Study of Fuel Economy and Exhaust Emission Reduction by Intake Flow Control

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Abstract

With the increasing demand for car engines with higher power and lower fuel consumption, this research was focused on a variable intake flow system as a promising technique that attains both targets. Using computational fluid dynamics (CFD) simulation and testing, the authors investigated the effect of an intake manifold that blocked a certain portion on combustion and fuel consumption. Subsequently, an engine with this system was installed in a car in order to verify the fuel consumption reduction. Regarding exhaust gas, the reduction of hydrocarbon (HC) emission during cold start was addressed, with particular focus on the relationship between after-radiation distribution representing fuel droplets burning up and HC emission. The results showed that the deviation in liquid fuel was relatively large and that considerable HC was emitted when part of the intake manifold was blocked. It was also found that after-radiation and HC decreased when an adequate intake flow prevented fuel droplets from adhering to the wall.

Key words: *Gasoline Engine, Intake System, Combustion*

1. Introduction

In recent years, global warming has become one of the most pressing environmental issues. Ever since the Industrial Revolution, humankind has taken out thermal energy from carbon resources trapped underground to produce motive power, but while emitting carbon dioxide (CO_2) into the atmosphere. In the 100 years following the Industrial Revolution, atmospheric CO_2 concentration has risen dramatically, causing the heat generated by solar radiation during the daytime to be absorbed by CO_2 and other greenhouse gases in the atmosphere. This process is thought to be causing the steady rise in the surface temperature of the earth.

In Japan, the transportation sector accounts for approximately 25 % of total CO_2 emissions in the country, making it the second largest polluter after the civil affairs sector. At the same time, political instability in the Middle East has been delayed the supply of crude oil, and price has risen suddenly. Against this background, car manufacturers have come under increasing pressure to further reduce the fuel consumption of their cars. For example, in Japan the 2015 fuel economy standards require reductions of approximately 30 % from the 2010 levels, and in Europe efforts are being made to introduce legislation that would limit CO_2 emissions from cars to 120 g/km.

In addition to these requirements, car manufacturers are also expected to improve engine power, which is a major part of the “driving pleasure”.

Engine-related efforts are being made to reduce fuel consumption, such as improved combustion by intensified in-cylinder flow, reduced pumping loss by exhaust gas recirculation (EGR) and timing retard of closing the intake valves, and reduced friction with low-tension piston rings and low-viscosity oil.

To achieve intensified in-cylinder flow and power at the same time, valves that control the intake air flow are increasingly being employed. During low-speed, low-load driving, the valves are closed to partially block the intake ports. This deflects the air flow, increasing in-cylinder tumble or swirl and thereby improving combustion and fuel economy. During high-speed, high-load driving, the valves are opened to send full of air into the cylinders (**Fig. 1**).

This paper discusses the valve that controls the flows of intake air (intake flow control valve (IFCV)), focusing on how the location and extent of blocking affect tumble characteristics, fuel consumption, and emissions reduction performance.

2. Specifications of test engine including variable valve train (VVT)

Table 1 shows the specifications of the engine used in the test. The VVT system uses controls a cam phase for the intake and exhaust valves independently.

3. Influence of tumble plate location on tumble ratio in constant flow

At first, in a constant air flow test setup, the valve location was varied to identify any influence on tumble ratio. In the test, a plate was used in place of the IFCV.

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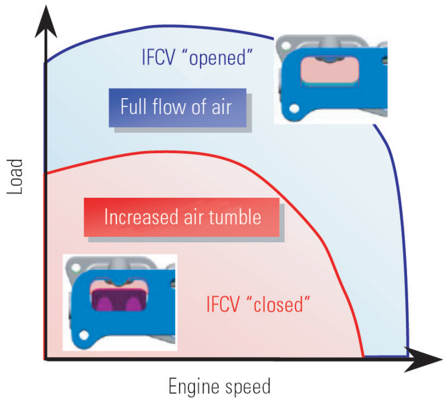

Fig. 1　Example of IFCV operation

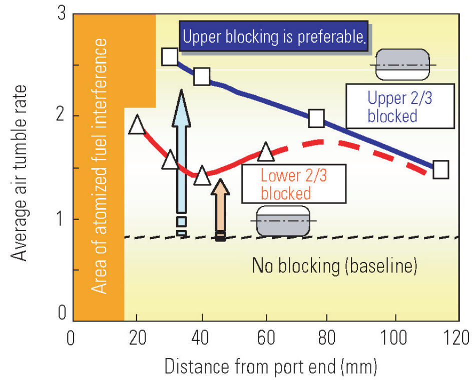

Fig. 2　Tumble plate location and tumble intensity

Table 1　Engine specifications

Fuel injection type / No. of cylinders	Port injection / 4	
Displacement	2.4 L	
Compression ratio	10.5	
Cam type	DOHC	
VVT actuator	Variable phase vane type	
VVT operation angle	Intake	50° CA
	Exhaust	50° CA

Table 3　CFD conditions for constant flow test

Test conditions	Valve lift: 9 mm
Cell type	Rectangular
Boundary layer	3 layers x 0.5 mm
No. of cells	765158 – 906849
Computational conditions	Incompressible constant flow analysis
Difference scheme	MARS (Monotone Advection and Reconstruction Scheme)
Turbulence model	RNG k-ε

Table 2　Specifications of constant flow test

Throat diameter	31 mm
Cylinder used	#2
Liner differential pressure	4.05 kPa

The test conditions are shown in **Table 2** and **Fig. 2**.

With the upper portion blocked, the tumble ratio increased as the tumble plate was moved closer to the cylinder head (C/H). In case of the lower portion blocked, the tumble ratio reached a minimum when the tumble plate was located at 40 mm upstream of C/H and then increased as the plate was moved further towards C/H. To find out the reasons for this, CFD simulation was carried out using STAR-CD by alternating the valve location up and down (**Table 3**). As shown in the left-hand graph in **Fig. 3**, the average tumble ratio relative to the valve location in the CFD simulation resembles the patterns identified in the constant air flow test (**Fig. 2**), with higher ratios achieved in upper blocking and a "dip" existed in lower blocking.

The middle and right-hand images in **Fig. 3** show flow lines in the intake port and cylinder.

With the upper portion blocked, air flow was deflected downward and continued along the nearly-straight bottom surface of the port down to the intake valve. The air flow then passed directly above the valve face towards the ignition plug. This flow pattern intensifies tumble flow.

With the lower portion blocked, air flow was deflected upward and then dispersed by the protruding injector mount. The flow line was thus disturbed and insufficient tumble flow resulted.

Then the injector mount protrusion was removed so that the air flow would not be disturbed. The result is shown in **Fig. 4**. Air flow was no longer dispersed and instead, ran along the upper surface of the port, resulting in strong tumble flow.

The above experiment showed that, irrespective of which side of the port is blocked with the valve, the port surface must have smooth contours at least where air flow is deflected so as not to disturb it.

4. Reduction of fuel consumption with tumble plate

Fuel consumption was evaluated using various blocking locations, extents and resultant intensities of tumble flow, and by varying EGR ratios under partial load (**Fig. 5**). Without EGR, intensification of tumble flow by partial blocking of the intake port hardly affected the fuel consumption. This is because the improvement of combustion recognized by retarded MBT ignition timing is nearly offset by the pumping loss caused by blocking and increased thermal loss from the higher maximum in-cylinder gas temperature due to improved combustion.

In relation with the introduction of EGR, without blocking, the improvement of the fuel consumption ceases at an EGR ratio of just 5 %. In contrast, with blocking, the EGR ratio at the same IMEP fluctuation reaches approx. 25 %, enabling the fuel consumption to

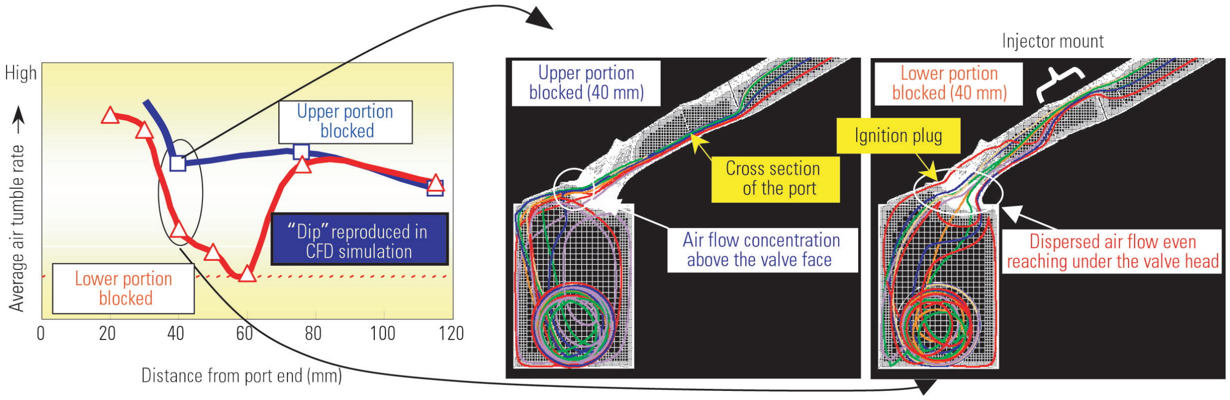

Fig. 3　CFD result of constant flow test

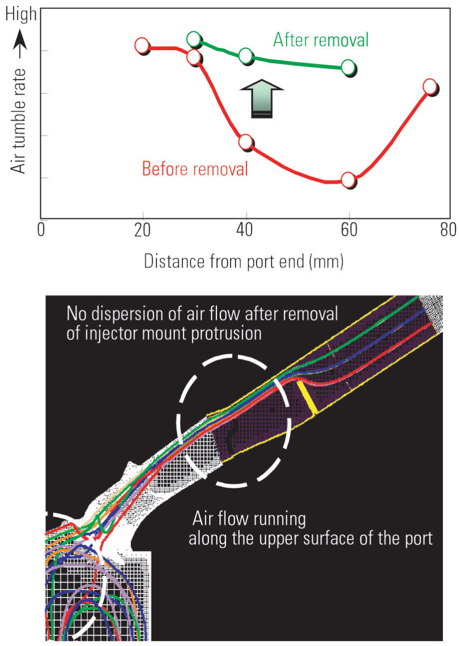

Fig. 4　Effect of modified injector installation area

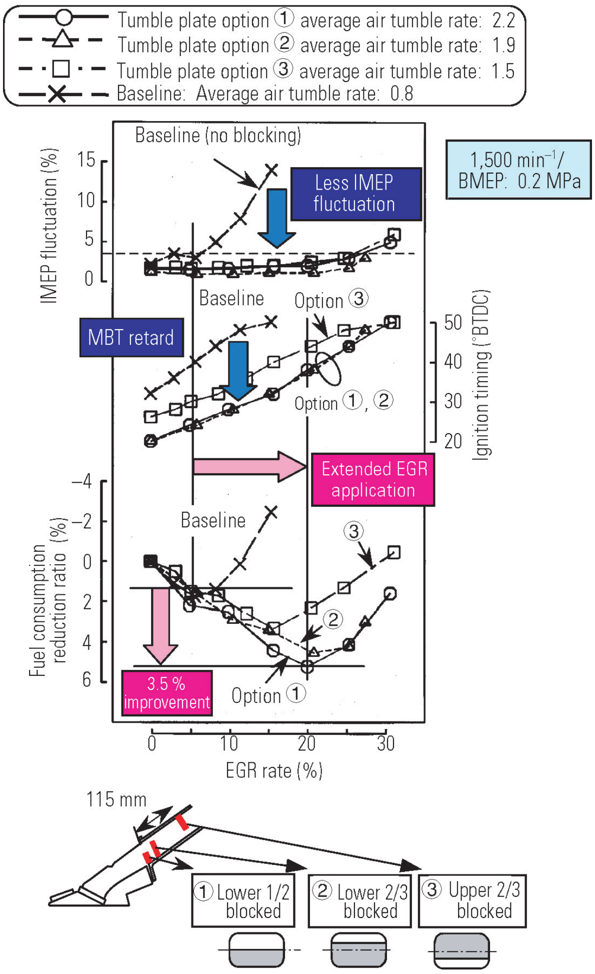

Fig. 5　Fuel consumption reduction by tumble plate

be greatly improved by the large amount of EGR. The greater the tumble ratio, the better the fuel economy. The average tumble ratio of 2.2 reduces fuel consumption by approximately 3.5 %. In addition, the introduction of EGR with tumble intensified improves combustion, which helps prevent excessive advancing of the ignition timing and minimizes the difference in ignition timing from other driving conditions, thus making the engine run more smoothly. This is another benefit of intensified tumble flow.

5. Performance evaluation of intake manifold with IFCV

5.1 Bench testing with constant flow

Bench testing was conducted in a constant air flow using an intake manifold based on the results of the previous testing discussed above. The results, averaged over the four cylinders, are shown in **Fig. 6**.

The average coefficient of air flow with IFCV was 3.8 % lower than that of the standard intake manifold. The average tumble ratio with IFCV was almost 2, this was near the target. **Fig. 7** shows the reduction of fuel consumption by the closed IFCV under partial load.

Combustion was more stable even at high EGR rates with IFCV closed than with IFCV opened. With IFCV closed, MBT ignition timing was more retarded than

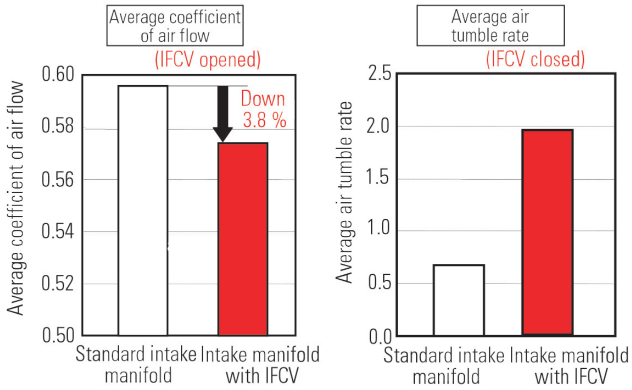

Fig. 6 **Constant flow test results for intake manifold with IFCV**

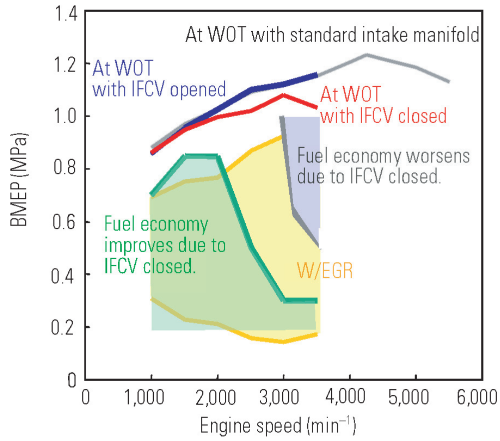

Fig. 8 **IFCV control and region of fuel consumption reduction**

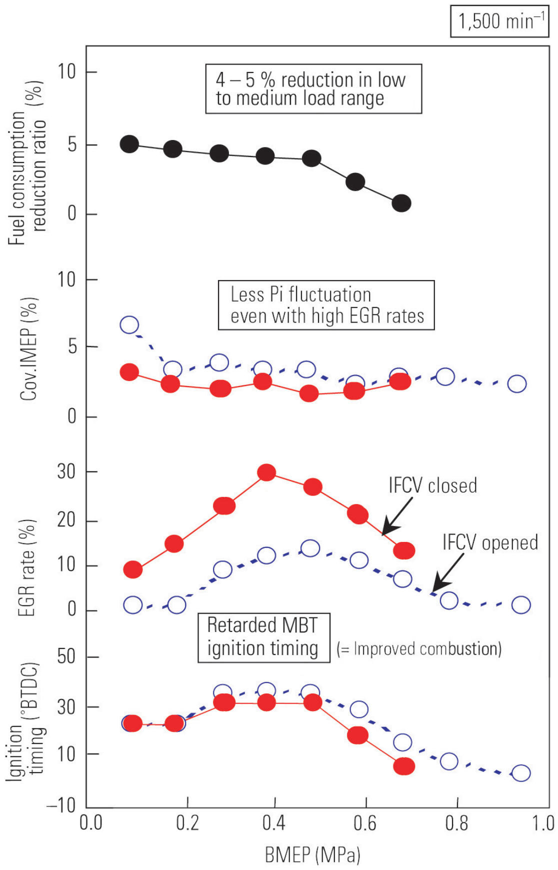

Fig. 7 **Fuel consumption reduction by IFCV**

that with IFCV opened. These facts indicated that the combustion was remarkably improved. A fuel consumption reduction of 4 to 5 % was obtained from the low to medium load range, and this trend continued until BMEP 0.7 MPa.

Fig. 8 shows the IFCV control strategy. As air flow rate increases with IFCV closed, more power is lost during air intake, thus offsetting the improved combustion. However, the operation area of improved fuel economy covers a wide region of practical driving range. The 10·15 and JC08 mode cycles can be driven with IFCV closed.

Table 4 **Fuel consumption reduction ratio in 10·15-mode cycle and JC08 (hot) mode**

10·15	JC08 (HOT)
3.5 %	2.6 %

5.2 Actual vehicle fuel consumption in driving mode cycles

With the IFCV-equipped intake manifold mounted on OUTLANDER of Japanese specifications, fuel consumption was measured in 10·15 and JC08 (HOT) mode driving, with IFCV opened and closed. Fuel consumption reductions of 3.5 % and 2.6 % were confirmed in 10-15 and JC08 (HOT) mode driving cycles respectively (**Table. 4**). The reductions were in part attributable to improved combustion leading to the retardation of MBT ignition timing, on low-speed, low-load operation near the MBT ignition timing range.

Fig. 9 shows fuel consumption reduction ratios and contribution ratios for the 10·15 mode driving cycles. The steady phase is the top contributor to the reduction with 42 %, followed by the acceleration phase with 30 %. The reduction ratio of the steady phase exceeds 5 %, which resembles the results in the bench testing. The reduction rate of the acceleration phase is just above 2 %, which is due to high engine load during the mode driving. The deceleration phase has a significant reduction ratio, which is due to improved combustion enabling the ignition timing to be set near MBT.

6. Reduction of HC at cold start

The startability of the engine using low volatility fuel can be improved by closing IFCV (**Fig. 10**).

This is because the intake air flow after the first combustion is accelerated by closing IFCV, improving the transport efficiency of fuel injected into the intake port. Based on this, with closed IFCV, the same level of startability as that with opened IFCV can be obtained using less fuel. Then, using a test unit of which fuel control is

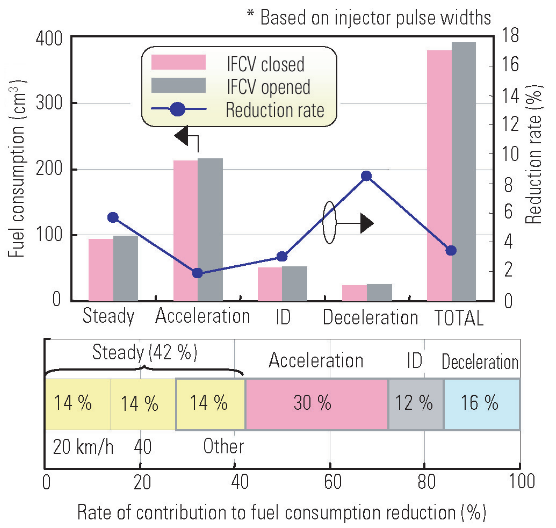

Fig. 9 **Fuel consumption reduction ratio in 10·15-mode cycle and contribution ratio of each driving mode**

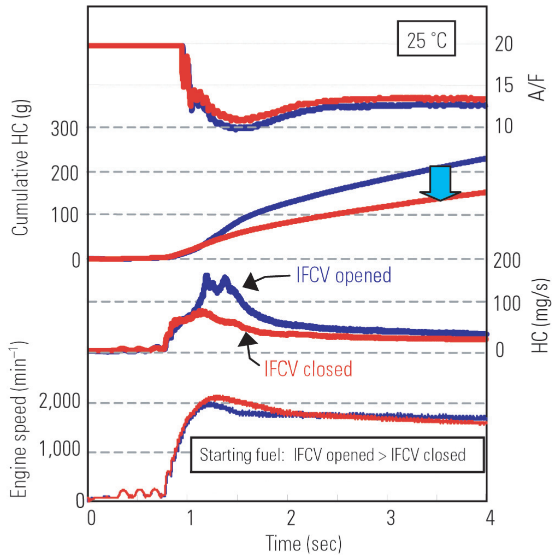

Fig. 11 **HC reduction during cold start (with the same startability as that using low-volatility fuel)**

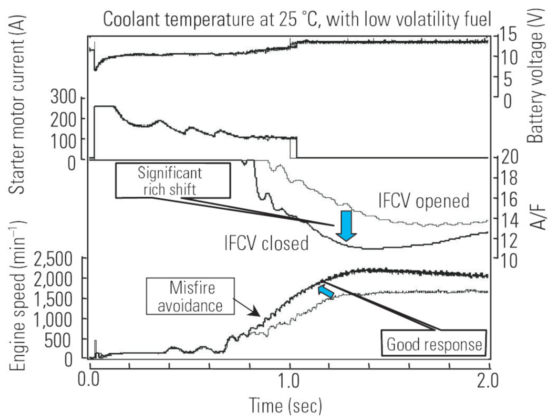

Fig. 10 **Effect of IFCV on cold startability with low-volatility fuel**

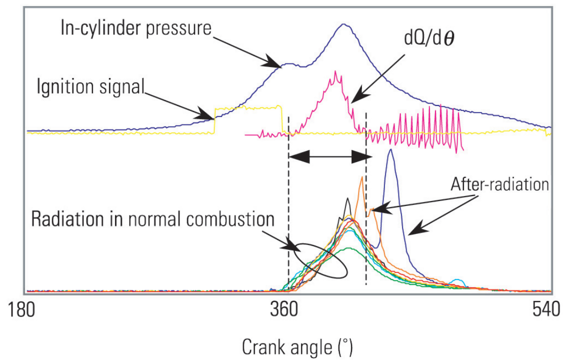

Fig. 12 **Definition of after-radiation**

set to assure the startability having an acceptable start feel under the condition with low volatile fuel and with IFCV closed, HC at engine start was measured using standard fuel. The results are shown in **Fig. 11**. There is less HC emission with closed IFCV than with opened IFCV.

7. Distribution of in-cylinder fuel droplets and HC emission at engine start with closed IFCV

To find out whether it would be possible to further reduce HC emission with closed IFCV, we attempted to indirectly analyze the distribution of fuel droplets in the cylinder. For this, a Visio knock of AVL, a combustion radiation measuring device, was used[1]. The device's 8-direction sensing unit was installed onto the spark plug to observe combustion radiation in radial directions during engine start.

In normal combustion, the profile of signals from the combustion radiation sensor resembles that of heat release rates ($dQ/d\theta$). In cold starting, however, signal spikes may be observed after heat release. This is assumed to be due to radiation that is generated when fuel droplets, after entering the cylinder, come into contact with flames and burn. With this, the ratio of the height of signals in normal combustion to that of spikes was defined as the intensity of after-radiation[2]. Then, assuming that the distribution of fuel droplets in the cylinder can be determined by observing the orientation of after-radiation intensity, the following experiments were carried out (**Fig. 12**). HC emission from the cylinder to which the Visio knock sensing unit was installed was measured using a high-speed HC meter.

Fig. 13 shows the intensities of after-radiation, measured with the IFCV opened and closed, and with the center of the port blocked. **Fig. 14** shows HC measurements with a high-speed meter.

With the IFCV closed, the intensity of after-radiation was stronger and concentrated on the intake side. With equal amounts of fuel injected, HC emission was

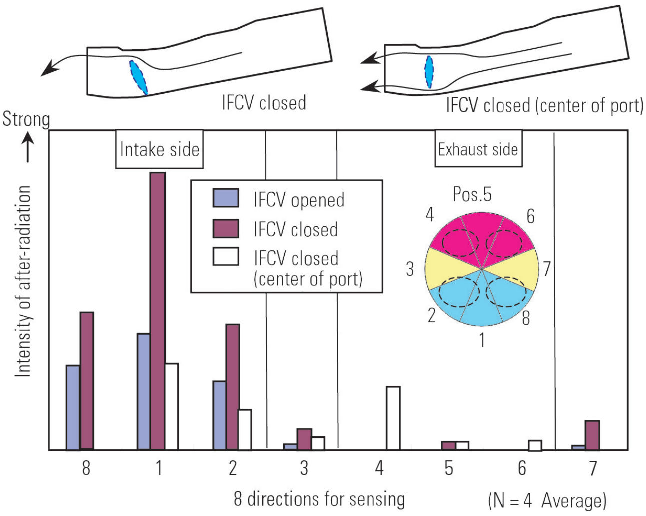

Fig. 13 Intensity of after-radiation

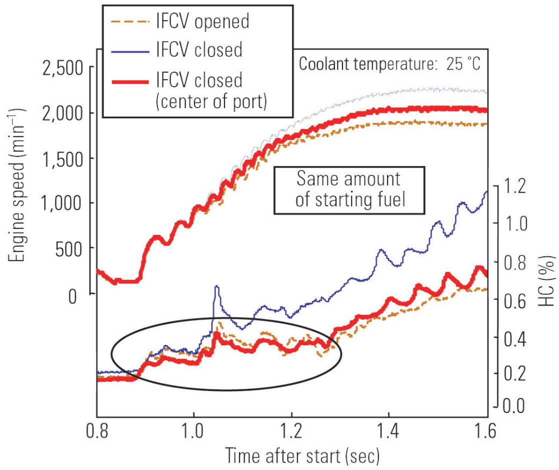

Fig. 14 Relationship between HC emissions and IFCV position

greater with closed IFCV than with opened IFCV. With the IFCV opened, the intensity of after-radiation was less strong and was more evenly distributed. Also, HC emission was less than IFCV closed test. It is thus considered that HC emission is greater with the IFCV closed because the air flow speed on the opposite side of the deflected intake air flow slows down, allowing more fuel to enter the cylinder as droplets.

With the center of the intake port blocked, both the intensity of after-radiation and HC emission were less severe. It is considered that the center blocking generated the rapid air flow near both the upper and lower portions of the intake port wall, which prevented fuel droplets from adhering on the lower surface of the port as happened with closed IFCV.

This suggests that HC could be reduced further by better controlling the intake air flow.

8. Summary

(1) Using IFCV, which partly blocks the intake manifold, intake air was controlled to intensify tumble flow, thereby enabling high EGR rates. This reduced fuel consumption by 3.5 % in the 10·15 mode driving cycle and 2.6 % in the JC08 (HOT) driving cycle.

(2) The IFCV system improved startability with low volatility fuel. Furthermore, the system also reduced HC emission at engine start with standard fuel.

(3) The relationship between intake air control at engine start and HC emission was analyzed by measuring combustion radiation. Where there is air flow in the cylinder that has been slowed down by intake air control, after radiation is seen, which suggests adherence of fuel droplets. This indicates that HC emission could be further reduced by better blocking the intake manifold.

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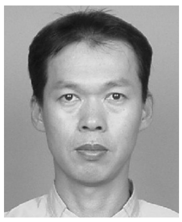
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