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EXPERIMENTAL INVESTIGATION OF CYLINDER DEACTIVATION IMPACT ON ENGINE PERFORMANCE AND EMISSION FOR SI ENGINE

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ABSTRACT

Cylinder deactivation is one of the promising fuel efficiency strategies that offers lower fuel consumptions and exhaust emissions by allowing the multi-cylinder gasoline engine running with smaller engine displacements at part load operation. Cylinder deactivation technology has been developed by several vehicles manufacturers and extended to as large as 6.5l V12 engine and as low as e3.5l V6 engine. Only few manufacturers has developed a 1.4 liter inline, 4-cylinder engine which is Volkswagen TSI Polo BlueGT. This is because the effectiveness of the cylinder deactivation concept depends on the power to weight ratio, engine balancing, and other factors. However, in this study an effective cylinder deactivation system is implemented for smaller engine displacement. The aims of this study are to investigate the potential of cylinder deactivation strategy for small SI engine with 1.3 liter in improving the fuel economy and emission at part load. The skip fire cycle method was applied to cylinder deactivation strategy using a relay-based system which was built to enable the manual control of ignition and injection for each cylinder. The effectiveness of the skip fire cycle method is measured at steady state for fuel consumption, emissions and vibration. To verify the feasibility and effectiveness of the skip fire cycle, a manual CDA was developed and set up to a research vehicle. The measurements show the improvements of fuel consumptions and exhaust emissions at the expense of the engine power loss and vibration. The results show the CDA strategy could be successfully implemented to small displacement engine with an improvement of the fuel consumption and emission.

Keywords: cylinder deactivation, fuel consumption, pumping loss, exhaust emission, throttle open angle.

INTRODUCTION

Cylinder deactivation (CDA) is defined as a method used to form a temporary engine downsizing in the technique of reduced the number a particular of cylinders which is able to shift its operations at light-load and specific condition. Utilizing the concept of deactivating cylinders with shutting off fuel and incorporate valve deactivation to increase the engine breathing (wider opening throttle) to reduce pumping losses. According to Leone, T. *et al.* (2001), the fuel economy benefit of CDA can range from 5-10% depending on engine displacements. At part load, the pumping loss is increasingly developed as the engine load is decreasing due to smaller throttle opening. Spark ignition (SI) engines can obtain up to 35% of effective efficiency at WOT (Wide Open Throttle). However, for the 10-20% of load which is typical of driving load, it would only achieve 10-20% of effective efficiency as shown in the research from Kutlar et al. (2005).

Kutlar *et al.* (2007) investigated skip cycle system strategy for allows changing the effective stroke of an engine through skipping some of the four stroke cycles. The researcher applied cutting off fuel injection and spark ignition strategy with integrate with additional rotary valves placed on the inlet and exhaust channels. This an operational strategy is to reduce the effective stroke volume of an engine and increase in combustion flame speed. The brake specific fuel consumption (BSFC) is decreased about 11% for the NSS (normal, skip and skip again) mode at very low speed and loads. The skip cycle system allows the engine to work at lower idle speed (45%) without any stability problems.

Yüksek *et al.* (2012) performed an experimental approach to describe the effect of the cycle-skipping method on brake specific fuel consumption (BSFC) and exhaust emissions of a stationary SI engine at partial loading conditions. They applied a fuel injection and ignition were cut off in skipped cycles integrate with new intake manifold assembly to maintain equal power output, also higher amount of air induction facilitated to keep air fuel ratio (AFR) at stoichiometry by increasing the throttle plate position. The key findings of the paper show that the cycle-skipping application decreased 4.3% the BSFC of the engine in all loading conditions. CO emission was reduced by 39% using the NS (normal and skip) operation mode at a low load condition. HC emissions improved a minimum of 5.4% and a maximum of 12.1% with NNS and NS operation modes. Wilcutts M. *et al.* (2013) defined the basic concept of dynamic skip fire operation is to use firings or non-firings of engine cylinders to satisfy engine torque demand rather than throttling or other torque reduction mechanisms which reduce thermal efficiency. The researcher develops a new lifter oil manifold assembly to incorporate full-authority valve deactivation. The author found out that fuel consumption benefits are achieved by reduction of thermal efficiency losses, primarily pumping losses and combustion inefficiency. Operation with high manifold pressure achieves reduction in pumping work, whereas combustion is generally more complete and can be more optimally phased in relation to the piston motion with larger cylinder air-fuel charge.

More recently, Volkswagen is the first carmaker to implement cylinder deactivation technology on four-cylinder engine 1.4 TSI of the Polo BlueGT, as it was previously the preserve of large eight or 12 cylinder engines. Shutting down the second and third cylinders during low and medium load states reduces fuel consumption. Active Cylinder Technology (ACT) mode of operation is active over an engine speed range between 1,400 and 4,000 rpm and torque outputs between approximately 25 to 100 Nm. Volkswagen was also able to use a very narrow single-scroll compressor in turbocharger selection allowing significantly accelerated pressure build-up as reported by Hadler *et al* 2012.

This study investigates the influence of the skip fire cycle method for applied CDA to small displacement engine on specific fuel consumption and exhaust emissions of a stationary SI engine at partial loading conditions. Skipping frequent sequential cycles will reduce the engine power performance and increase the engine vibration. This approach allows the manipulation of engine characterization and engine parameter before being implemented on a real vehicle engine with a complex CDA control system. To verify the feasibility and effectiveness of the skip fire cycle, a manual CDA was developed and set up accordingly.

SKIP FIRE CYCLE MODES

The main aim of the skip fire cycle method is to improve the fuel consumption and gas emission while reducing pumping loss at part load. The first mode of operation was a normal mode called standard which indicates the normal run. The second mode was called CDA1 mode, which deactivate one consecutive cylinder. The third mode was CDA2, which deactivate two cylinders. Fuel injection and ignition were cut off in skip fire cycles mode, Hence the circuit for both systems have been modified to enable manual control. Manual CDA control system for each cylinder is equipped with a switch connected in series as shown in Figure 1. Oxygen sensor position was also changed from its original position to the number four exhaust pipe to allow the sensor detect a representative proportion of the exhaust gas from the engine to maintain correct fueling at all driving conditions.

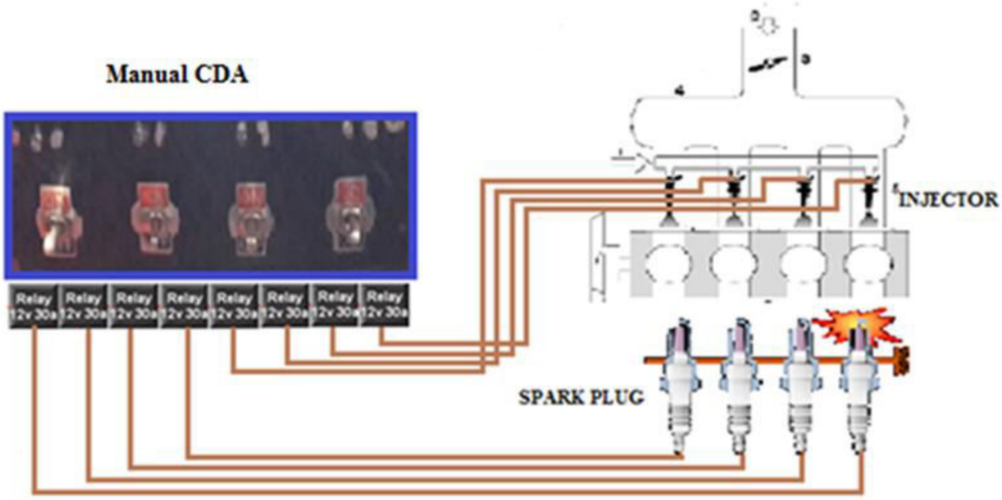

Figure-1. Manual CDA schematic diagram CDA indicate cylinder deactivation.

EXPERIMENTAL SETUP AND PROCEDURES

The experimental vehicle for the purpose of this study is using the engine model K3-VE 1.3*l* DOHC 4-cycle system equipped with Electronic Fuel Injection (EFI) and Dynamic Variable Valve Timing (DVVT). The experimental apparatus was set up to measure and verify engine power using chassis dynamometer. A scan tool Launch X-431, PD 400 Liquid Flow Sensor and Automobile Exhaust Gas Analyzer SV-5Q were used to obtain throttle open angle, fuel consumption and emissions. The experimental method was carried out using a stationary test at FKM, UTeM chassis dynamometer. Experiment was conducted in three modes as shown in Table-1.

Table-1. Experimental parameter.

Mode	Firing order		Experimental parameter		
	Cylinder active	Cylinder deactivate	Chassis dynamometer test	Fuel consumption test	Emission test
Standard	1-3-4-2	N/A	2000 – 7000 rpm	850 - 6000 rpm	Idling - 2000 rpm
CDA1	1-3-4	2	2000 – 7000 rpm	850 - 6000 rpm	Idling - 2000 rpm
CDA2	1-4	2-3	2000 – 7000 rpm	850 - 6000 rpm	Idling - 2000 rpm

RESULTS AND DISCUSSIONS

PERFORMANCE TEST

From the chassis dynamometer result, the maximum engine power for standard mode is 48.39 kW at 5500 rpm and the maximum torque is 93.12 Nm at 5800 rpm. The result for CDA1 mode for maximum power is about 28.04 kW at 4700 rpm and torque is 58.60 Nm at 4200 rpm. For the CDA2 mode, shows maximum power of 12.46 kW at 4540 rpm and 31.72 Nm torque at 3000 rpm. The graph of power and torque versus engine speed is shown in Figure-2. It shows that the maximum engine power and maximum torque for CDA1 mode and CDA2 are decreasing as compared to the Standard mode. Reduction of engine power and torque at CDA1 mode and CDA2 mode was predictable because one or two-cylinder engine has been deactivated. Maximum engine power reduction for CDA1 mode compared with STD mode is 42%, while CDA2 mode has been reduced to 74%. Similarly, maximum torque, compared CDA1 mode with STD mode reduced by 37% and for CDA2 mode has been reduced by 65%.

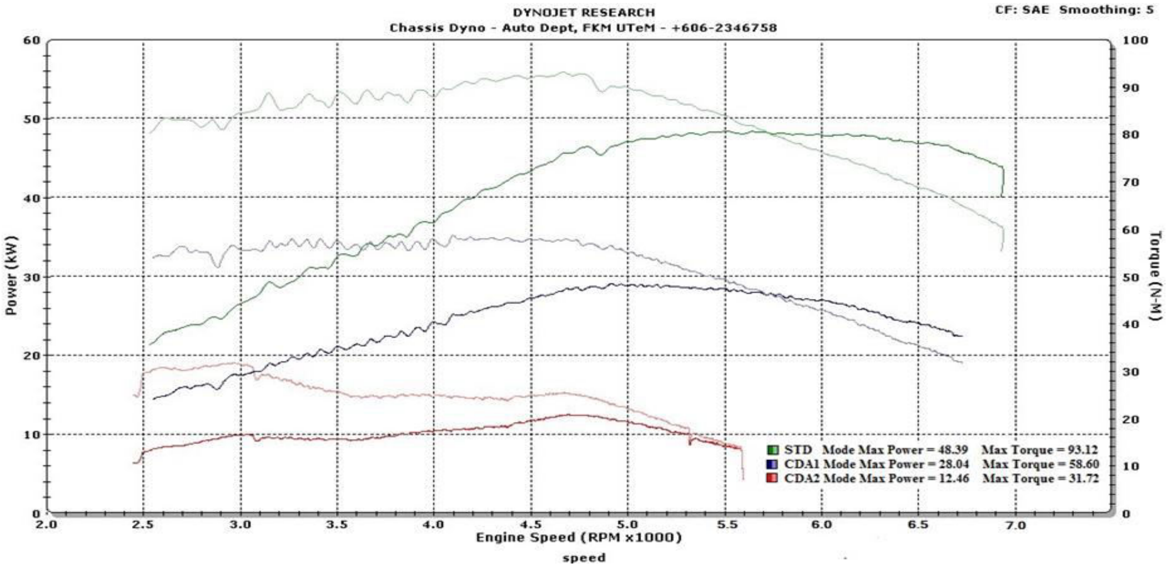

Figure-2. Graph vehicle power performance at all modes.

FUEL CONSUMPTION AND THROTTLE OPEN ANGLE TEST

Utilizing PD 400 Fluid Flow Sensor and Scan Tool X-435, the result is shown in Figure 3. The speed ranged from 750 rpm to 6500 rpm with 500 rpm intervals. For CDA2, the data result at idling speed was not available due to the inconsistency of reading and engine frequently stopped. Therefore, new idling speed for CDA2 mode was reorganized at 850 rpm. The average percentage of increment for the fuel consumption between 1000 to 5700 rpm compared against the CDA1 mode is 11 %, but the decreased average was around 10% from 3800 to 5800 rpm but later increased back to an average of 30%. The average percentage of fuel consumption increase compare between the Standard against CDA2 mode is 40%. The average fuel savings is approximately around 10%. However, no decrease in fuel consumption was observed when CDA2 mode was deployed, even the fuel consumption increased on average of 30%, due to the amount of fuel injected into the engine increasing in direct proportion to the opening angle between throttle with engine speed.

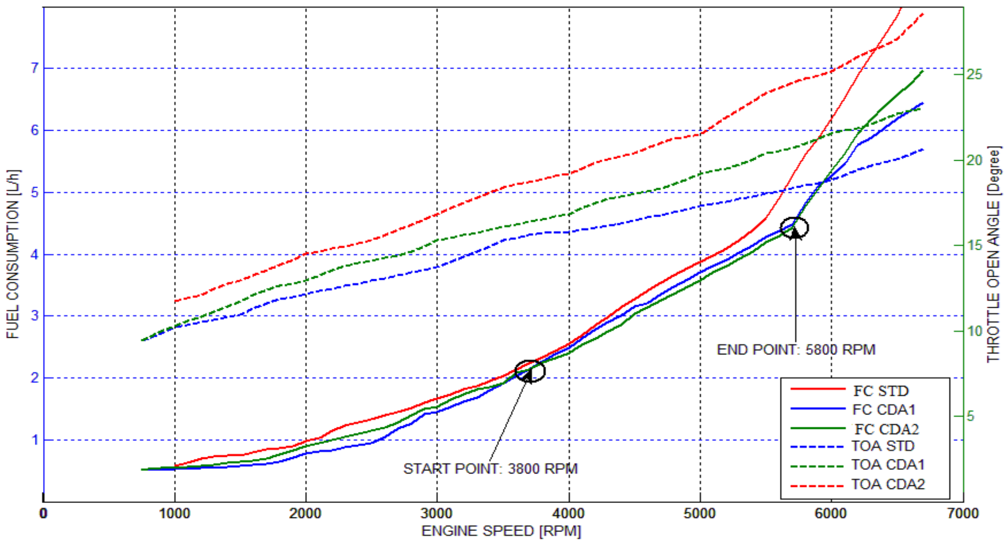

Figure-3. Graph fuel consumption and throttle angle versus engine speed. FC indicate fuel consumption. TOA indicate throttle open angle.

From the throttle open angle result shown in Table-2, it was observed that CDA1 and CDA2 modes throttle open is higher than the Standard mode. This result aligned with the findings in Paimon *et al.* (2014), where the throttle losses become more significant as the engine speed up. By opening the throttle wider in CDA mode, the throttle losses (pumping losses) can be reduced significantly. Less pumping effort will resulted in much less negative work in the cylinder which will benefit the fuel economy.

From the experimental conducted, it was observed that the CDA1 could perform better CDA strategy for K3-VE Gasoline 4 cycles 1.3-liter engine at cruising speed from 3800 to 5800 rpm. The CDA2 mode could perform better CDA strategy only at parking states because it was observed that the CDA2 mode increased the fuel consumption up to 30% as compared to the Standard mode. This is due to the engine power and torque output produced by the engine CDA2 was reduced in the range of 74% and 65%.

Table-2. Fuel consumption and throttle open angle data result.

Engine speed [RPM]	STD Mode		CDA1 Mode		CDA2 Mode	
	Fuel consumption [Liter/hour]	**Throttle open angle** [^{0}]	**Fuel consumption** [Liter/hour]	**Throttle open angle** [^{0}]	**Fuel consumption liter/hour**	**Throttle open angle** [^{0}]
750	0.51	9.41	0.50	9.41	N/A	N/A
1000	0.52	10.2	0.54	10.3	0.57	11.76
1500	0.57	10.98	0.64	11.76	0.75	12.94
2000	0.77	12.16	0.89	12.94	0.91	14.51
2500	0.9	12.94	1.14	14.12	1.33	15.29
3000	1.45	13.73	1.62	15.29	1.67	16.86
3500	1.91	15.29	2.00	16.08	2.03	18.43
4000	2.48	15.8	2.41	16.86	2.55	19.22
4500	3.06	16.47	3.03	18.04	3.27	20.39
5000	3.7	17.35	3.58	19.22	3.88	21.52
5500	4.28	18.04	4.19	20.39	4.57	23.92
6000	5.26	18.82	5.35	21.57	6.19	25.19
6100	5.47	19.14	5.64	21.73	6.54	25.62
6500	6.18	20.06	6.57	22.74	7.84	27.07

EMISSION TEST

The emission test was conducted using the Gas Analyzer model SV-5Q and recorded manually as shown in Table 3. CO_2 emission was reduced by 4.8 % using the CDA1 mode and 5.7 % using CDA2 mode at an idle speed. HC emissions reduced a minimum of 2.2 % for CDA1 and 6.8 % for CDA2 mode. At the engine speed of 1000 rpm, CO_2 emission increase by 4.8% using the CDA1 mode and 7.5 % using CDA2 mode. HC emissions also reduces to 5.5 % for CDA1 and 8.4 % for CDA2.

Table 3. Gas emission data result.

Mode	RPM	CO_2 [%]		HC [ppm]		λ	
		Max	Avg	Max	Avg	Max	Avg
Standard	Idling	4.59	4.54	789	765	0.79	0.78
	1000	4.60	4.37	836	801	0.90	0.89
	2000	5.90	5.60	1286	1272	0.93	0.92
CDA1	Idling	4.86	4.32	793	748	0.78	0.76
	1000	5.04	4.58	784	757	0.91	0.90
	2000	5.60	5.30	1208	1180	0.93	0.91
CDA2	Idling	4.70	4.28	723	713	0.81	0.80
	1000	4.86	4.70	748	733	0.91	0.91
	2000	5.80	5.20	1278	1210	0.93	0.92

At engine speed of 2000 rpm, the CO_2 emission was reduced by 5.4 % using the CDA1 mode and 7.5% using CDA2 mode. HC emissions reduce to 7.2 % for CDA1 and 4.8 % for CDA2. It was found that the CO_2 emission reductions are mainly depending on the lower amount of fuel consumption. From this point of view, it was concluded that the obtained CO_2 emission reductions were also a result of the increased combustion efficiency. This finding could be validated against Pedro Mello *et al* (2014) research, where the HC emissions are the incomplete combustion products. Flame quenching, crevice mechanism, oil adsorption and AFR also has an important effect on the HC emissions. The higher the in-cylinder pressure, the lower the quench distance, in CDA1 and CDA2 modes of operation in-cylinder pressures of fired cycles are higher than standard operation mode, thus HC emissions related with the flame quenching are expected to be decreased.

CONCLUSIONS

The manual CDA using SFC method for small engine displacement in order to reduce the fuel consumption and emission was the focus throughout this investigation. Using a reduced number of cylinders to produce the necessary power is more efficient than employing the full complement of cylinder for light load. The wider throttle position produces better breathing capability of the engine thereby lower pumping losses and improved fuel consumption. These experimental findings are summarized as follows:

a. CDA1 could perform effective CDA strategy for K3-VE Gasoline 4 cycles 1.3-*liter* engine especially at cruising speed from 3800 to 5800 rpm. CDA2 mode could perform good CDA strategy only at parking states because it increased the fuel consumption up to 30% compared to the Standard mode. By opening the throttle wider in CDA mode, the pumping losses can be reduced significantly. Less pumping effort will result in much less negative work in cylinder which will benefit the fuel economy.

b. CO_2 emission reductions in CDA1 and CDA2 modes were also a result of the increased combustion efficiency. HC emissions in CDA1 and CDA2 modes of operation in-cylinder pressures of fired cycles are higher than the standard operation mode, thus HC emissions related with the flame quenching are expected to decreased.

Further work will be concentrated on implementation of automatic control CDA base on vehicle speed variable and feedback input from throttle angle. It will be concentrated on investigating other novel technologies that could additionally enhance efficiency such as the use of turbocharger on the small displacement engine. This will further improve fuel consumption and will focus on the actuation mechanism of the locking plate at the intake air manifold to construct a high pressure air into the cylinder. By doing this, it will increase engine performance and expand the CDA triggering time. Active engine mounting was recommended to overcome the engine instability and excessive vibration during cylinder deactivation mode.

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