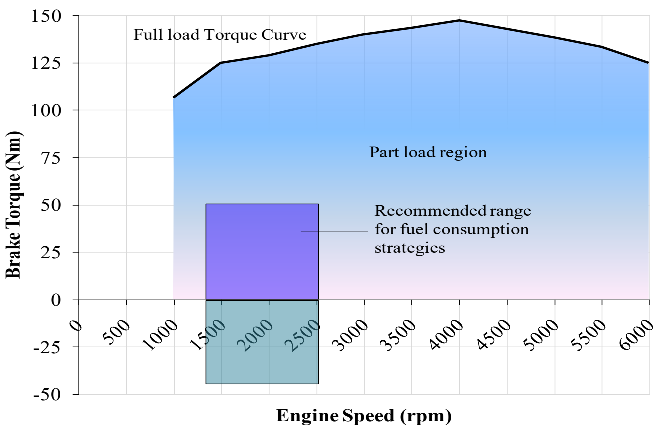

Fig. 13 - Recommended brake torque range [11]

4. Conclusion

An engine cycle simulation progress of a naturally aspirated gasoline engine with the CDA strategy was presented in this paper. The objective is to obtain a better understanding of engine characteristics during operation in half of the total cylinders. The base engine simulation results showed an excellent agreement with engine testing results. The engine model then successfully runs with CDA mode at the part-load conditions. The results indicate a significant improvement in terms of fuel usage of the engine in the CDA mode compared to the normal 4-cylinder mode. By operating the engine in CDA mode operation can contribute to 16% fuel saving compared to normal 4-cylinder operation. However, there are still possible improvements that could be applied to the CDA strategy to maximize its benefits. Actual on-bench testing is needed to verify the simulation results and the combustion characteristics at part load and full load conditions for both normal 4-cylinder mode and CDA mode.

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