

Development of NOx Reduction System Based on Exhaust Valve Controls for Use in Small Motorcycle Engine

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ABSTRACT

An internal EGR system was devised that opens and closes an exhaust valve slightly at the beginning of the compression stroke, or between the end of the intake stroke and the beginning of the compression stroke. When this valve timing is used, the fresh air-fuel mixture charging rate shows practically no decrease because the action occurs when the intake stroke is more or less over. Sufficient burnt gas for NOx reduction rapidly flows into the cylinder because the in-cylinder pressure is negative. The thermal energy and turbulence kinetic energy of the burnt gas activate the air-fuel mixture in the cylinder. Therefore, this system does not require variable valve timing, and it was designed to use a solenoid to operate an EGR cam that is located on the same shaft as the exhaust camshaft. As a result, the system achieved favorable drivability while reducing NOx by approximately 50% and reducing CO by approximately 20% in the Euro 3 driving mode. Significant reduction of NOx also enabled a reduction of approximately 70% in the catalyst volume needed to satisfy Euro 3 exhaust emissions standards.

1. Introduction

As motorcycle exhaust emission standards have become more stringent every year, the reality of current exhaust emission reduction systems is that they are dependent on the conversion efficiency performance of the catalyst. It is necessary to increase the conversion efficiency of the catalyst in particular when greater NOx reduction is sought. Therefore, it is necessary to consider stoichiometric control of the air-fuel ratio, increasing the catalyst volume, the location of the catalyst inside the muffler, the temperature of the catalyst, and other such factors. As the result, the system often becomes expensive. Moreover, when the air-fuel ratio is increased in order to reduce fuel consumption, the NOx conversion efficiency of the catalyst decreases significantly. Consequently, lean-burn measures cannot be taken. Therefore, lower-cost technology to reduce NOx without depending on the catalyst becomes necessary⁽¹⁾⁻⁽³⁾.

In the present study, an internal exhaust gas recirculation (EGR) system with a two-stage opening of the exhaust valve has been designed and is of reasonable

cost. It opens and closes the exhaust valve slightly at the beginning of the compression stroke, or between the end of the intake stroke and the beginning of the compression stroke. This paper describes the NOx reduction effect of that system and the method used to achieve the effect.

2. Development Goals

The goals in development of this system are to reduce the volume of catalyst used to decrease exhaust emissions by means of a reduction in NOx emissions, and to satisfy both environmental performance and economic efficiency in small motorcycles. Therefore, the following items were set as requirements:

- (1) Activating the air-fuel mixture in the cylinder by the thermal and turbulence kinetic energy of the burnt gas, and reducing NOx significantly;
- (2) Not decreasing significantly the charging rate of the fresh air-fuel mixture by the inflow of the burnt gas by the EGR in order to obtain favorable drivability;
- (3) Establishing the low-cost internal EGR system with lightness and compactness.

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Table 1 Engine specifications

Items		Specifications
Engine type		4-stroke Single-cylinder
Cooling type		Liquid cooled
Bore × stroke	(mm)	50.0 × 55.0
Displacement	(cm ³)	108
Compression ratio		11.0
Valve train		SOHC
Valve diameter (mm)	Inlet	φ25.5 × 1
	Exhaust	φ21.0 × 1
Max. power	(kW/r/min)	6.6/7 500
Max. torque	(Nm/r/min)	9.3/6 000

3. Outline of Developed System

3.1. System Actuation Mechanism

Table 1 shows the main specifications of the present engine. Figure 1 shows a general view of the EGR cam actuation mechanism in this system. As shown in Fig. 1, simplicity of the valve train mechanism is realized by placing the EGR cam on the same shaft as the camshaft and causing it to slide in the shaft direction. Switching between the deactivated EGR cam (EGR OFF) and the activated EGR cam (EGR ON) is conducted by a solenoid through a link. The main items considered in this system layout are shown below.

- (1) By adding a link mechanism and giving it leverage, an appropriate EGR cam slide stroke could be obtained by the smaller stroke of the solenoid.
- (2) The EGR cam and the ordinary exhaust valve cam actuate the exhaust valve by means of the same rocker arm.

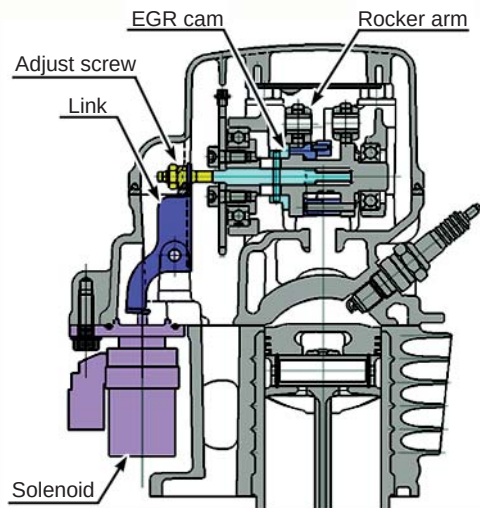


Fig. 1 EGR cam actuation mechanism

- (3) The cumulative clearance from the tolerances of each part is absorbed by adding an adjustment screw to the link mechanism.

Figure 2 shows the lift curves for the exhaust valve when the EGR cam is actuated.

3.2. Confirmation that System Enhances Combustion

3.2.1. Results of combustion analysis on a present engine

Figure 3 shows the in-cylinder pressure, the exhaust pipe pressure, and the intake pipe pressure in the case of EGR OFF and EGR ON.

This graph shows that when the EGR cam is actuated, the exhaust pipe pressure simultaneously decreases and the in-cylinder pressure increases. In other words, this makes it clear that the in-cylinder pressure is negative during actuation of the EGR cam, so that when the exhaust valve is opened by the EGR cam, burnt gas simultaneously flows into the cylinder from the exhaust port and causes the in-cylinder pressure to rise.

There is practically no increase in the intake manifold pressure, so essentially no burnt gas flows into the intake manifold. Consequently, it can be considered that the energy of the burnt gas is being used effectively to activate the air-fuel mixture in the cylinder.

The P-V diagram and the rate of heat release ($dQ/d\theta$) are shown in Figs. 4 and 5 in the case of EGR OFF and EGR ON. As is clear from these graphs, the in-cylinder pressure rises higher in the EGR ON state than in EGR OFF, and $dQ/d\theta$ also rises higher. Figure 6 shows the in-cylinder temperature in the EGR OFF and ON states. In EGR ON, even though the temperature rises during the compression stroke, the maximum temperature during the combustion stroke has been lowered.

As indicated by the above, the valve-open timing of the EGR cam in this system is set to the beginning of the compression stroke or the end of the intake stroke. The valve-close timing is set to the compression stroke, and it became clear that making this valve-close timing coincide with a state of negative pressure inside the cylinder causes combustion to be enhanced while the maximum temperature in the cylinder is reduced.

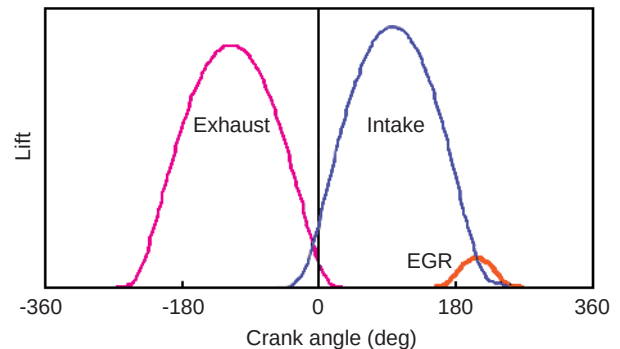


Fig. 2 Exhaust valve lift curves during actuation of EGR cam

3.2.2. Results of Computational Fluid Dynamics (CFD) Analysis of In-Cylinder Flow and Combustion

(1) Conditions for computation

In order to confirm the effects of the inflow of burnt gas and turbulence kinetic energy based on the test results in Sub-section 3.2.1, verification of the combustion analysis including in-cylinder flow was performed by computational fluid dynamics (CFD) analysis.

CFD computation was performed using commercially available code for 3D thermo-fluid analysis called FIRE (from AVL List GmbH). The standard $k-\epsilon$ model was applied for the turbulence model and the extended coherent flame model (ECFM) was applied for the combustion model. The initial conditions for computation and the boundary conditions were set using pressure and temperature measurement values for the various parts as obtained from present engine measurements. The fuel

sprayed from the injector was assumed to have completely vaporized in the intake port during the interval before the intake valve opens, and the process whereby fresh air-fuel that is homogeneous and single-phase (equivalence ratio=1) flows into the cylinder, mixes with the burnt gas,

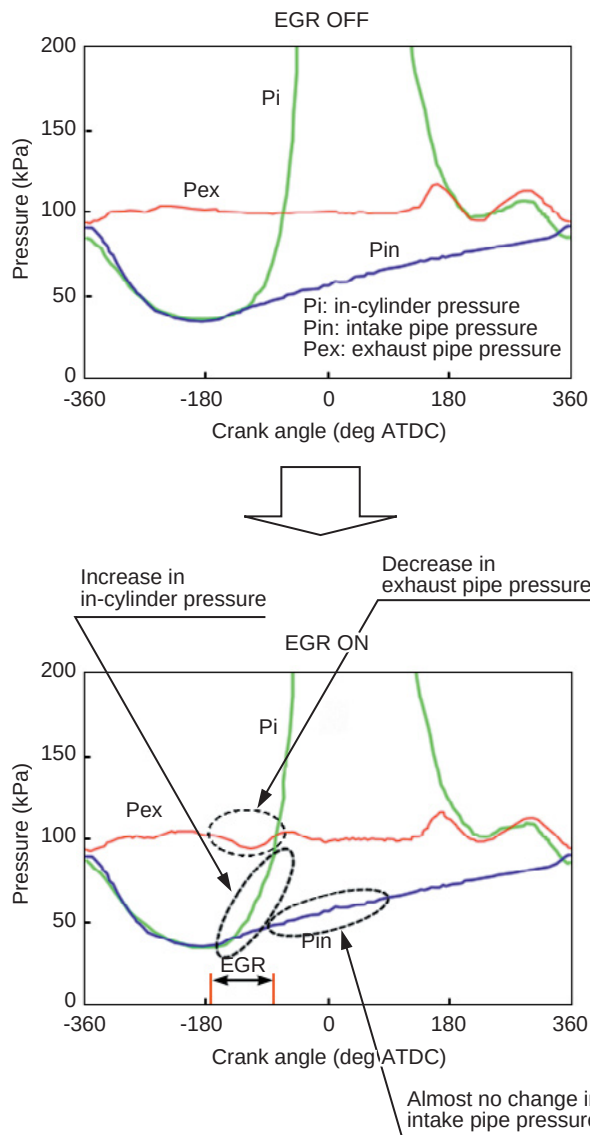


Fig. 3 Pressure applied to each part when EGR cam is in OFF and ON state

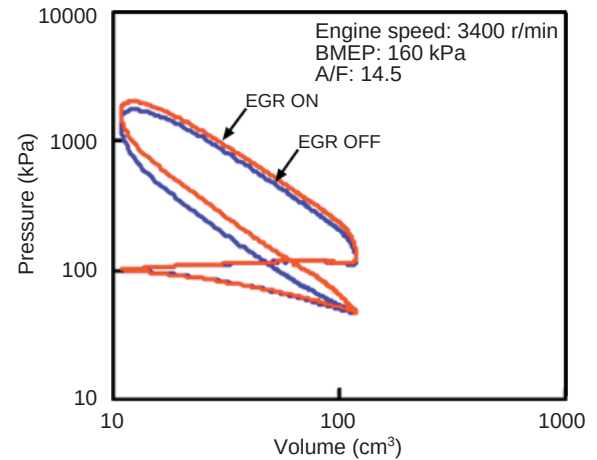


Fig. 4 P-V diagram when EGR cam is in OFF and ON state

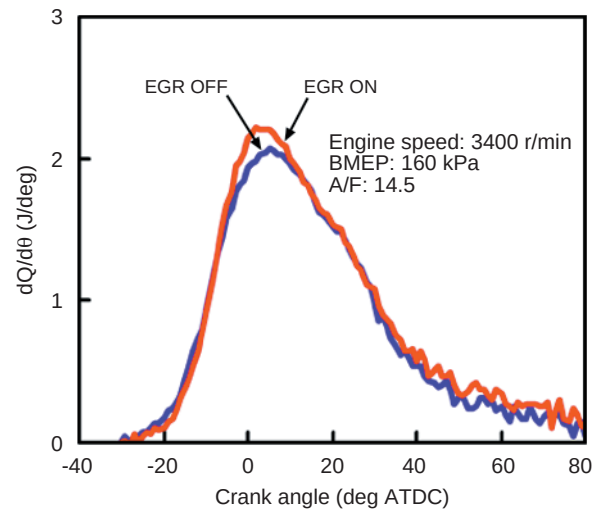


Fig. 5 $dQ/d\theta$ when EGR cam is in OFF and ON state

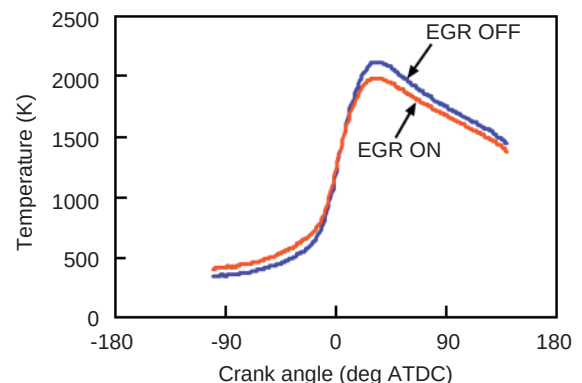


Fig. 6 In-cylinder temperature when EGR cam is in OFF and ON state

and undergoes combustion was computed.

(2) EGR gas distribution

Figure 7 presents views of burnt gas from the exhaust pipe flowing into the cylinder and EGR gas distribution with EGR OFF and ON. When EGR is ON, the exhaust valve is opened again by the EGR cam with timing at the beginning of the compression stroke (from -160 to -100 deg ATDC). It is clear that the burnt gas in the exhaust pipe flows into the cylinder along the cylinder wall and the EGR ratio in the cylinder increases. This enabled confirmation in greater detail of the phenomenon of burnt gas inflow to the cylinder that can be extrapolated from the various pressure measurement values obtained when EGR is actuated.

(3) Turbulence kinetic energy in the cylinder

Figure 8 shows the turbulence kinetic energy around the spark plug with EGR OFF and ON. Figure 9 shows

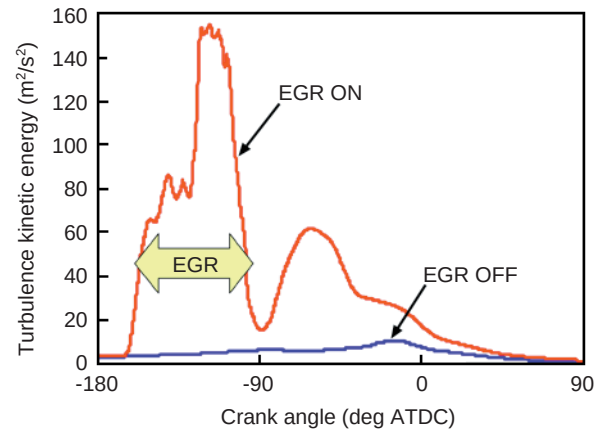


Fig. 8 CFD analysis of turbulence kinetic energy around spark plug

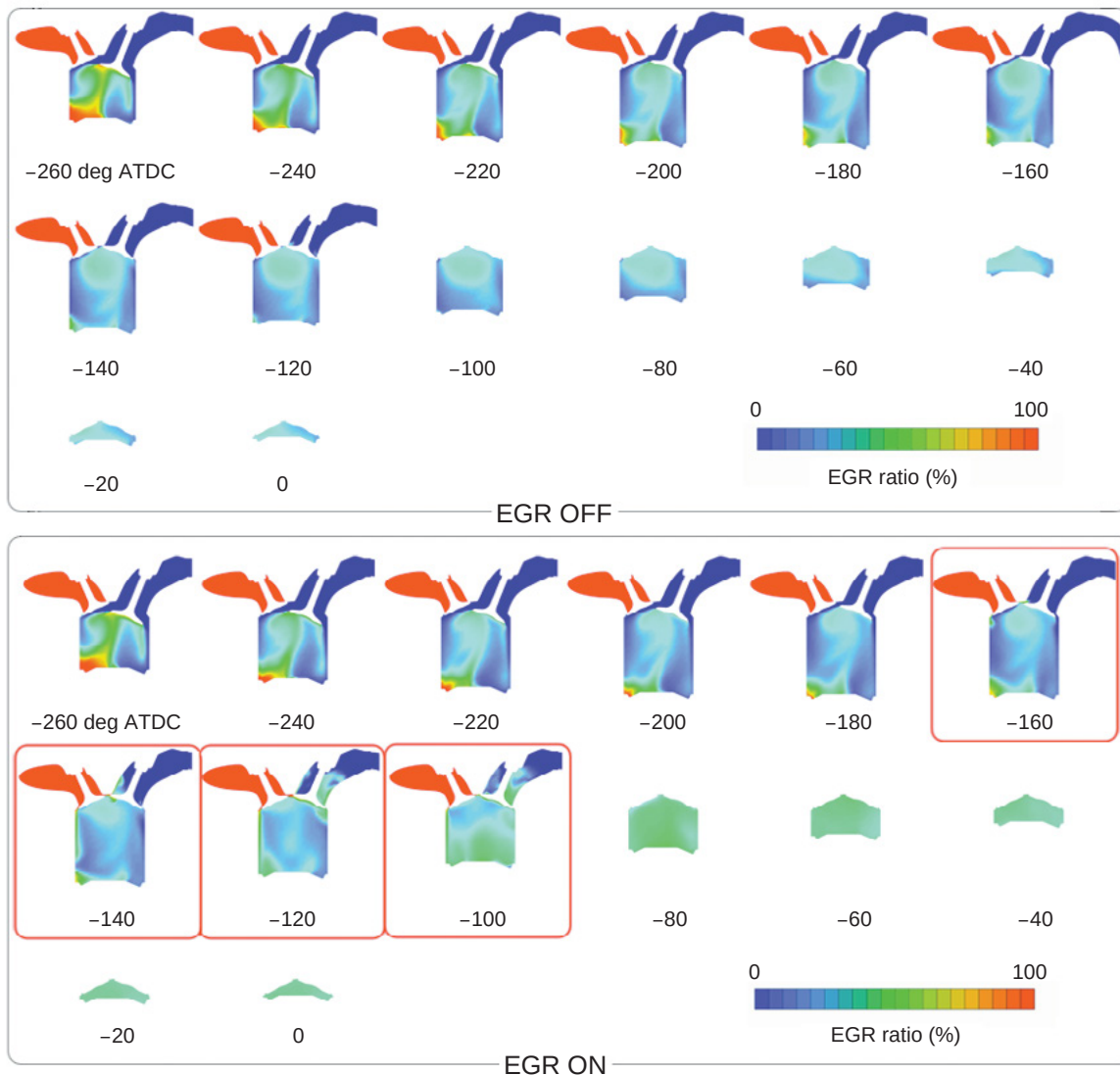


Fig. 7 CFD analysis of EGR

the average turbulence kinetic energy in the cylinder. It is clear that when EGR is ON, the turbulence kinetic energy in the cylinder increases. When EGR is actuated, the burnt gas that flows in due to the difference between the pressure in the exhaust pipe and in the cylinder becomes the source of the increase in turbulence kinetic energy. Thus, the changes in turbulence kinetic energy, which is considered one factor of enhanced combustion in this system, could be confirmed in greater detail.

(4) Flame propagation

Figure 10 shows flame propagation with EGR OFF and ON. It is clear that although some ignition delay occurs when EGR is ON, flame propagation occurs rapidly after ignition. This is thought to be due to the turbulence kinetic energy in the cylinder from EGR gas inflow and the increased thermal energy from the internal

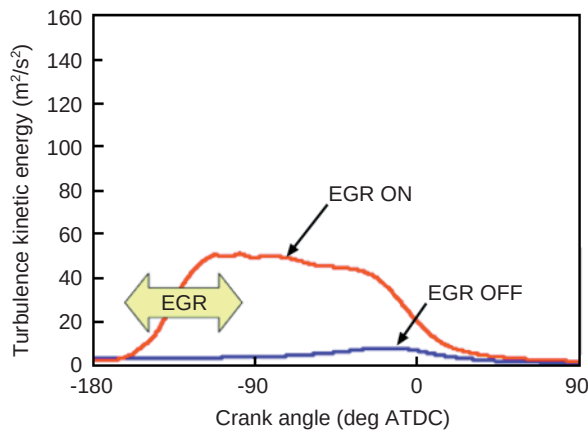


Fig. 9 CFD analysis of average turbulence kinetic energy in cylinder

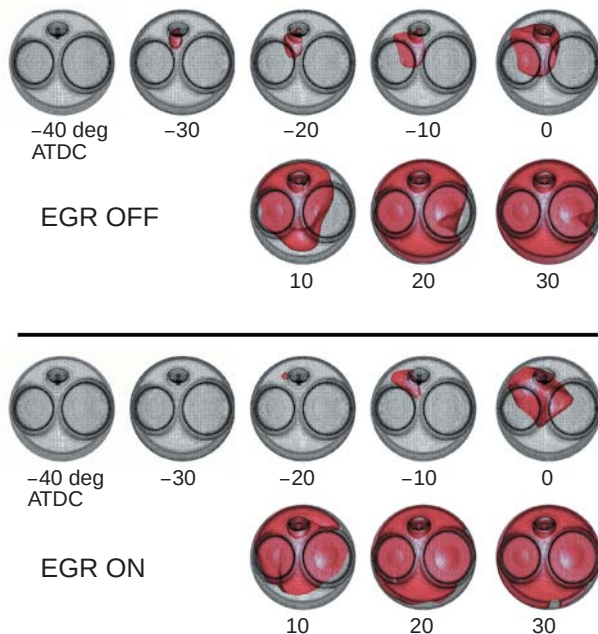


Fig. 10 CFD analysis of flame propagation

EGR. It is clear that combustion is enhanced despite the higher EGR ratio, just as in the test results.

(5) In-cylinder temperature

Figure 11 shows changes in in-cylinder temperature during the combustion stroke with EGR OFF and ON.

It is clear that when EGR is ON, the in-cylinder temperature during the combustion stroke is reduced.

These results confirmed that the system can enhance combustion while reducing the combustion temperature even in CFD analysis.

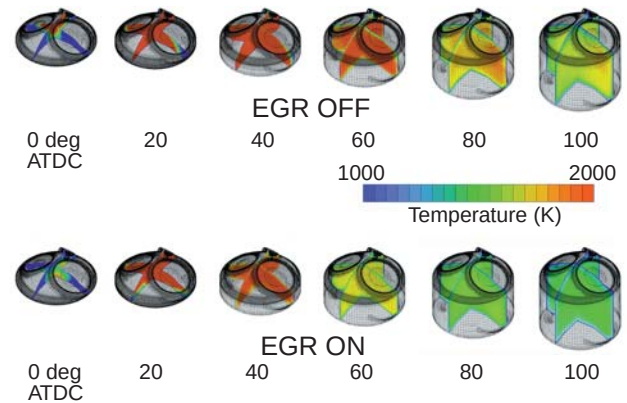


Fig. 11 CFD analysis of in-cylinder temperature

4. Configuring the EGR Cam Actuation Characteristics

4.1. Actuation Timing

Figure 12 shows the exhaust valve lift curves for each specification (1, 2, 3) in which the EGR cam lift is kept constant and the actuating timing is varied. The engine speed and load were also changed in each specification and the resulting NO_x was measured. Those measurement points (a, b, c, d, e, and f) are shown in Fig. 13, and the results for the NO_x reduction rates obtained due to EGR at each measurement point are shown in Fig. 14.

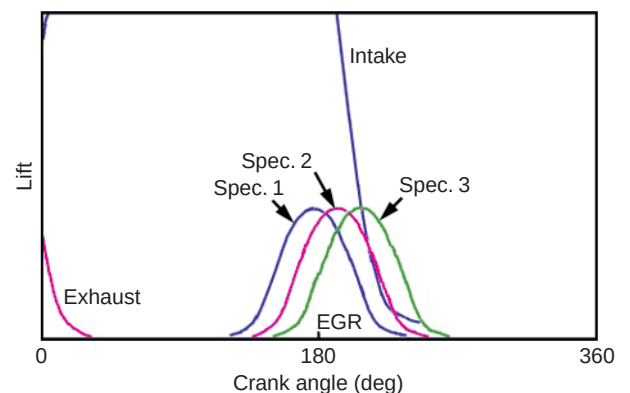


Fig. 12 Exhaust valve lift curves by difference in actuating timings of EGR cam

All the specifications are alike in obtaining an NOx reduction rate that is higher at lower speeds and lower loads. This is because the magnitude of the negative pressure inside the cylinder is greater when the EGR cam is actuated, thereby increasing the volume of burnt gas that flows into the cylinder. On the other hand, the NOx reduction rate is lower when the speed and load are higher. This is because the magnitude of the negative pressure inside the cylinder is lower when the EGR cam is actuated, decreasing the volume of burnt gas that flows into the cylinder.

In specifications 2 and 3, however, NOx was reduced in the high-speed, high-load region (measurement point f). This is because, with the EGR cam timing for closing the valve, the in-cylinder pressure was greater than the exhaust pipe pressure, so that the air-fuel mixture in the cylinder escaped out of the cylinder to the exhaust port. As a result, the reduction in compression pressure caused combustion to deteriorate. Figure 15 shows the in-cylinder pressure, exhaust pipe pressure, and intake manifold pressure at that time. Figure 16 shows $dQ/d\theta$ as derived from the in-cylinder pressure. It is also clear from these graphs that combustion had deteriorated.

It is apparent from these results that specification 1

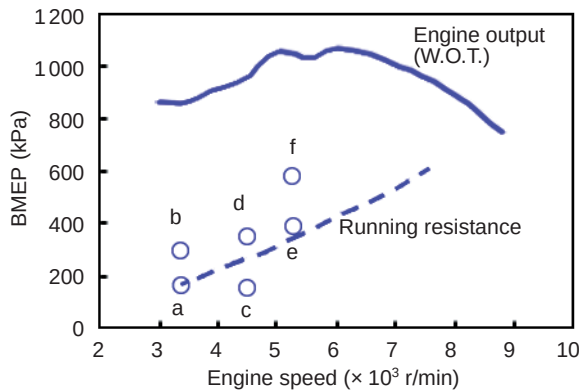


Fig. 13 EGR effect verification points

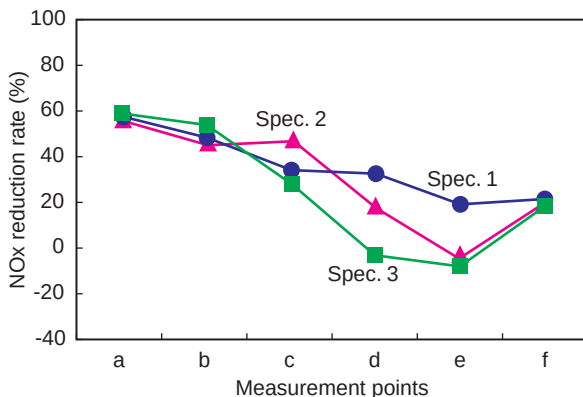


Fig. 14 NOx reduction rate by difference in actuating timings of EGR cam

offers better EGR cam actuating timing for obtaining the NOx reduction effect from low load to high load without causing combustion to deteriorate.

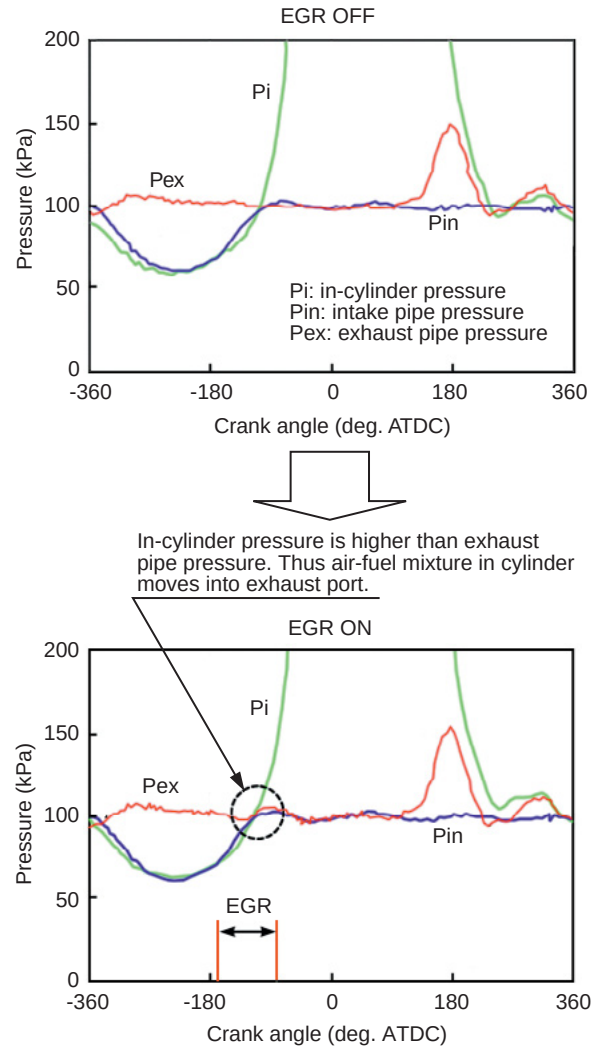


Fig. 15 Pressure applied to each part at measurement point "f" in specification 3

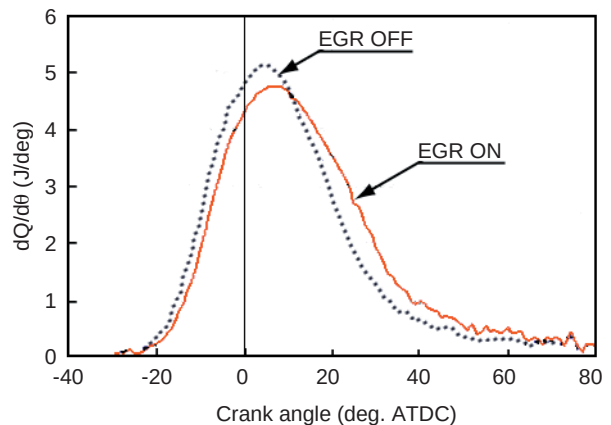


Fig. 16 $dQ/d\theta$ at measurement point "f" in specification 3

4.2. Actuation Lift

Figure 17 shows the exhaust valve lift curves for specifications (A, B, C, and D) in which the EGR cam closing timing was fixed (specification 1 in section 4.1) and the lift height was changed. For each of these specifications, the engine speed and load were also changed and the resulting NOx was measured. The measurement points were those points shown in Fig. 13, and the NOx reduction rate results due to EGR are shown in Fig. 18.

With low lift (specification A), the opening area of the exhaust valve was smaller so that the amount of burnt gas that flowed into the cylinder was smaller. Consequently, the NOx reduction rate was also smaller. On the other hand, with high lift (specification D), the NOx reduction rate became high over all of the measurement points used. This was due to the opening area of the exhaust valve being larger so that the amount of burnt gas that flowed into the cylinder became large. In the low-speed and low-load region (measurement points a and c), however, combustion deteriorated and the amount of HC increased, as shown in Fig. 19, because an excessive amount of burnt gas flowed into the cylinder.

It became clear from the above that the optimum EGR cam specification for the purpose of reducing NOx in the present test engine was specification 1 in terms of EGR cam actuating timing and specification C in terms of lift. It was decided to provide ON/OFF control of EGR cam actuation based on engine speed (N_e) and throttle position (θ_{th}).

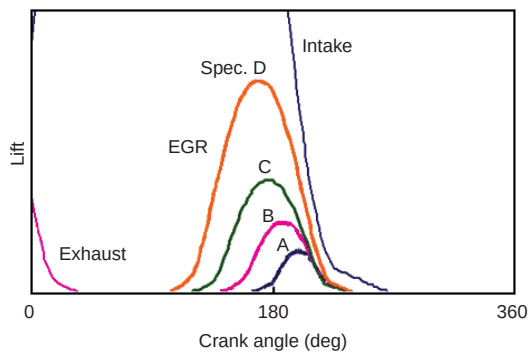


Fig. 17 Exhaust valve lift curves by difference in EGR cam lifts

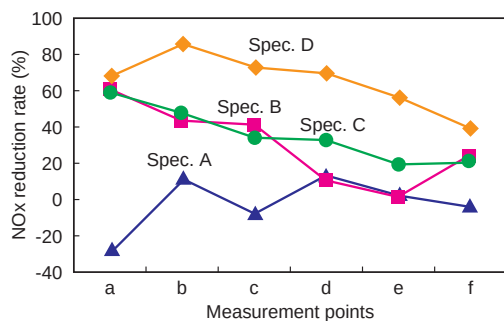


Fig. 18 NOx reduction rate by difference in EGR cam lifts

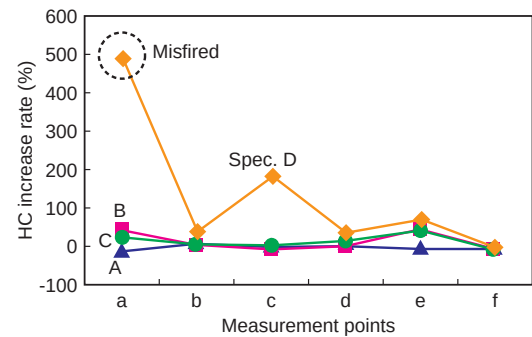


Fig. 19 HC increase rate by difference in EGR cam lifts

5. Exhaust Emission Performance

This system was used to confirm exhaust emissions on a vehicle. Figure 20 shows the test results for driving mode under exhaust emission standards (Euro 3) without the catalyst. It is clear from this graph that NOx and CO are reduced, not only when running at steady speed but also when accelerating and decelerating.

Figure 21 shows the total exhaust emissions in Euro 3 driving mode without the catalyst. As the graph indicates, NOx is reduced by approximately 50% with this

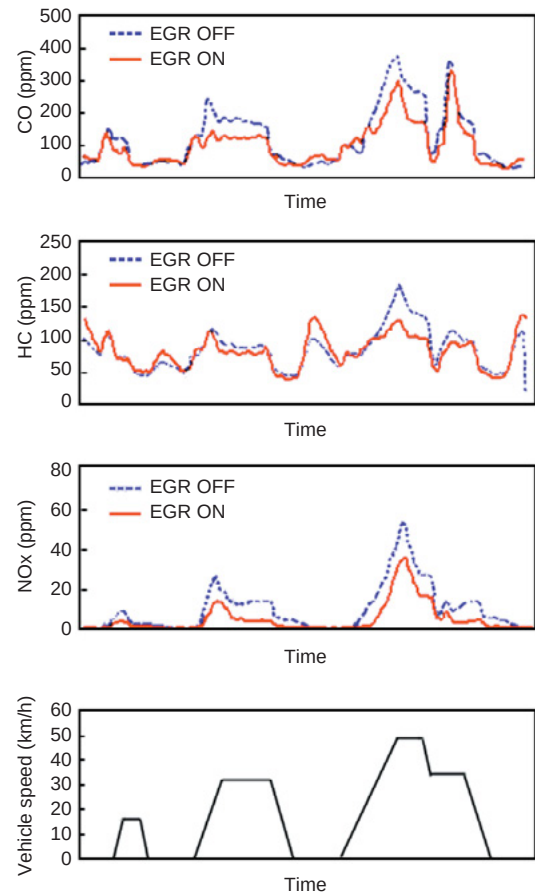


Fig. 20 Time history of exhaust emission in Euro 3 driving mode

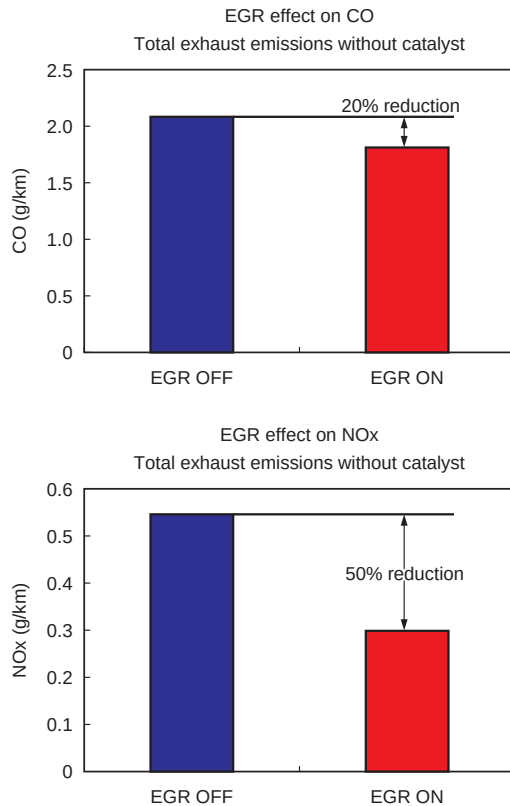


Fig. 21 Exhaust emission reduction effect by developed system in Euro 3 driving mode

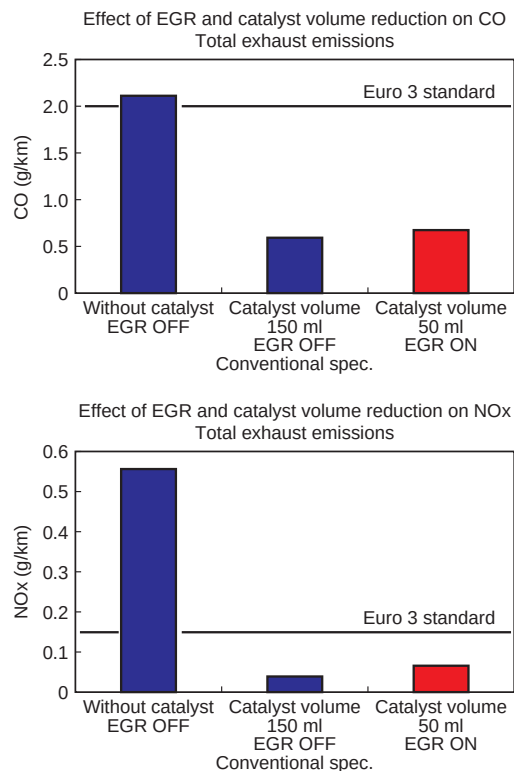


Fig. 22 Catalyst volume reduction effect by developed system in Euro 3 driving mode

system and CO is reduced by approximately 20%. Exhaust emissions were then measured in Euro 3 driving mode with the catalyst volume reduced. Figure 22 shows that the catalyst volume needed to satisfy Euro 3 exhaust emissions standards can be reduced by approximately 70% from the volume that was formerly needed.

6. Conclusion

The internal EGR system that was devised as described here yielded the following findings and results:

- (1) It is preferable to delay actuation by the EGR cam as much as possible so that the valve will open and close when the in-cylinder pressure is negative;
- (2) Exhaust emissions values in Euro 3 driving mode showed that NOx is reduced by approximately 50% and CO is reduced by approximately 20%;
- (3) The significant reduction in NOx enabled the catalyst volume needed to satisfy Euro 3 exhaust emissions standards to be reduced by approximately 70%.

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