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EFFECTS OF CAM PHASE AND SPARK RETARD TO INCREASE EXHAUST GAS TEMPERATURE IN THE COLD START PERIOD OF AN SI ENGINE

D.-S. KIM* and Y.-S. CHO

Graduate School of Automotive Engineering, Kookmin University, Seoul 136-702, Korea

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ABSTRACT−The effects of spark timing and exhaust valve timing change on exhaust gas temperature during cold start period of an SI engine are studied through engine bench tests. The exhaust gas temperature increases when the spark timing or valve timing are retarded individually, due to late combustion or slow flame speed. Therefore, exhaust gas temperature shows a large increase when the two timings are retarded simultaneously. However, it is considered that combustion stability during cold start deteriorated under these retarded conditions. To increase exhaust gas temperature for fast warmup of catalysts while maintaining combustion stability, an optimal condition for spark and valve timing retard should be applied for the cold start period.

KEY WORDS : Catalyst, Cold start, Exhaust valve timing, Spark ignition timing, Exhaust gas temperature

1. INTRODUCTION

After the successful application of three-way catalytic converters (TWCs) in SI engines in 1980s, the exhaust emission levels from these engines became very low with technological developments associated with the TWCs. TWCs are very effective to lower the emission levels from vehicles, but they also have inherent problems related to catalytic chemical reaction. Conversion rates of CO, HC and NOx of a TWC are between 80 and 90% after it becomes fully heated up to a normal operating temperature. Since the catalyst stays at lower temperatures during cold start period of a vehicle, harmful species such as CO and HC pass through the TWC without catalytic reaction and the level of exhaust emissions becomes very high in this period. Therefore, the key technologies to meet the stringent emission regulations such as LEV, ULEV and SULEV of California and to protect the air quality in urban areas are closely related to reduce the time required to warmup the catalysts in the cold start period (Summers *et al.*, 1993; Cho and Kim, 2004; 2005).

Previous studies showed that the change of spark ignition timing significantly affects exhaust gas temperature in cold start period (Russ, Lavoie and Dai., 1999). When spark ignition timing is retarded, the start of combustion is delayed, resulting in a lower maximum cylinder pressure. On the other hand, flame stays up to a later stage of the expansion stroke and the exhaust gas temperature is higher than the cases of normal spark ignition timing. Although energy loss is considerable with retarded spark timing, rapid warmup of catalyst in a cold engine start situation can be achieved due to an increase in the exhaust gas temperature.

Recent development in engine control unit (ECU) and variable valve timing (VVT) technology is also very helpful to minimize the warmup time of catalysts in cold start. A VVT system can change the intake or exhaust valve timings to optimize the gas exchange processes, and the engine operating parameters such as engine speed, load and coolant temperature change accordingly (Roberts and Stanglmaier, 1999). Changes in the intake and exhaust valve timings affect flame speed, temperature and residual gas fraction that control the combustion processes in the cylinder. Therefore, a proper change of valve timing can raise the exhaust gas temperature for rapid warmup of the catalysts in the cold start period (Monaghan, 2000).

The main objectives of this study are to optimize the spark ignition timing and exhaust valve timing in order to increase the exhaust gas temperature during the cold start period for rapid warmup of catalysts. For this purpose, the effects of exhaust valve timing and spark ignition timing on cold start operation are investigated through engine bench tests. Exhaust valve timing is changed using a variable timing camshaft and spark ignition

**Corresponding author.* e-mail: lordduke@kookmin.ac.kr

timing is changed by an external ECU. The changes in combustion characteristics and exhaust gas temperature are measured and analyzed.

2. EXPERIMENTAL SETUP

2.1. Experimental Apparatus

A 2-liter, naturally aspirated, four-cylinder SI engine is used as a test engine and its specifications are described in Table 1. Figure 1 shows a schematic diagram of the experimental setup. Pressure of cylinder #1 is measured using a spark-plug type Kistler 6052B pressure transducer. Measured pressure signals are converted to voltage signals by a charge-to-voltage amplifier, and acquired and analyzed them by a data acquisition system. Pressure in the intake plenum chamber is measured by a Kistler 4045B, an absolute pressure sensor.

A programmable ECU changes spark ignition timing in order to set the timing values at the test conditions. Other signals such as engine speed and exhaust gas temperature are stored in the data acquisition PC.

In the test engine, a variable timing camshaft that can change the phase of cam events is installed for changing

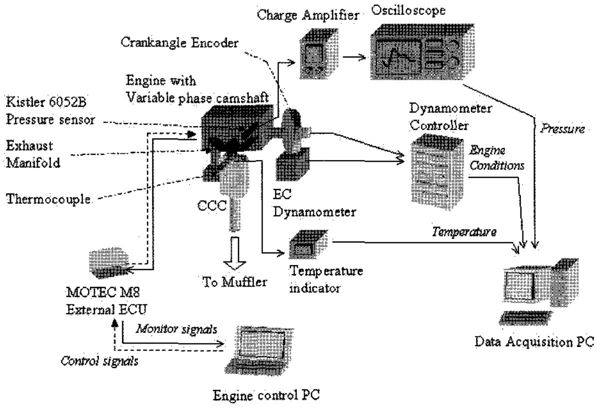
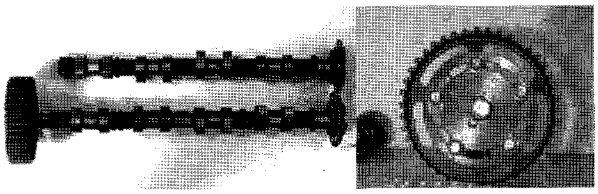


Figure 1. Schematic diagram of experimental setup.

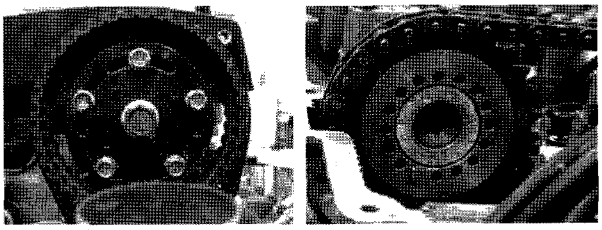
Table 1. Specification of test engine.

Items	Specifications
Type	4 cylinder, spark-ignition, In-line, DOHC
Bore	82 mm
Stroke	93.5 mm
Compression ratio	10.3
Idle speed	800 ± 100 rpm
Spark timing	BTDC 10° ± 5°
Intake valve timing	BTDC 8°/ABDC 40°
Exhaust valve timing	BBDC 50°/ATDC 10°
Valve overlap	18°



(a) Valve train (b) Cam sprocket

Figure 2. Variable timing camshaft and sprocket.



(a) Front side (b) Rear side

Figure 3. Variable timing camshaft mounted on the cylinder head.

exhaust valve timing. Figure 2 shows the variable timing camshaft and modified sprocket for the experiments. Figure 3 shows the camshaft installed in the cylinder head. The cam sprocket and chain pulley can be disassembled from camshaft while the engine is on the test bench. Exhaust cam phase can be changed by simply turning the camshaft when the sprocket and pulley are disconnected. As shown in Figure 3(b), there are 16 keyholes on the pulley and 15 holes on the camshaft mount. Consequently, the minimum change of cam phase is 3° crank angle (CA).

2.2. Test Conditions

Since the goal of this study is to investigate the effects of spark timing and exhaust valve timing on the exhaust gas temperature in a cold start period, the test engine is soaked at 20°C of coolant water temperature before each test. The exhaust valve timing is changed to BBDC 50° ±12° CA. Similarly, in order to investigate the effects of spark timings, spark ignition timing is changed to BTDC 10°±5° CA. In each case, the same amount of fuel is supplied, through the control of fuel injection pulse width using an external ECU (Motec M8). Because the engine is started under the cold start condition (20°C), the stoichiometric feedback control of fuel supply is not applied. The amount of fuel for the baseline case that has original spark and exhaust valve timings are determined through a preliminary test and a proper fuel injection duty for starting and stable operation of the engine was established using the external ECU. The same fuel injection duty map is applied to other test cases. Exhaust gas temperature is measured from beginning to 200 seconds after engine start, and cylinder pressure is measured at 300 seconds after engine start. At this time, the engine becomes sufficiently warmed and the coolant temperature is near 80°C.

3. RESULTS AND DISCUSSION

3.1. Effects of Exhaust Valve Timing

In order to investigate the feasibility of valve timing change for raising exhaust gas temperature, the effects of changes of exhaust valve timing on cold engine performance are experimentally tested. Figure 4 shows exhaust gas temperature variations with the change of exhaust valve timing. In this figure, exhaust gas temperature increases when exhaust valve timing is retarded 12°CA from the baseline case. On the contrary, when exhaust valve timing is advanced 12°CA, the similar increase ratio of temperature until 100 seconds, and after 150 seconds relatively small decrease can be shown. Consequently, it is considered that retarded exhaust valve timing is beneficial for increasing exhaust gas temperature.

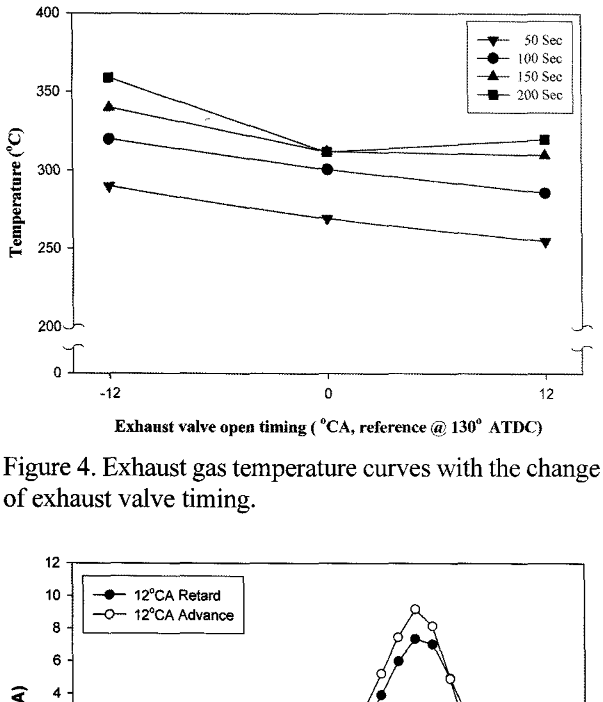


Figure 4. Exhaust gas temperature curves with the change of exhaust valve timing.

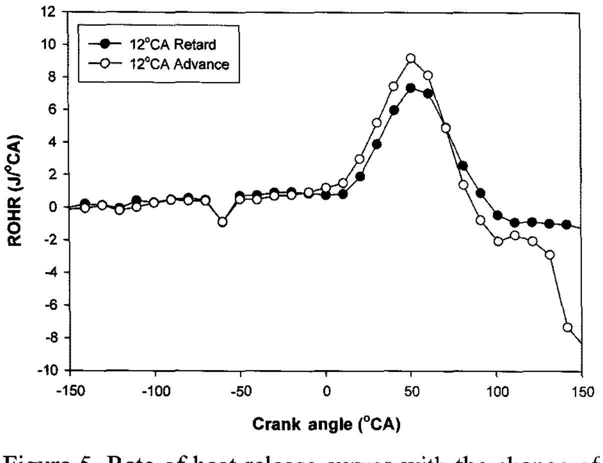


Figure 5. Rate of heat release curves with the change of exhaust valve timing.

Figure 5 is the rate of heat release (ROHR) curves with the change of exhaust valve timing. The pressure curves to calculate ROHR (Heywood, 1988) are obtained by averaging 200 consecutive cycles under each test condition. The ROHR curves for ±12°CA cases are obtained from the cylinder pressure data. As shown in Figure 5, the ROHR curves reach their peak values at around 50°CA, and decrease later on. This means that combustion rate and flame propagation speed are highest at around 50°CA and they are rapidly decreasing after the point. When the exhaust valve timing is advanced, the peak value is higher but combustion ends earlier. On the other hand, when the exhaust valve timing is retarded, the peak value at 50°CA is relatively lower but heat release from fuel continues longer. It can be explained by flame speed. When flame speed is faster, burning rate at the earlier stages is higher, resulting in a higher value of ROHR at around 50°CA. However, a rapid decrease in ROHR occurs because considerable amount of fuel is already burned. The opposite is also possible when the flame speed is lower. Therefore, the retarded exhaust valve timing is beneficial for higher exhaust gas temperature because heat release continues to a later stage of the expansion stroke.

When using the variable timing camshaft, it is possible to change the exhaust valve open and close timings but there is no way to change the cam profile. It means when the valve open timing is retarded or advanced, the valve close timing should be changed accordingly. Only the exhaust valve timing is changed in this experiment, and the intake/exhaust valve overlap period must be altered because there is no change of intake valve timing. During idle operation of an SI engine, pressure in the intake manifold is much lower than that in the exhaust manifold. This causes a backward flow of exhaust gas during valve overlap period and increases the amount of residual gas in the next cycle (Koo and Bae, 2001).

When the exhaust valve timing is advanced, the exhaust valves close earlier, and the overlap becomes shorter. On the contrary, when the exhaust valve timing is retarded, the overlap becomes longer, and the amount of residual gas increases. The higher residual gas fraction leads to the lower the flame speed and engine stability, especially in idle conditions. However, flame lasts longer due to a slow burn process, and the exhaust gas temperature increases.

3.2. Effects of Spark Timing

Figure 6 shows variations in exhaust gas temperature with the change of spark timing. As shown in this figure, exhaust gas temperature increases when spark timing is

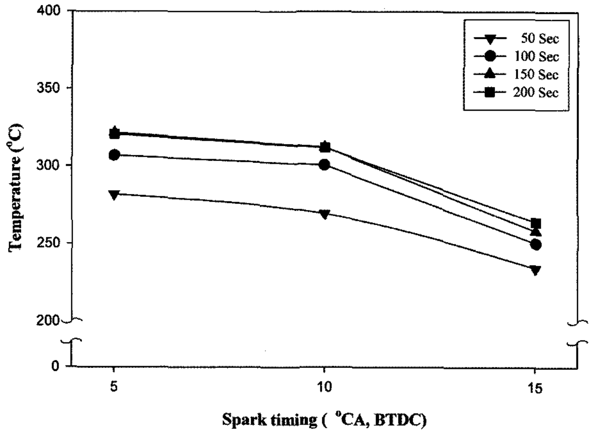


Figure 6. Exhaust gas temperature curves with the change of spark timing.

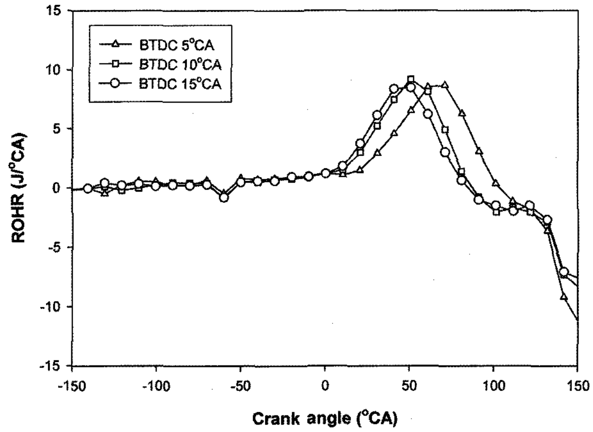
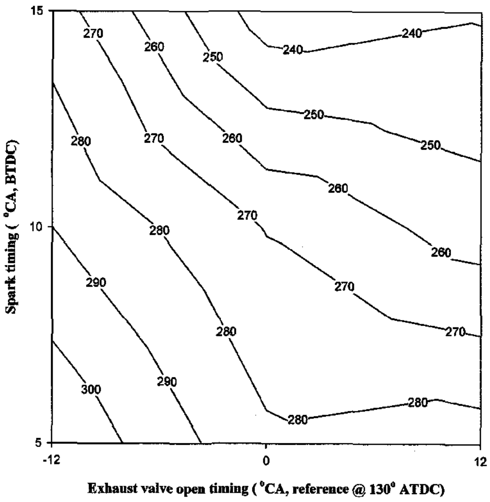
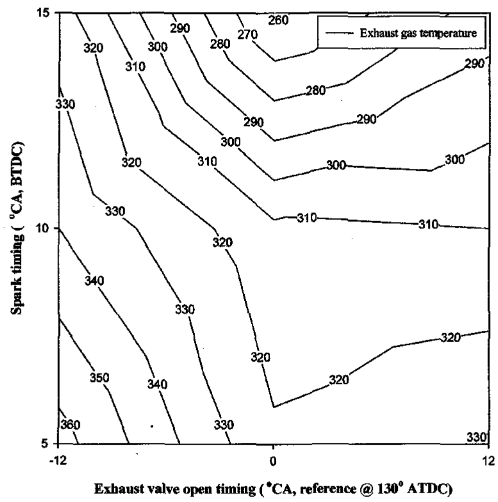


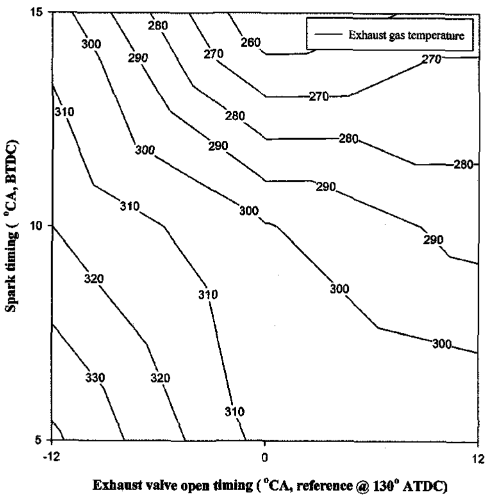
Figure 7. Rate of heat release curves with the change of spark timing.



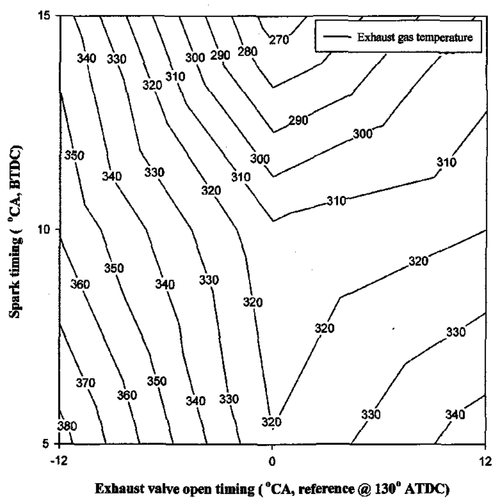
(a) 50 seconds



(c) 150 seconds



(b) 100 seconds



(d) 200 seconds

Figure 8. Exhaust gas temperature contours with the change of spark timing and exhaust valve timing.

retarded to BTDC 5°CA from the baseline case. On the contrary, when spark timing is advanced to BTDC 15°CA, the exhaust gas temperature rapidly decreases compared with the baseline case. Figure 7 shows the ROHR with the change of spark timing. As shown in this figure, it is obvious that the crank angle at which maximum heat release occurs moves to the right side, resulting in an increase in the exhaust gas temperature.

Based on the above results, it is obvious that there are two important factors to hold the flame longer in the combustion chamber, in order to obtain a higher exhaust gas temperature. First, retarded exhaust valve timing increases the valve overlap period and residual gas fraction under idle and cold start conditions. The flame propagation becomes slower and late burn occurs to raise exhaust gas temperature. Second, when spark ignition timing is sufficiently retarded, start of combustion is delayed and the flame lasts longer before the exhaust valves open. This late burn or partial burn phenomena are favorable for increasing the pressure and temperature of the exhaust gas.

3.3. Relation of Spark and Exhaust Valve Timing

Based on the results discussed so far, it is known that both retarded spark timing and retarded exhaust valve timing are beneficial for obtaining higher exhaust gas temperature. Figure 8 shows contours of exhaust gas temperature with the change of spark timing and exhaust valve timing, measured at 50, 100, 150 and 200 seconds after cold start of the test engine. As shown in this figure, the exhaust gas temperature tends to increase with retarded spark timing and exhaust valve timing. The increase of exhaust gas temperature with the advanced exhaust valve timing is also observed, resulting from a faster blowdown process, but the amount of increase is smaller compared with that of the retarded spark timing. In these results, it is obvious that the retards of spark and valve timing are helpful to increase exhaust gas temperature for fast warmup of catalysts. However, in the tests, it is also observed that the engine becomes unstable with the considerable changes spark and exhaust valve timing. Therefore, it is considered that the increase of exhaust gas temperature using the change of parameters causes instability of engine. Therefore, an optimal condition for spark and valve timing retard should be applied for the cold start period, to increase exhaust gas temperature for fast warmup of catalysts while maintaining combustion stability and a further study is in progress to find the relationship between engine stability and engine operating conditions.

4. CONCLUSIONS

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

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

(2) When the spark ignition timing is retarded, the start of combustion is delayed and flame stays longer in the cylinder, resulting in a higher exhaust gas temperature.

(3) Retarded spark ignition and exhaust valve timing are helpful to increase exhaust gas temperature. However, an optimal condition for spark and valve timing retard should be applied for the cold start period, to increase exhaust gas temperature for fast warmup of catalysts while maintaining combustion stability.

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