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THEORETICAL FLOW ANALYSIS AND EXPERIMENTAL STUDY ON TIME RESOLVED THC FORMATION WITH RESIDUAL GAS IN A DUAL CVVT ENGINE

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ABSTRACT–Recently, a variable valve timing system has been widely adopted in internal combustion engine in order to improve the fuel economy and torque at low engine speed. In addition, it is known that varying valve timing according to the various engine operations could reduce exhaust gas, especially NOx, because of residual gas by valve overlap. In this study, to improve the low exhaust gas and fuel economy at part load condition, the residual gas and back flow of exhaust gas due to valve overlap were calculated computationally. Moreover, the characteristics of engine performances and NOx formations were investigated with the experiment of combination of intake and exhaust valve timing condition. Under these various valve operating conditions, the effects of both the positive valve overlap and negative valve overlap (valve underlap) were examined simultaneously. Finally, the characteristics of cyclic THC emission were analyzed by using Fast Response FID (FR-FID) in the cylinder, intake port and exhaust port positions. Besides, the effect of the different gradients of the valve timing change on engine performance was investigated and an optimum control strategy was suggested.

KEY WORDS: VVT, Valve overlap, Internal EGR, Residual gas, Fast response FID, Cyclic THC emission

1. INTRODUCTION

In recent years, engine development has been focused on the two issues: reduction of CO_2 and air pollution. To address these technologies, CVVT (Continuously Variable Valve Timing) system is widely adopted since it can enhance the performance, while simultaneously reducing exhaust emissions and fuel consumption. With the CVVT system of intake cam phaser, maximum torque and power are improved through the optimization of valve timing according to the overall engine operating condition (Parvate-Patil *et al.*, 2003; Lee *et al.*, 2005). Exhaust valve timing has influenced on the providing of internal EGR (Exhaust Gas Recirculation) to reduce the NOx and fuel consumption with a longer valve overlap period at part load. Dual CVVT allows very flexible control of valve overlap (Jang *et al.*, 2002; Sutela *et al.*, 2001), which can be used to aggressively reduce throttling losses, increase EGR, lower NOx emissions and fuel consumption (Ohm and Lee, 2003; Kim and Cho, 2006; Fiorenza *et al.*, 2003). Therefore, an optimal combination of intake and exhaust valve timing is essential for improvement of engine performance. However, quantitative analysis on the residual gas fraction at in-cylinder and intake ports is difficult to apply to the CVVT engine.

In this study, the residual gas fraction was investigated for mainly at part load condition using a specially designed 1-D engine simulation model. Based on the computational results, the performance of the CVVT engine such as flow characteristics at the intake manifold and combustion phenomena was examined and analyzed accord-

Table 1. Specification of test engine.

Item	Specification
Engine type	In-line, DOHC 16
Bore (mm)	75.5
Stroke (mm)	83.5
Displacement (cc)	1495
Valve timing (°CA)	IVO: BTDC 30~ATDC 5
	EVC: BTDC 10~ATDC 25
Valve duration (°CA)	Intake: 228
	Exhaust: 236

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ing to various combinations of intake and exhaust valve timing. Back flow at the intake port due to positive valve overlap and negative valve overlap were discussed, and cyclic THC (Total Hydro-carbon) emission characteristics were acquired in the cylinder, intake port, and exhaust port using FR-FID (Fast Response Flame Ionization Detector). Finally, the engine instability by rapid change of the valve timing gives rise to a serious problem for the exhaust gas quality, the characteristics of crank angle based cyclic flow and combustion were examined closely with the fast movement of cam phasing angle.

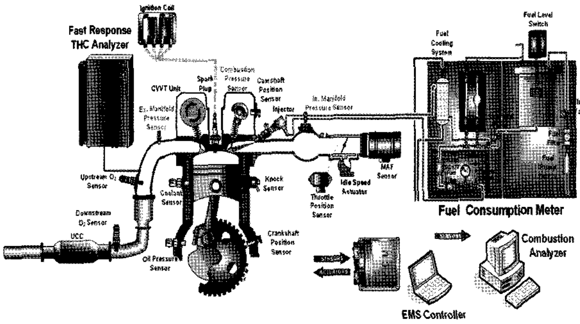
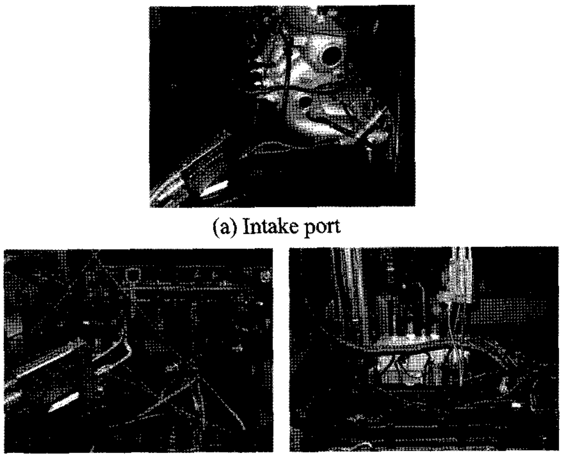


Figure 1. Schematic diagram of test equipment.



(a) Intake port

(b) Exhaust port (c) In-cylinder

Figure 2. Sampling positions of FR-FID probe.

2. TEST ENGINE AND SIMULATION MODEL

2.1. Test Engine and Equipments

In this study, an in-line gasoline engine with 16 valves was tested, and its bore, stroke and displacement were 75.5 mm, 83.5 mm and 1495 cc, respectively. Table 1 shows the specifications of the test engine. A CVVT unit installed on the exhaust camshaft controls the intake valve timing by changing the cam phasing angle of the intake valves.

Moreover, to examine the effects of the change in the exhaust valve timing, the cam sprocket was remodeled for mechanical adjustment. Since the valve duration of tested engine is fixed for every valve timing condition, early IVO (Intake Valve Open) or EVO (Exhaust Valve Open) means early IVC (Intake Valve Close) or EVC (Exhaust Valve Close). In this study, 24 cases of valve timing combinations were simulated and experimented simultaneously, from BTDC 10°CA to ATDC 25°CA for EVC and BTDC 30°CA to ATDC 5°CA for IVO. Table 2 shows the valve timing conditions used for the study. In the table, IVO=−30 represents that IVO is 30 degrees as the crank angle before TDC and EVO=−46 means BTDC 46 degrees. According to the different valve timing conditions, the valve overlap periods are ranged from −15 to 55 as the crank angle base.

For the valve overlap, a negative sign means "negative valve overlap or valve underlap". Generally, positive valve overlap creates residual gas in the cylinder and intake port when the closing part of the exhaust valve and the opening part of the intake valve are overlapped, and

Table 2. Various intake and exhaust valve timing conditions used for experiment and simulation.

EVC / IVO	-10	-5	0	5	10	15	20	25
-30	TDC Ex In	TDC Ex In	TDC Ex In	TDC Ex In	TDC Ex In	TDC Ex In	TDC Ex In	TDC Ex In
-10	TDC Ex In	TDC Ex In	TDC Ex In	TDC Ex In	TDC Ex In	TDC Ex In	TDC Ex In	TDC Ex In
5	TDC Ex In	TDC Ex In	TDC Ex In	TDC Ex In	TDC Ex In	TDC Ex In	TDC Ex In	TDC Ex In

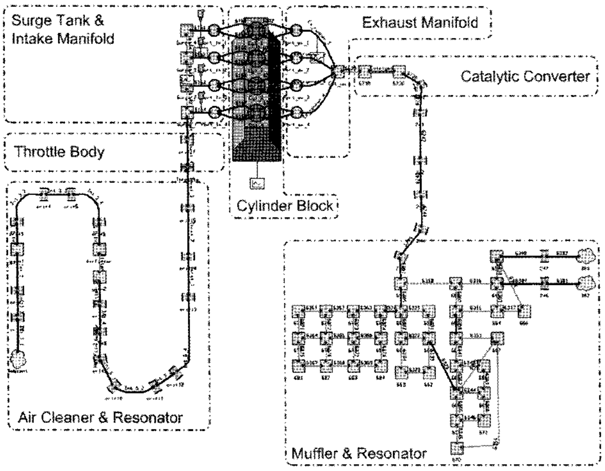


Figure 3. 1-D computational engine model.

negative valve overlap generates residual gas in cylinder when the exhaust gas is trapped by the early closing of the exhaust valve before the piston reaches the top dead center. So the effects of both positive and negative valve overlap were investigated.

Figure 1 shows the schematic diagram of the experimental apparatus. To verify the transient flow distribution and the effects of unburned hydrocarbon in residual gas and back flow, FR-FID by Cambustion was used for various engine operating conditions (Kim *et al.*, 2007; Reavell *et al.*, 1997; Liu and Wallace, 1997; Ishizawa, 1997; Myung *et al.*, 2004). To examine the exhaust gas formation with VVT operation, exhaust emissions were analyzed with MEXA-8120D by Horiba because residual gas plays a key role in reducing NOx. Figure 2 represents the sampling probe locations of FR-FID which are positioned at the intake port, exhaust port and in-cylinder locations.

2.2. Modeling of 1-D Engine Simulation

To analyze the engine performance for various valve timings and specific engine operating conditions, a 1-D engine simulation was modeled with WAVE by Ricardo (Ricardo Ltd., 2004). The 1-D simulation focused on examining the residual gas amount and back flow characteristics in the intake port. The simulation model was matched as closely as the real engine geometric dimensions and experimental performance data. Therefore, the verification of the residual gas distribution and combustion phenomena can be confirmed through the comparison between the simulation and experimental data. Figure 3 shows the 1-D computational engine model.

3. RESULTS AND DISCUSSIONS

3.1. Mass Flow Rate through Intake Valve

Figure 4 shows the computational mass flow rate through the intake valve and experimentally measured surge tank pressure. The top figure presents the simulation result of a mass flow rate through the intake port at 1800 rpm, BMEP (Brake Mean Effective Pressure)=2.0 bar, and stoichiometric air fuel ratio. The exhaust valve timing is EVC=BTDC 10°CA and ATDC 25°CA, and the intake valve is IVO=BTDC 30, 10°CA, and ATDC 5°CA.

When the intake valve opens, the first back flow into the intake port is occurred because of the expansion of the burned gas due to the pressure difference and volumetric gas displacement as the piston rises toward TDC. This back flow amount rises as the valve overlap period increases. The bulk of the back flow is moved into the intake port at the overlap stage in which the intake valve and exhaust valve are opened simultaneously. But in the case of EVC/IVO=−10/5, the intake and exhaust valves are closed at the same time for a crank angle of 15 degrees, the trapped exhaust gas in cylinder is expanded after compression during the exhaust stroke and then flows back into the intake port as soon as the intake valve opens. Under the part load and low rpm condition at the later part of the IVO step, there exists a second back flow into the intake port because of the low intake gas charge momentum as the piston rises. And during this period, the intake flow fluctuates because of pressure oscillation in the intake manifold.

The bottom figure shows the pressure oscillation profile which is measured experimentally at the surge tank. This result means that back flow occurs as the decrement of surge tank pressure is influenced by the movement of other cylinders.

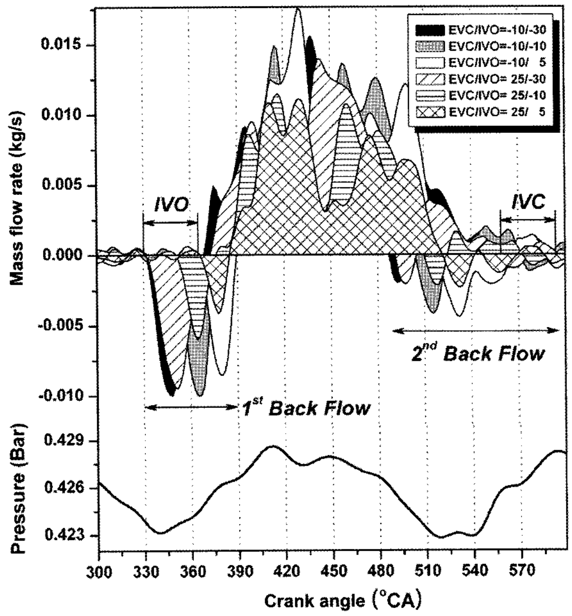


Figure 4. Computed mass flow rate through the intake valve and experimentally measured surge tank pressure.

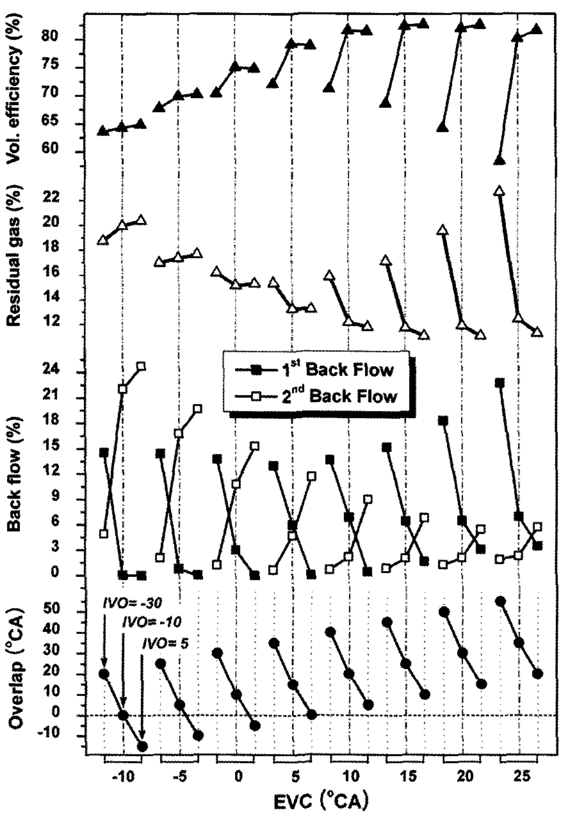


Figure 5. Volumetric efficiency, residual gas and back flow fraction through intake valve with respect to various valve overlap.

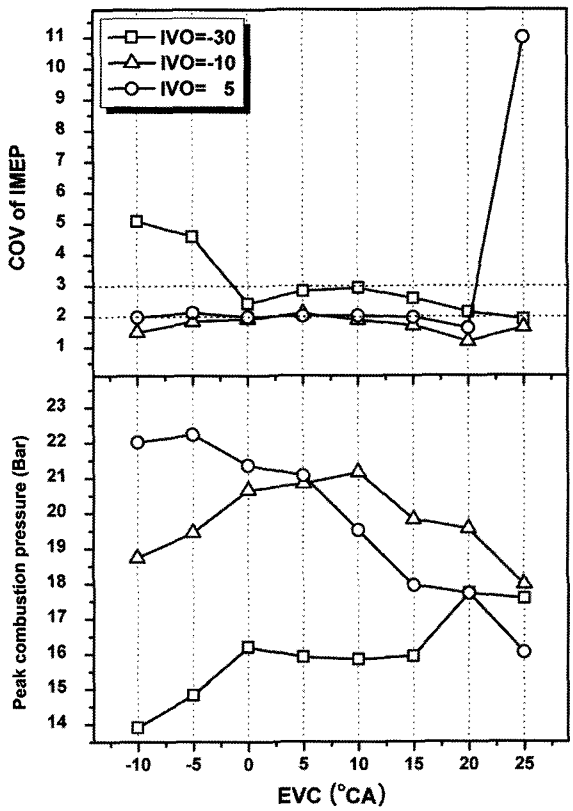


Figure 6. Peak combustion pressure in cylinder and COV of IMEP.

For this reason, the second back flow occurs in advance, and the mass flow rate fluctuation lasts for long period. Consequently, these factors influence on the formation of residual gas at the cylinders and intake ports with CVVT engine.

3.2. Volumetric Efficiency, Residual Gas and Back Flow Fraction

Figure 5 shows the back flow level through the intake valve and the volumetric efficiency by simulation. Engine operation condition is 1800 rpm, BMEP=2.0 bar and air excess ratio (λ)=1.0. There are negative valve overlaps in the case of EVC=BTDC 10°, 5°, and TDC. As shown in the figure, the first back flow in the early stage of the intake stroke is the percentage of air mass flow rate between the opening of the first intake valve and the closing of the last exhaust valve for cylinder No. 1. The first back flow amount reached its maximum level in the case of the longest positive valve overlap period among all the cases, and a very small quantity flowed back at negative valve overlap. The second back flow in the last stage of the intake stroke is defined by the percentage of air mass flow rate between the closing of the last exhaust valve and the closing of the last intake valve for cylinder No. 1. As the EVC is advanced or retarded IVO, the quantity of second back flow increases.

The reverse flow in the intake manifold affects the volumetric efficiency and performance of the CVVT engine. From the top figure, the volumetric efficiency is improved up to 80% as the EVC and IVO retarded. Additionally, too much advanced IVO causes negative effect on the volumetric efficiency under 65%.

The residual gas proportion in cylinder rises as the advanced EVC because of the increment of trapped gas in cylinder. Moreover, the level of residual gas also increases over 20% as the retarded EVC and advanced IVO timings due to the augmented valve overlap period. The moderate fraction of residual gas improves the fuel economy because of the high intake manifold pressure and low pumping loss during the intake stroke.

3.3. Combustion Pressure Analysis and COV of IMEP with Valve Timing

Figure 6 shows the experimental test results of combustion pressure and COV (Coefficient of Variance) of IMEP (Indicated Mean Effective Pressure). Engine operation condition was 1800 rpm, BMEP=2.0 bar and stoichiometric air fuel ratio.

The peak combustion pressure at IVO=BTDC 30° rises as the EVC is retarded because the maximum expansion work is acquired according to the retarded EVO. However, when IVO is in the retarded case, maximum peak pressure presents with advanced EVC timing. This can be explained in that the excessive valve overlap due to advanced IVO reduces the combustion pressure. Consequently, high combustion pressure can be achieved by negative valve overlap for the advanced EVC and proper positive valve overlap for the retarded EVC after TDC.

Increasing the residual gas fraction by valve overlap may be harmful to combustion stability. However, almost all experimental cases except aggressive IVO advance timing shows that COV of IMEP is within 3% at part load operation, and it explains that engine operation with proper positive or negative valve overlap can contribute to stable combustion quality.

3.4. Crank Angle Resolved THC at Intake Port

Variation of the residual gas proportion by valve overlap may affect the hydrocarbon formation. Besides, the unburned hydrocarbon that flow back into the intake manifold has influence on the next combustion cycle. Because of this, the quantities of back flowed THC were measured cycle by cycle at various EVCs and IVOs. The pressure in the CP (Constant Pressure) chamber of the FR-FID was 420 mmHg, and ΔP was 70 mmHg, and the transit time between detector and sampling point was not corrected in this study.

Figure 7 shows the THC level at the intake manifold for five cycles. In case of EVC=−10 and IVO=−30 with 20°CA overlap period, lots of unburned hydrocarbon is spit back into the intake manifold. However in case of EVC=0 and IVO=−30, the back flowed THC decreased due to the longer combustion period in the cylinder by the retarded EVC (or retarded EVO). For all of the above cases, the intake and exhaust valve time events occurred before TDC; in other words, the piston rises upward. At the most retarded EVC=20 and IVO=−30, the exhaust valve closes after TDC and intake valve opened before TDC. But in this case, the intake and exhaust flow would be affected by upward and downward piston motion simultaneously. Therefore, the unburned hydrocarbon decreases due to the longer combustion period as the retarded exhaust valve time, however, this continuous up and down strokes make high oscillations on the THC behavior comparatively. In the case of IVO=−10 which has small overlap, THC at intake manifold shows a relatively low level compared to IVO=−30.

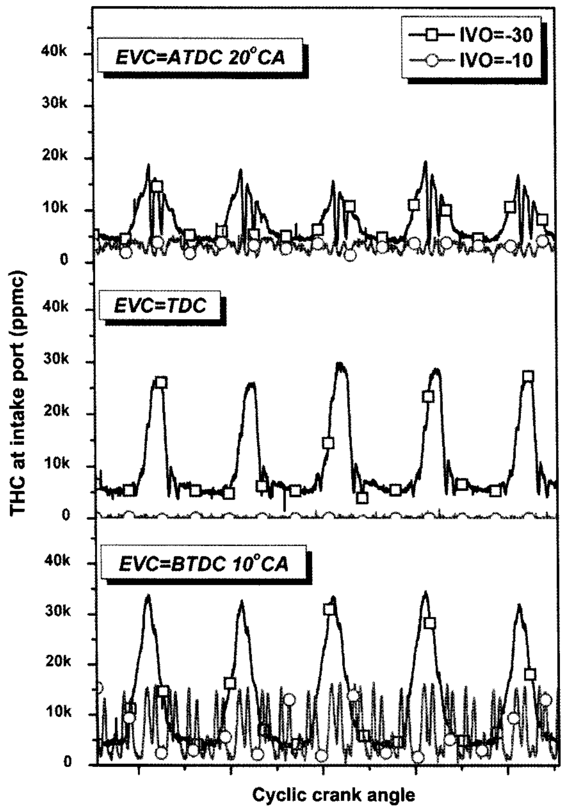


Figure 7. Back flowed THC in residual gas at intake port for 5 cycles.

3.5. Crank Angle Resolved THC in Cylinder

A spark plug type HC sampling probe of FR-FID was installed to quantify the time resolved THC distribution in the cylinder. Engine operating condition was $\lambda=1.0$, S/A (Spark Advance)=−20.

Since the momentum of the first back flow becomes

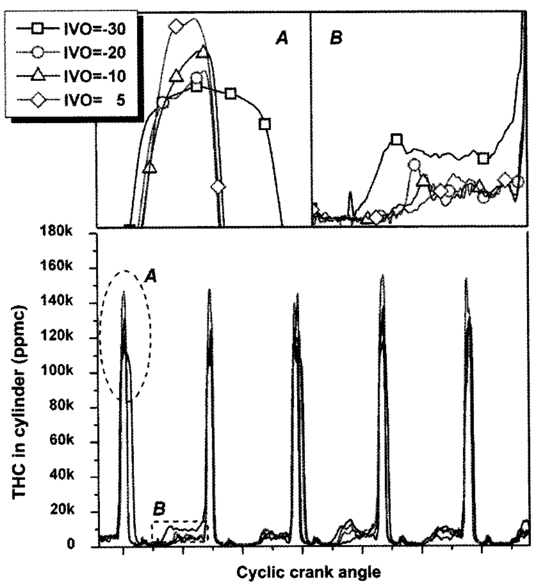


Figure 8. THC formation in cylinder for 5 cycles.

stronger as the valve overlap becomes longer, it pushes the wetted fuel in intake manifold back to the surge tank at the moment when the intake valve opens. As a result, lower amount of fuel is supplied to the cylinder than that of the actual injection rate. As IVO timing is advanced, so the evaporation of fuel is affected by the high intake runner pressure due to residual gas.

Accordingly, the peak THC concentration in the cylinder remains high at the retarded IVO, as in the 'A' region in Figure 8. Accurate THC analysis at intake and exhaust strokes in the cylinder is not easy because of the relatively low pressure for FR-FID. However, when only the trend of THC distribution is considered at the intake stroke, this result has the validity for the increasing trend of residual gas in advanced IVO from the 'B' stage.

3.6. Crank Angle Resolved THC at Exhaust Port

To verify the effect of residual gas on THC formation, cyclic THC was measured at exhaust port using FR-FID. The pressure in the CP chamber of FR-FID was 300 mmHg and ΔP was 100 mmHg, and the transit time between detector and the sampling point was not corrected.

Figure 9 shows the crank angle resolved THC emission in the exhaust port. The bottom figure shows the THC emission for different IVOs at EVC=10, λ=1.0. For the S/A=–40 and –20, THC decreased as the IVO advanced because of the after-burning of unburned hydrocarbon which flowed back into the intake manifold by valve overlap. As the spark timing is retarded, the amount of the unburned HC decreases because combustion period increases between cylinder and exhaust port. THC peak values are plotted as a function of IVO timing during the exhaust stroke in the top figure. THC peak levels decrease when the spark timing is retarded and valve overlap has a large value.

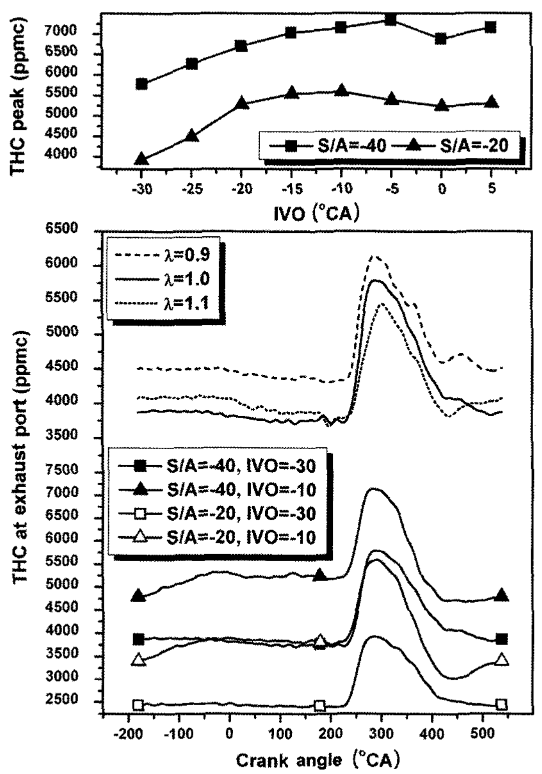


Figure 9. Crank angle resolved THC emission in exhaust port.

3.7. NOx Concentration

Residual gas in the cylinder affects emissions with valve overlap, especially NOx formation.

Figure 10 shows the engine-out NOx concentration with respect to spark timing, IVO and EVC. At λ=1.0, EVC =10°CA, NOx level of various spark timings as a function of different IVO timings are shown in the top figure.

Earlier spark timing shows high NOx concentration throughout all of the IVO range. Since the high peak combustion pressure by the advanced spark timing results in higher peak burned gas temperature and higher NOx formation rates. Minimum amount of NOx was formed when there was more residual gas in the cylinder with a long valve overlap period according to the advanced IVO.

When the S/A=–40 case as shown in the bottom figure, NOx level by combinations of IVO and EVC has the least values with the most advanced IVO timing and the quantity is much smaller as the EVC is further advanced. When the EVC is retarded, in spite of the longer valve overlap period, heat release rate is improved

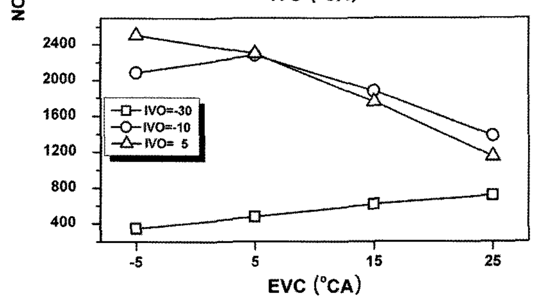


Figure 10. Engine-out NOx with respect to spark timing, IVO and EVC.

by increased expansion work. On the contrary, as the IVO retarded, NOx concentration decreases at retarded EVC. This is because the cylinder temperature is dropped according to the low peak combustion pressure with the same reason as mentioned above. Consequently, this result shows the similar tendency according to the previous peak combustion pressure in the cylinder.

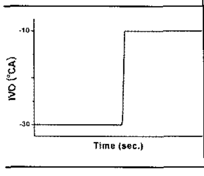
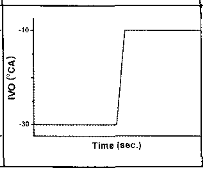
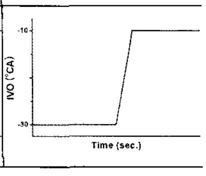
3.8. Transient Valve Timing Change on Engine Performance

Momentary valve timing change with various engine operating conditions may decrease the performance, stability, and emission quality of the CVVT engine. Therefore, the experiments with different time steps to change the valve timing (or gradient) were performed to verify the effects on the swift valve timing change.

Table 3 shows the three stepwise conditions according to the different valve timing change intervals. In that case, the crank angle of 76 degrees was changed per second, and the time to change 20 degrees was 0.26 second. Additionally, different two cases were tried with more gentle gradients; the times to change 20 and 10 degrees for the crank angle were 0.96 and 1.87 seconds, respectively.

Figure 11 shows the characteristics of the CVVT engine operation at EVC=10 when the IVO timing was changed instantaneously BTDC 30°CA to 10°CA. Air mass flow rate increases instantly because the reduction of residual gas by the valve overlap difference causes additional fresh air into the intake manifold. This wide fluctuation becomes more frequent as the gradient of valve timing is changed rapidly. The intake pressure was fallen suddenly with a momentary change of valve timing. The air excess ratio shows similar tendency similar to that of air mass flow rate and intake pressure profile. Transient HC formation can be controlled with the optimization of valve timing operation scheme as well. In conclusion, the optimum control strategy of the valvetrain was suggested for stable engine running using this test results.

Table 3. Three gradient conditions of valve timing change.

1st Case	2nd Case	3rd Case
		
Gradient		
76°CA/sec.	20°CA/sec.	10°CA/sec
Time for IVO 20°CA Change		
0.26 sec.	0.96 sec.	1.87 sec.

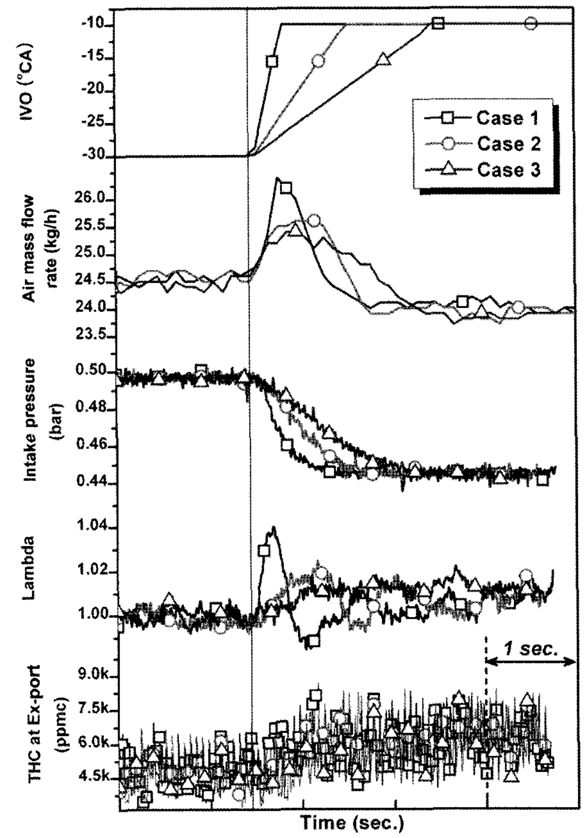


Figure 11. Variation of engine characteristics for different times to change IVO timing at 1800 rpm, S/A=BTDC 40.5°CA.

Figure 12 represents the change of the COV of IMEP for 100 cycles when the valve timing is changed instantly. The 'A' line in the figure is the COV of IMEP when the engine operation condition is at 1800 rpm and IVO = −30°CA. And the 'B' line is at IVO=−10°CA. However, when the valve timing was changed transiently within 100 cycles, the COV increased; that is engine stability

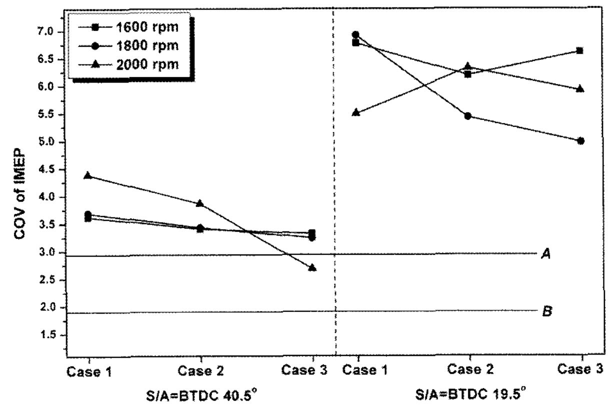


Figure 12. COV of IMEP according to momentary changes of IVO timing for 100 cycles.

was getting worse. Additionally, the COV was more increased when the spark timing was retarded. Overall, as the time for valve timing change was longer, the COV was decreased more. But this trend is not absolute applicable for every engine revolution. Therefore, the valve timing should be changed carefully, by considering the load and engine revolution to achieve stable engine operation and low emission.

4. CONCLUSIONS

The effect of residual gas due to the valve overlap of the dual CVVT engine was studied. From the results, it is ascertained that optimized valve timing can improve the engine performance and reduce additional exhaust gas. The results are summarized as follows:

(1) Back flows in the intake manifold that affects residual gas distribution and mass flow rate were influenced by not only the positive valve overlap but also the negative valve overlap, and this effect increased with flows of other cylinders by the reduction of moment at the last stage of intake stroke.

(2) The first back flow increases as the retarded EVC, and the second back flow increases as the advanced EVC.

(3) The residual gas fraction in the cylinder shows large sum values at EVC before TDC, and it also increases by more valve overlap at EVC after TDC. This valve overlap may negatively affect combustion pressure and volumetric efficiency. Combustion pressure has the highest value with the negative valve overlap, and it is confirmed that these combustion pressures play a key role with the amount of the residual gas.

(4) Back flowed THC increased with more valve overlap, but the excessive overlap period has negative influence on the fuel evaporation by high intake pressure and valve underlap; it may affect the intake flow. However, longer valve overlap does not mean much back flows because of the combustion period and so on.

(5) Exhausted THC at the exhaust port is decreased as the IVO is advanced. Additionally, the other factors such as, after-burning and combustion period can affect the reduction of THC.

(6) NOx emission is decreased as the retarded spark timing and high level of residual gas fraction. NOx formation shows a similar tendency according to the peak combustion pressure in the cylinder.

(7) It is verified that a momentary valve timing change in real engine operation, can affect the combustion characteristics in the cylinder and exhaust gas formation. Therefore, the gradient and angle of the valve timing change should be selected more suitably.

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REFERENCES

Fiorenza, R., Pirelli, M., Torella, E., Pallotti, P., Kapus, P. E., Kokaji, G. and Lebenbauer, M. (2003). VVT+Port deactivation application on a small displacement SI 4 cylinder 16V engine: An effective way to reduce vehicle fuel consumption. *SAE Paper No.* 2003-01-0020.

Ishizawa, S. (1997). Analysis of HC in residual gas and combustion efficiency of spark ignition engine. *SAE Paper No.* 972939.

Jang, J., Park, Y., Bae, C. and Kim, W. T. (2002). Effect of operating conditions on the residual gas fraction in an SI engine. *Trans. Korean Society of Automotive Engineers* **10**, **6**, 11–18.

Kim, D. S. and Cho, Y. S. (2006). Idle performance of an SI engine with variations in engine control parameters. *Int. J. Automotive Technology* **7**, **7**, 763–768.

Kim, W. S., Lee, J. H., Yoo, J. S., Rhee, B. O. and Park, J. I. (2007). Numerical analysis of sampling module for a fast response exhaust gas analyzer. *Int. J. Automotive Technology* **8**, **2**, 149–154.

Lee, H., Choi, S., Min, K. and Cho, S. (2005) Effect of various VVA systems on the engine fuel economy and optimization of CVVT-VVL SI engine using 1D simulation model. *Proc. Fall Conference, Korean Society of Automotive Engineers,* **1**, 98–104.

Liu, H. and Wallace, J. S. (1999). An experimental investigation into the characteristics of a fast-response flame ionization detector for in-cylinder sampling. *SAE Paper No.* 1999-01-3538.

Myung, C., Park, S., Kim, H., Min, K. and Choi, M. (2004). Experimental investigation of the effect of thin-wall substrates and spark timing retard on total hydrocarbon emissions during cold start for super-ultra-low-emission vehicle application. *Proc. Instn. Mech. Engrs.* **218**, **D**, 427–433.

Ohm, I. and Lee, W. (2003). The effect of valve timing dual equal retard/advance on performance in an SOHC SI engine. *Trans. Korean Society of Automotive Engineers* **12**, **6**, 30–36.

Parvate-Patil, G. B., Hong, H. and Gordon, B. (2003). An assessment of intake and exhaust philosophies for variable valve timing. *SAE Paper No.* 2003-32-0078.

Reavell, K. St. J., Collings, N., Peckham, M. and Hands, T. (1997). Simultaneous fast response NO and HC measurements from a spark ignition engine. *SAE Paper No.* 971610.

Ricardo Ltd. (2004). Wave Manual V.5.3. U.K.

Sutela, C., Hands, T., and Collings, N. (2001). Intake manifold burned gas backflow measurements. *JSAE Paper No.* 20015302. *Proc. Society of Automotive Engineers of Japan*. 9–12.