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THE STUDY OF THE EFFECT OF INTAKE VALVE TIMING ON ENGINE USING CYLINDER DEACTIVATION TECHNIQUE VIA SIMULATION

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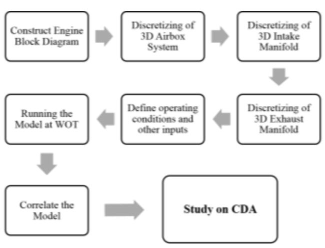
Graphical abstract



Abstract

There are many technologies that being developed to increase the efficiency of internal combustion engines as well as reducing their fuel consumption. In this paper, the main area of focus is on cylinder deactivation (CDA) technology. CDA is mostly being applied on multi cylinders engines. CDA has the advantage to improve fuel consumption by reducing pumping losses at part load engine conditions. Here, the application of CDA on 1.6L four cylinders gasoline engine is studied. One-dimensional (1D) engine modeling work is performed to investigate the effect of intake valve strategy on engine performance with CDA. 1D engine model is constructed based on the 1.6L actual engine geometries. The model is simulated at various engine speeds at full load conditions. The simulated results show that the constructed model is well correlated to measured data. This correlated model is then used to investigate the CDA application at part load conditions. Also, the effects on the in-cylinder combustion as well as pumping losses are presented. The study shows that the effect of intake valve strategy is very significant on engine performance. Pumping losses is found to be reduced, thus improve fuel consumption and engine efficiency.

Keywords: Cylinder deactivation, CDA, pumping losses, 1D engine model, valve timing, engine performance

1.0 INTRODUCTION

Recent technologies for gasoline engines focus on lean combustion which among others include direct injection and homogenous charged compression ignition [1-3], optimizing intake and exhaust valve timing and valve lift, and cylinder deactivation systems (CDA). These technologies have been applied to improve the engine efficiency and improve fuel economy.

Cylinder deactivation (CDA) is a promising method in reducing fuel consumption and emission at part loads in SI engines [4-6]. Deactivation of half the number of cylinders require the remaining firing cylinders to operate at a higher Indicated Mean Effective Pressure (IMEP) to provide similar overall Brake Mean Effective Pressure (BMEP) or engine torque. In other words, the work required by the firing cylinder is much more than normal operation.

Hence, in order to supply the required work with only half the number of cylinders, each cylinder needs more air and fuel than it would when all cylinders are firing [7]. Therefore, the intake manifold pressure must be higher (less throttled), which seriously reduce the pumping work of the engine [8].

In cylinder deactivation mode, the combustion chambers of the unfired cylinders are kept shut by the closed valves. As a result, the enclosed air works like a pneumatic spring which is periodically compressed and decompressed without effecting overall pumping work [9]. Cylinder deactivation creates an effective variable displacement engine, where the engine provides the required power based on demand with potential fuel economy benefits without sacrificing the overall actual power.

In achieving better engine performance, the characterization of the CDA technique is very crucial. It is important to understand the details of CDA technology, their interaction and parameters that affect the engine performance. Therefore, a one-dimensional (1D) fluid dynamic computation simulation was used to assess the CDA engine performances. The software called GT-Power is used to construct an engine model based on the 1.6-liters natural aspirated, spark-ignition (SI), port-fuel injection (PFI) four-cylinder engine. This model is used to study the effect of intake valve open timing and lift on CDA engine performance.

2.0 METHODOLOGY

This work focuses on the investigation of intake valve timing and lift on the performance of CDA engine. Initially a one-dimensional (1D) engine simulation tool is used to construct the CDA engine model and to investigate the effect of intake variables on engine performance. Before the CDA engine model was constructed, the four cylinders naturally aspirated (NA) engine model was developed and correlated to measured data.

Many input data were defined during the engine model construction. Some of the inputs include engine characteristics, cylinder geometry, and intake and exhaust system geometries, fuel properties, injector characteristics, valve sizes, ambient conditions and engine operating conditions. The model was run at various engine speeds and at wide open throttles (WOT) conditions. To fully investigate the accuracy and reliability of the constructed model, the simulated results from the model were correlated to the measured data.

In validating the results, the constructed model is tuned so that the simulated results agreed well with the measured data. After both results were thoroughly scrutinised, then the model was accepted as the correlated model. This correlated model is then used to simulate the CDA engine performance.

3.0 ENGINE MODELING

3.1 Model Construction

It is important to produce an accurate engine model to get better simulated output. In this study, the steps to produce engine model are presented in Figure 1.

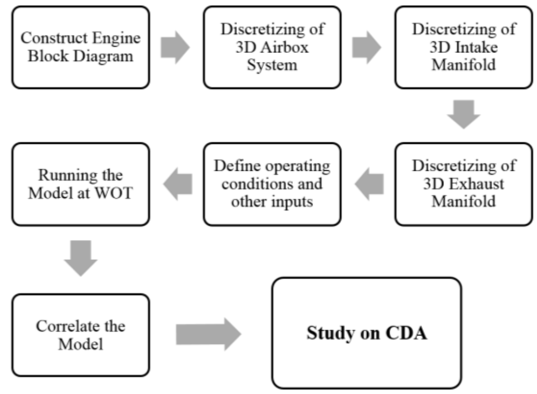


Figure 1 Steps of engine model construction [10]

The engine model was built from the intake air box system until the exhaust tailpipe systems. For the intake and exhaust systems, almost all components are modelled as pipes. In GT-Power, pipes are used to represent these systems as tubes and they are connected by junctions. The flow model involves the solution of Navier-Stokes equations, namely the conservation of continuity, momentum and energy equations [10].

In order to model an air box in the GT-Power environment, a 3D CAD model of this air box is used. The 3D model is discretized using SolidWork CAD software to extract the exact dimension of each part. Inlet and outlet diameters of each pipe (snorkel, duct, zip-tube). Their lengths were also defined in GT-Power environment. Upper and lower air box were defined by their volume. Discharge coefficient was introduced to represent pressure losses of the air filter.

A similar discretization process was applied to the intake and exhaust manifold (Figure 1). Here, the intake and exhaust runners are modelled using bent pipes. Basically, the bend pipes will take into account the pressure loss due to the effect of bending geometries. The diameters of the inlet and outlet, as well as the angles and bending radius were defined to model these runners. The intake plenum was defined using Y-split part, where the volume of each runner section was applied.

The most important step in engine modelling is to use the right combustion model. A fully predictive combustion model known as 'SI Turbulence' function was applied. This combustion model is more suitable for the prediction study of partial load engine operation, exhaust gas recirculation (EGR), and spark timing effect, cylinder knocking combustion chamber design and spark plug gap [6]. This model predicts the combustion pressure as well as IMEP and other performance parameters.

Input data includes *.stl file* of combustion chamber shape, spark timing at each rpm at wide open throttle (WOT) condition, spark plug location and gap as well as fuel octane number.

In order to model intake and exhaust valves for this engine, it is required to define the detail characteristics of a cam-driven valve including its geometry, lift profiles and flow characteristics. Both intake and exhaust valves open timing are set according to the actual engine configuration.

Once all the input data were defined in the model, the next step was to define the engine operating conditions. Here, the constructed model simulated the engine at speed of 1000 to 7000 rpm (at 500 rpm interval) at WOT condition. After the simulations were completed, the results of engine performance were plotted. These results are then used to correlate the model with experimental data.

3.2 Model Correlation

A series engine performance test was carried out at WOT conditions ranging from 1000 to 7000 rpm with incremental speed of 500 rpm.

The accuracy of the constructed model was verified by correlating the model to the intake manifold air pressure and exhaust manifold back pressure as shown in Figure 2. In the engine modeling, the best practice is to make sure that the differences between measured and simulated data are less than 2% for the intake manifold pressure and 5% for the exhaust manifold pressure. The result shows that the model and measured data compared very well, giving less than 1% difference for intake pressure and 3% for back pressure. This proof the intake and exhaust systems are well modeled.

As depicted in Figure 2, the correlated model for brake torque, brake specific fuel consumption (BSFC), engine air flow rate, manifolds pressures and volumetric efficiency (VE) are found to be very close to the measured data, with differences of less than 5% in average. Thus, this correlated model is considered to successfully represents the real engine and it can be used for other simulations or studies as well as optimization works.

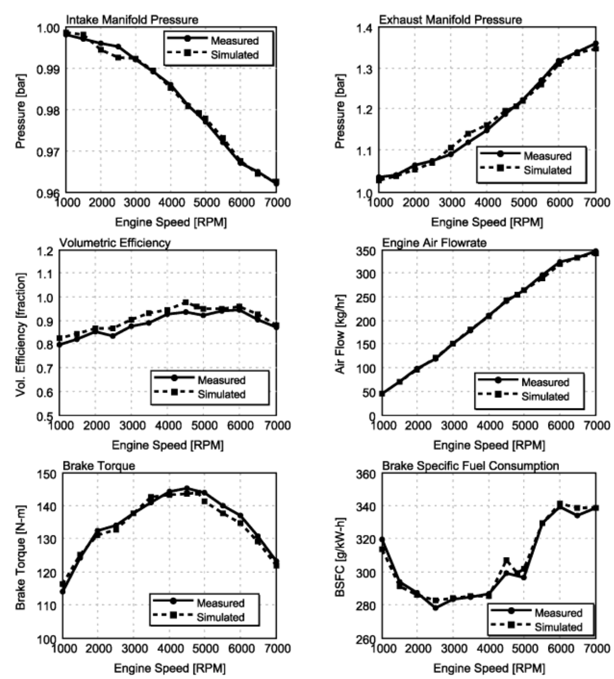


Figure 2 Comparison between measured and simulated results

3.3 CDA Application

After the correlation process on the constructed model has been successful, the model is then applied as a prediction tool to analyse the application of CDA technology on engine performance. Here, the model was set to run using 2-cylinder mode which is on CDA mode. Cylinders number 2 and 3 were deactivated by defining zero intake and exhaust valves lift. Combustion model for both cylinders were ignored and fuel to air ratio was set to 0. Now the engine only operates with cylinders number 1 and 4. The CDA model uses similar intake and exhaust valves timing and lift and is also having similar air-fuel ratio (AFR) as the 4-cylinder mode.

Table 1 shows the performance outputs between the 4 and 2-cylinder modes. Both modes were operated at part load conditions. They operate at engine speed of 2500 rpm, BMEP of 3 bars and AFR of 12.2. In order to achieve the target operating conditions, CDA requires more air flow to the active cylinders, thus increasing the VE and lowering the indicated specific fuel consumption (ISFC). Larger throttle opening angle is required to allow for more air to flow into cylinders 1 and 4, hence promote the reduction of pumping loss.

Total engine performance of CDA and normal modes are also listed in Table 1. As the total AFR was set to 12.2, lower fuel flow rate contributes to the reduction of air consumption in the engine. This is clearly recorded in the reduction of VE of the engine

Table 1 Comparison between 4 and 2-cylinder mode

Performance	Unit	4-cylinder mode (Normal)	2-cylinder mode (CDA)	% Different
Air Flow[1]	mg/cycle	168	308	83.3
ISFC[1]	g/kWh	259	234	-9.7
VE[1]	%	36.2	66.7	84.3
PMEP[1]	bar	-0.57	-0.31	-45.6
IMEP[1]	bar	3.98	8.09	103.3
Indicated Eff[1]	%	31.9	35.2	10.3
Max. cyl. press[1]	bar	16.4	27.5	67.7
Burn residual[1]	%	7.91	4.69	-40.7
Throttle angle[2]	deg	6.55	7.12	8.7
Fuel flow rate[2]	kg/h	3.42	3.16	-7.6
BSFC[2]	g/kWh	343	317	-7.6
VE[2]	%	36.2	33.5	-7.5
Intake Plenum Press. [2]	bar	0.48	0.81	68.8

Note :
[1]measurement at cylinder 1
[2]measuarement for engine

when CDA was applied. Reduction of fuel flow rate and BSFC of the engine were detected during CDA mode operation.

Maximum cylinder pressure, intake plenum pressure, indicated thermal efficiency and indicated mean effective pressure (IMEP) show increments when CDA is applied. These are due to the fact that only two active cylinders are used to achieve 2500rpm and BMEP of 3 bars. Burnt residual gases found to have been reduced, thus promote to better indicated thermal efficiency in 2 cylinder mode.

Figure 3 presents the predicted results of cylinder pressure for both 4 and 2-cylinder modes. At normal operation, all cylinders generate almost similar peak pressure. However, cylinders number 1 and 4 produced higher combustion pressure during CDA mode is compared to the normal mode. Cylinders 2 and 3 recorded similar pressure profiles and this is due to non-combustion activity on the deactivation cylinders.

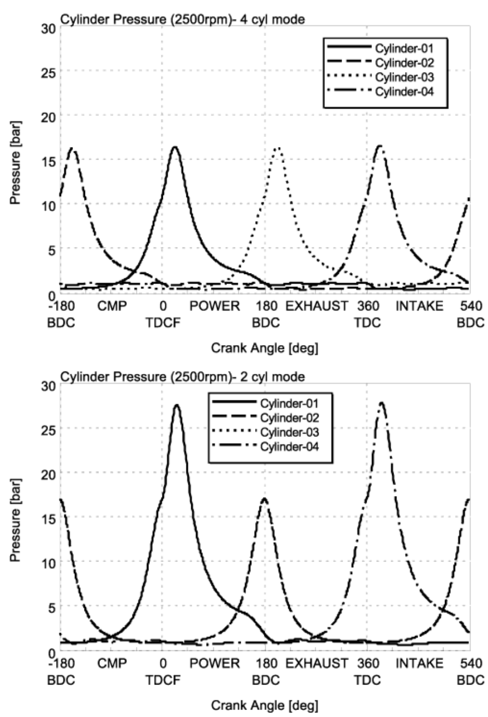


Figure 3 Simulation of combustion pressure for normal and CDA operations at BMEP=3bar

When CDA or 2 cylinder mode is applied, cylinders number 1 and 4 are activated, while 2 and 3 are deactivated. It is found that the active cylinder (cylinder 1) will produce less pumping loss as depicted in Figure 4. However, cylinder 2 recorded no energy production due to no combustion activity.

Comparisons between simulated and actual test results on 2 cylinder mode were also performed. The data show a close agreement, as listed in Table 2. This indicates that the constructed engine model running on CDA is well correlated to actual data. Thus, this model can be used to investigate the effect of intake valve open timing and lift on the engine performance when CDA mode is applied.

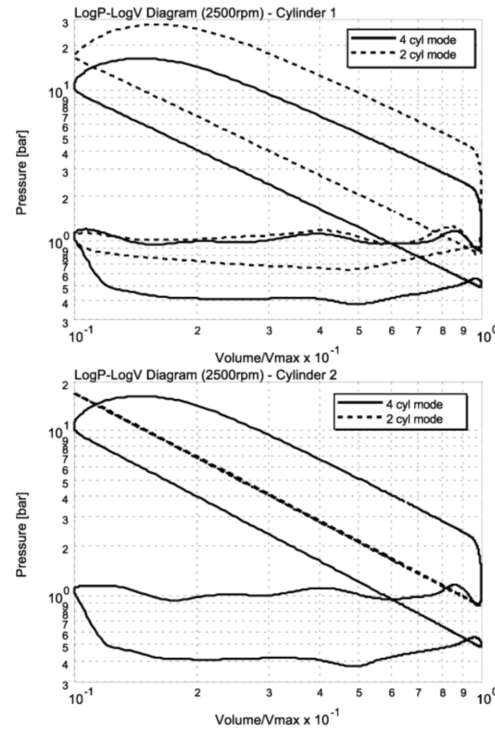


Figure 4 Log PV for cylinder number 1 (top) and 2 (bottom) at normal and CDA modes for BMEP of 3bar.

Table 2 Actual test data of CDA operation compared to simulated model

Performance	2-cyl. Mode Simulated	Actual Test	% Different
Fuel flow rate	3.16 kg/h	3.03 kg/h	4.3
BSFC	317 g/kWh	310 g/kWh	2.3
VE	33.5 %	32.0 %	4.7
Intake plenum press.	0.81 bar	0.78 bar	3.8

Note : measurement for the engine

3.4 Effect of IVO Timing and Lift

In this study, the model is used to investigate the effect of intake valve open (IVO) timing as well as maximum lift on CDA mode performance. Only cylinder 1 and 4 are activated. The analysis was performed at 2500 rpm and BMEP of 3bar. Similar AFR 12.2 was applied.

Figure 5 indicates simulated engine performance at various IVO timing. BSFC reduces significantly at late open timing. This due to the less amount of air induced to the cylinder, which means less fuel as well. It is noticeable that the burn residual in the cylinder reduces at late timing, thus improved the indicated efficiency slightly.

The investigation on the effect of valve lift on CDA mode operation is depicted in Figure 6. As the maximum intake valve lifts become higher, it also increases the BSFC and trapped fresh air in cylinder 1. The increase of fresh air also increases the amount of fuel injected to the cylinder, thus increases the BSFC. Burn residual was found to be higher and contribute to the lowering of the indicated efficiency.

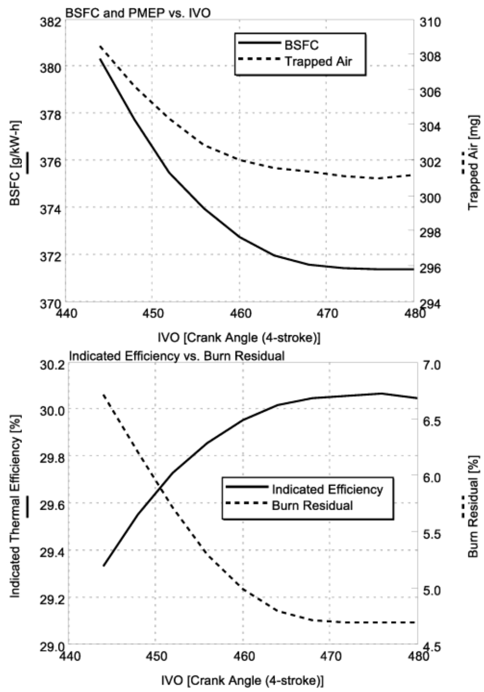


Figure 5 Effect of IVO timing on engine performance for CDA mode at cylinder 1 for 2500rpm at 3bar.

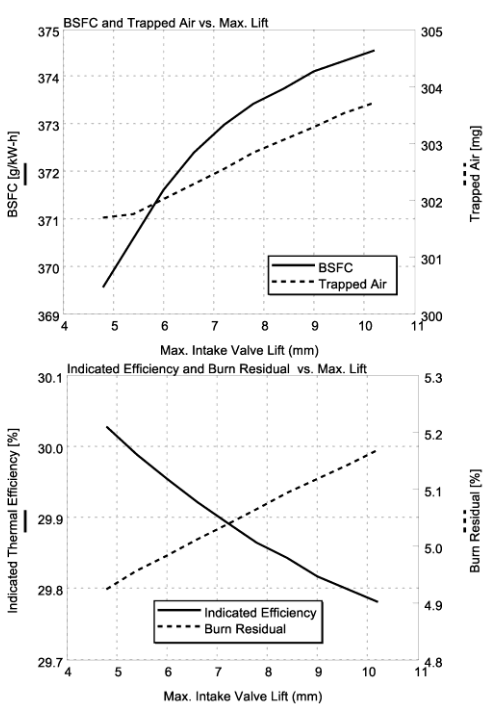


Figure 6 Effect of valve lift on engine performance for CDA mode at cylinder 1 for 2500rpm at 3bar

4.0 CONCLUSION

Computer simulation techniques are applied to obtain better understanding of a 1.6 litre engine using cylinder deactivation technique on engine performance. 1D engine model of the 4-cylinder 1.6-liter SI engine was constructed. The model was proven to be well correlated with measured data.

The engine model was successfully run with CDA mode where cylinders 2 and 3 were deactivated. It shows that the CDA mode produces better performance in achieving BMEP of 3 bar at 2500rpm. Low fuel consumption and pumping loss were recorded. The effect of IVO timing produces better performance at late open timing. However, the performance decreases when the engine operates at higher valve lift.

Acknowledgement

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