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A study on characteristics and control strategies of cold start operation for improvement of harmful exhaust emissions in SI engines

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Abstract

Emission regulations for automobiles have become more stringent and the improvement of emission during cold start has been a major key issue to meet these regulations. Among many kinds of factors that affect cold start operation, ignition timing is crucial to improve emission characteristics due to the influence on exhaust gas temperature. Recent progress in variable valve timing allows optimized valve event strategies under various ranges of engine operating conditions including cold start. This study investigates effects of ignition and exhaust valve timing on exhaust gas temperature, combustion stability and emission characteristics through cold start bench tests of an SI engine.

Experimental results show that exhaust valve timings and ignition timings significantly affect exhaust gas temperature and stability of engine operation under cold start condition. Exhaust valve timing also affects CO and NO_x emission due to changes in residual gas fraction of the combustion chamber. Ignition timing mainly affects exhaust gas temperature and HC emission. A control strategy, advanced exhaust valve timing and retarded ignition, is plausible in order to achieve reduction of exhaust emission while maintaining stability under cold start operation of SI engines.

Keywords: Exhaust valve timing; Ignition timing; Combustion stability; Exhaust gas temperature; Close-coupled catalytic converter; Cold start

1. Introduction

The three-way catalyst (TWC) is a highly effective technology for the reduction of harmful emissions of SI engines. The only weakness of the TWC is that it might show very poor conversion efficiency before it becomes fully heated up to a light-off temperature. Much of harmful emission is emitted during the cold-start period when the TWC temperature is low and about 80% of HC is charged during this period in FTP-75 mode test. [1] It is a major reason why many researchers have performed several studies on harmful emission during cold start. Combustion, characteristics of harmful emissions, exhaust gas temperature and AFR control have become main topics for the improvement of cold start emission. [2, 3] Among these various topics, a promising solution may be provide that retarded ignition timing increases exhaust gas temperature rapidly. However, severe retarded ignition can deteriorate combustion stability of the engine, with severe fluctuation in engine speed and IMEP. [4, 5] Changes in exhaust valve timing during idle operations affect intake flow phenomena which may be a reason to change the residual gas fraction, flame propagation speed and exhaust gas temperature.

The purpose of this study was to find efficient control strategies for the ignition and exhaust valve timings in order to enhance catalyst warmup and to reduce harmful emission during cold start. A specially-designed variable timing camshaft manipulates valve timings and a programmable ECU controls spark ignition timings. Combustion characteristics exhaust

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gas temperature and exhaust gas composition are measured and analyzed through the whole tests. In addition, variations of combustion stability by these changes in parameters are also investigated. Through the study, this paper tries to understand the characteristics of cold start operation. Furthermore, effective timings are suggested to increase exhaust gas temperature while maintaining combustion stability during cold start operation.

2. Experimental Setup

2.1 Experimental setup for measurements and controls

These experiments were performed in a 2-liter, naturally aspirated four-cylinder SI engine. Table 1 describes specifications of the engine. Fig. 1 depicts a schematic diagram of experimental setup. A piezo-electric pressure transducer with spark plug type mount is installed at 1^{st} cylinder to measure cylinder pressure variations. A crank-angle encoder, connected to the crankshaft, generates pulses by 1 degree of crank angle interval and these pulses from encoder are synchronized with data acquisition system.

Table 1. Specifications of test engine.

Items	Specifications
Bore	82 mm
Stroke	93.5 mm
Compression ratio	10.3
Idle speed	800 ± 100 rpm
Spark timing	BTDC 10° ± 5°
Intake timing	BTDC 8°/ABDC 40°
Exhaust timing	BBDC 50°/ATDC 10°
Valve overlap	18°

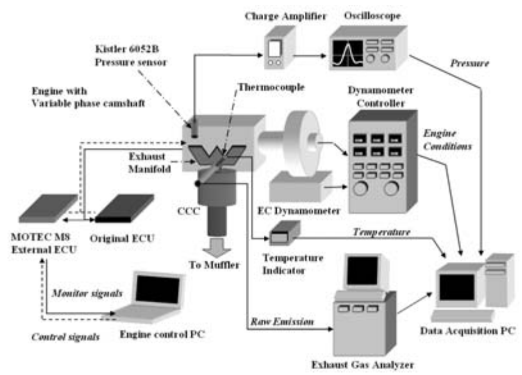


Fig. 1. Schematic diagram of experimental setup.

A thermocouple is installed at the center of exhaust manifold. Exhaust gas temperature is measured for 200 seconds after cranking. A variable timing camshaft is installed so that the phase of exhaust cam events can be controlled. Fig. 2 shows the variable timing camshaft and modified sprockets mounted on the test engine. This camshaft is able to change exhaust valve timing without interference of intake valve timings.

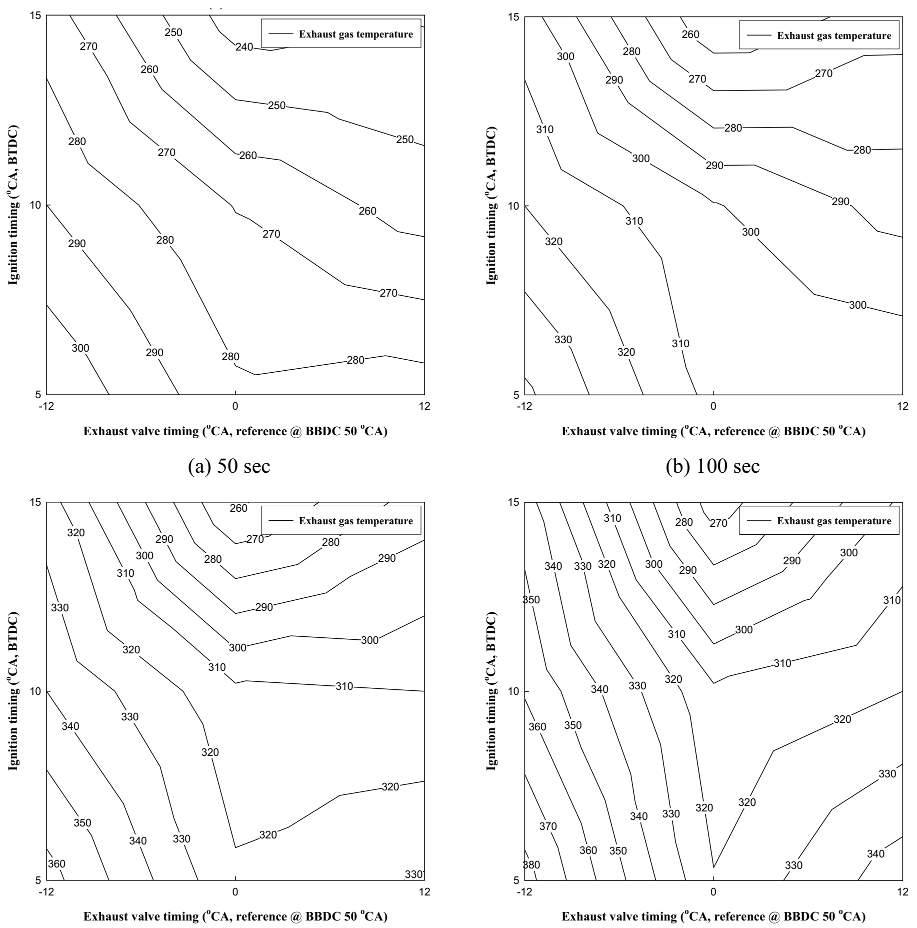
An exhaust gas analyzer (Horiba, EXSA-1500) is used to measure exhaust gas compositions. When exhaust measurements are performed after catalyst, changes due to the controls of engine operating parameters become weaker because of catalytic reactions. Therefore, as shown in the Fig. 1, a sampling probe is installed at the end of exhaust manifold to measure engine-out emissions

2.2 Test conditions

In this study, every test was achieved on cold start condition after soaking the engine of which the coolant temperature was 20℃. After cranking, the engine began idle cold-start operation during 200 seconds. After 200 seconds, the engine became stable and the speed was 900 ± 30 rpm. The timings of exhaust valve open (EVO) was the base line (BBDC 50 °CA), advanced to BBDC 38 °CA and retarded 62 °CA. The timing of ignition was the base line (BTDC 10 °CA), advanced to BTDC 15 °CA, and retarded to BTDC 5 °CA. The variable camshaft only affected the phase of valve events. Therefore, the retarded or advanced EVO corresponded to the same movement of exhaust valve close (EVC) timings.

To investigate variation in the thermal process, the rate of heat release (ROHR) was calculated from the measured cylinder pressure [6]. It was defined as the rate of thermodynamic heat release per unit crank angle. The measured pressure also determined variations in indicated mean effective pressure (imep) and

Fig. 2. Variable timing camshaft mounted on test engine.



(a) 50 sec (b) 100 sec

(a) 50 sec (b) 100 sec

Fig. 3. Distributions of exhaust gas temperature for various ignition and EVO timings.

the rate of heat release. An index to evaluate combustion stability (COV_{imep}) was defined in the following expression [6].

$$COV_{imep} = \frac{\sigma_{imep}}{\overline{imep}} \times 100(\%) \tag{1}$$

3 Experimental results

3.1 Distributions of temperature

Fig. 3 shows the distribution of exhaust gas temperature with respect to ignition and EVO timings. From the figure, exhaust gas temperature is dominant on changes in ignition timings. Fig. 4 shows rate of heat release with changes in ignition timing. As shown in this figure, it is obvious that the crank angle at which maximum heat release occurs moves to the right side with retarded ignition timing. It results in an increase in the exhaust gas temperature. Retarded EVO timing is another effective way to increase exhaust gas temperature. One possible reason to explain this is variation in residual gas fraction. Only the exhaust valve timing is changed in this experiment and the intake/exhaust valve overlap period must be altered. During idle operation of an SI engine, backward flow of exhaust gas during valve overlap is evident and it increases the amount of residual gas in the next cycle [7]. Fig. 5 shows ROHR curves with changes in exhaust valve timings. Advanced EVO, thus advanced EVC, leads to maximum value of ROHR higher than that of the retarded case. However, in the vicinity of EVO timing of the next cycle, ROHR of the retarded case becomes higher. Therefore, it is possible to say that the flame remains at near the end of the expansion stroke when EVO or/and EVC is retarded even if the maximum burning

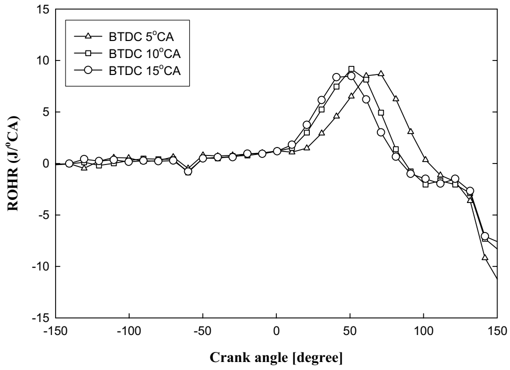


Fig. 4. Variations in rate of heat release as ignition timings varied.

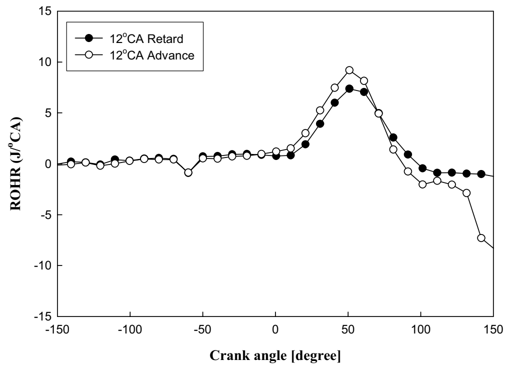


Fig. 5. Variations in rate of heat release as exhaust valve timings varied.

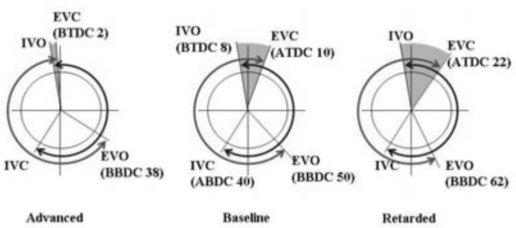
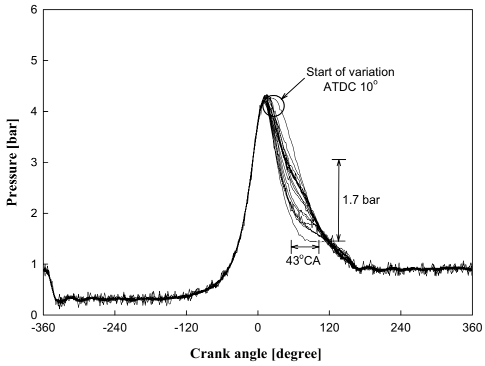
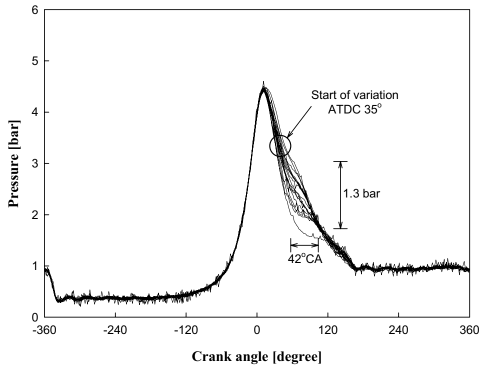


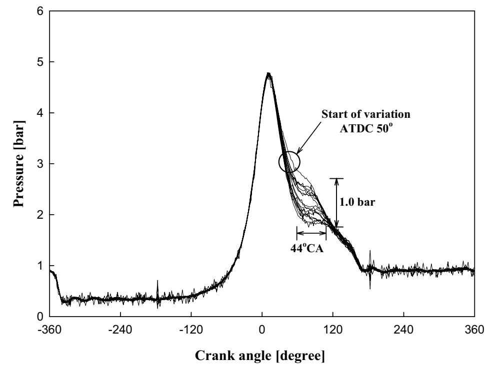
Fig. 6. Schematic diagram of valve timings and valve overlap variations.



(a) spark timing : BTDC 15°(+5°), exhaust valve open : BBDC 50°



(b) spark timing : BTDC 10°, exhaust valve open : BBDC 50°(base)



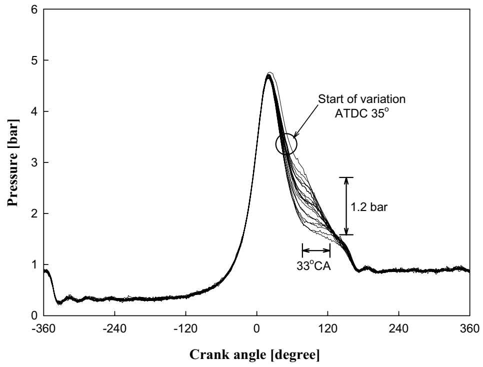
(c) spark timing : BTDC 5°(-5°), exhaust valve open : BBDC 50°

Fig. 7. Ensemble-averaged pressure curves for various spark timings (EVO @ BBDC 50°CA).

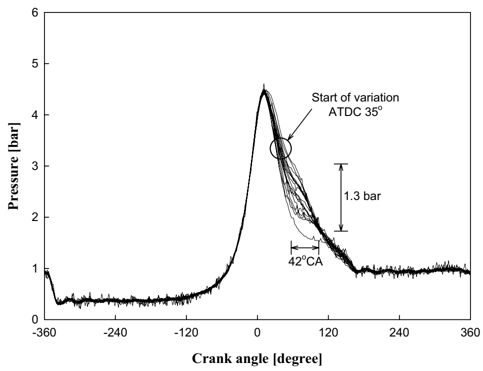
3.2 Combustion stability

Fig. 7 and Fig. 8 are the ensemble-averaged pressure-crank angle (P-θ) diagrams at various ignition and exhaust valve timings, respectively. In Fig. 7, it is observed that the pressure near top center strongly varies when the ignition timing is advanced. Compared with that, the pressure variation is not so serious with the retarded ignition timing. It is also understood that the pressure variation of retarded exhaust valve timing is larger than that of advanced timing from Fig. 8. For further study, it is considered that the relationship of intake valve timing and temperature should be meaningful.

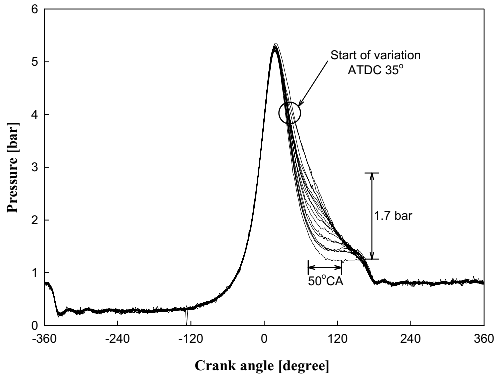
Table 2 shows the COV_{imep} variation for ignition and exhaust valve timings and Fig. 9 is a graph with the data shown in the table. From previous discussion, the retarded exhaust valve timing results in the increase of residual gas and the decrease in combustion stability. Therefore, it is concluded that the retarded



(a) spark timing : BTDC 10°, exhaust valve open : BBDC 56°(+6)



(b) spark timing : BTDC 10°, exhaust valve open : BBDC 50°(base)



(c) spark timing : BTDC 10°, exhaust valve open : BBDC 44°(-6)

Fig. 8. Ensemble-averaged pressure curves for various exhaust valve timings (Spark @ BTDC 10°CA).

exhaust valve timing causes the increase of exhaust gas temperature at the cost of combustion stability due to the change of residual gas fraction. It shows that the change of exhaust valve timing should be carefully applied in order to help the warmup of the catalyst. Compared with that, retarded ignition timing improves combustion stability as well as the increase of exhaust gas temperature. It is also concluded that

Table 2. Variations in COV_{imep} (%) as valve timing and ignition timing varied.

Ignition timing \ Valve timing	6°CA Advanced	Baseline case	6°CA Retarded
BTDC 5°	10.83	13.91	14.66
BTDC 10°	12.44	14.23	15.62
BTDC 15°	14.36	17.81	18.5

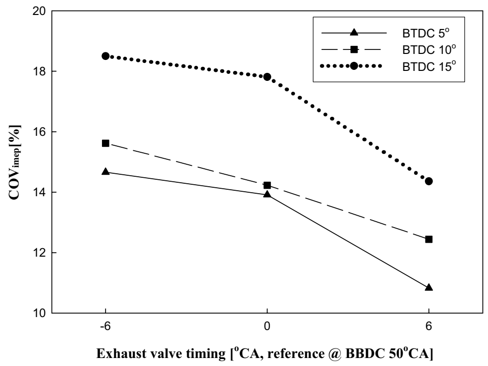


Fig. 9. Variation of COV_{imep} for exhaust valve timing and ignition timing changes.

the retarded ignition timing will be useful for the cold start period to increase exhaust gas temperature for fast warmup of catalysts while maintaining combustion stability.

3.3 Emission concentration

Generally, emission concentrations are very sensitive to air/fuel ratio and temperature in the combustion chamber. As mentioned before, the original ECU controls all parameters including the amount of fuel injection and MOTEC M8 controls ignition timings. The coolant temperature is kept about 80℃ in each test conditions and the amount of fuel injection is in feedback control. Measurements of air/fuel ratio through the exhaust gas analyzer were about 14.0~14.25 in each condition.

Fig. 10 shows CO concentrations under various test conditions. As exhaust valve timing is retarded, CO concentration increases clearly. The change of residual gas in the cylinder could be the most crucial reason for such effects because CO concentration is very sensitive to the amount of fresh air. Therefore, increasing the amount of residual gas due to the backflow during the valve overlap period promotes dilution of burned gas and an increase in specific heat of the mixture. Therefore, it is considered that CO would

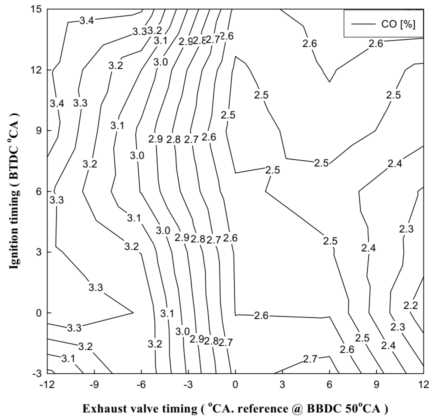


Fig. 10. Distribution of CO concentration for various ignition and exhaust valve timings.

be hard to perform sufficient chemical reaction.

Fig. 11 shows NO_x concentration under various test conditions. It is clear that NO_x concentration depends on temperature of burned gas. When the EVO timing is retarded, residual gas fraction increases due to the increase in valve overlap period. The decrease in flame propagation speed and the increase in specific heat, which are due to the residual gas as well as internal EGR, result in the decrease in mean temperature of burned gas during combustion and a decrease in NO_x concentration.

In the Fig. 11, ignition timing is not a dominant factor that affects NO_x concentration but retarded ignition timings slightly increase NO_x emissions, especially when the EVO timings are advanced. As mentioned before, the retarded ignition timing increases the temperature in the combustion chamber during idle operation. At medium or high speed operations, retarded ignition from MBT timing causes a decrease in maximum flame temperature and cylinder pressure due to the expansion stroke of pistons. However, the mean piston speed of idle operations is lower and flame stays longer in the expansion stroke when ignition timings are retarded.

From these results, it is clear that the changes of EVO cause residual gas in the cylinder and there are two opposite effects on exhaust gas composition and the stability of combustion. Advanced EVO is effective to reduce COV_{imep} and CO but it also increases NO_x emission. The effects are similar of the effects of EGR. Especially, these factors may interact more strongly in idle operations. Therefore, the controls should be much more precise in idle and cold-start operations. At the same time, CO concentrations also

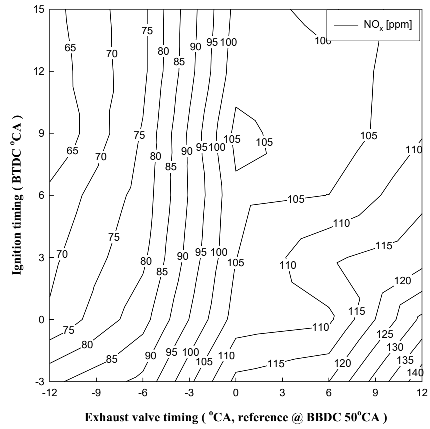


Fig. 11. Distribution of NO_x concentration for various ignition and exhaust valve timing.

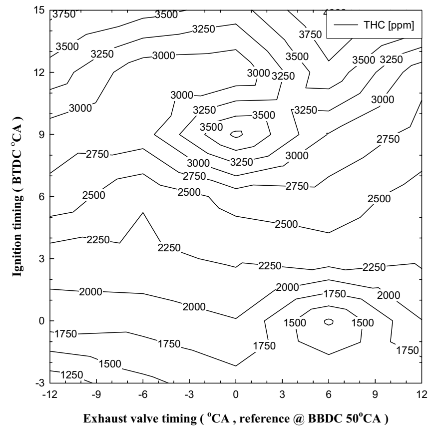


Fig. 12. Distribution of THC concentration for various ignition and exhaust valve timing.

show fast increase from the same EVO timings. Therefore, advanced EVO about 4~5°CA, which is BBDC 45~46°CA, is considered as an optimal EVO timing of the test engine in terms of stability and CO emission. NO_x emissions should be compromised to achieve combustion stability or additional strategies for effective reductions of NO_x should be suggested to achieve the two targets at the same time.

Fig. 12 shows emission concentrations of THC for various ignition and EVO timings. On the contrary to CO and NO_x emissions, HC emissions depend on spark timings. [8, 9] It is clear that the retarded ignition timing decreases the concentration of THC. Generally, two major parameters that determine HC emissions are flame temperature and duration of combustion. As mentioned before, retarded spark timings are helpful to increase exhaust gas temperature. Furthermore, the combustion process lasts near the end of the expansion stroke.

From the experiments, it is possible that retarded ignition timings are efficient for the reduction of HC, in addition to the increase of exhaust gas temperature. However, slight increases of NO_x emissions are also observed. From the point of view of COV_{imep}, it is considered that the retarded ignition timing of near BTDC 3° CA will compromise HC and COV_{imep}.

Finally, the retarded spark and advanced EVO is beneficial to increase exhaust gas temperature and to improve combustion stability. Through the idle control strategies, emission reductions are also expected. Additional strategies for effective reductions of NO_x should be suggested, such as control of the amount of fuel. Furthermore, unexpected problems in transient operating regions should be considered in order to apply to the control strategies

4. Conclusions

The effects of exhaust valve timing and ignition timing on exhaust gas temperature during cold start period are experimentally investigated and analyzed. From this experimental study, the following conclusions are obtained:

A retarded exhaust valve timing without change of intake valve timing leads to an increase of residual gas and a lower flame propagation speed. It causes a slow burn in the cylinder and the exhaust gas temperature increases when the exhaust valve opens.

As the ignition timing is retarded, the start of combustion is delayed and flame stays longer in the cylinder, resulting in a higher exhaust gas temperature.

Retarded ignition is helpful to increase exhaust gas temperature. Retarded exhaust valve timing increases the temperature at the cost of COV_{imep}. The change of ignition timing affects the pressure variation near top center and COV_{imep}, and retarded ignition timing is also helpful to improve combustion stability.

CO and NOx emissions are sensitively changed with the changes of EVO. Retarded EVO results in the increase of CO and decrease of NO_x. Dilution of fresh air with residual gas affects air-fuel ratio and CO concentrations. An internal EGR effect of residual gas controls NO_x concentrations

Changes in ignition timings are the main parameter of hydrocarbon emissions and retarded ignition timings lead to decrease of HC concentrations. It is considered that the changes of heat release characteristics can determine the cylinder temperature as well as the duration of the combustion process.

The retarded ignition and advanced EVO will be helpful to increase exhaust gas temperature and to improve combustion stability. Through the idle control strategies, emission reductions are also expected. It is considered that ignition timing is controlled near BTDC 3° CA and exhaust valve open timing is controlled near BBDC 45~46°CA

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