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The Performances of a Diesel Engine with the Application of a Unique EGR System

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In this paper, a Two Stage Combustion EGR (TSCE) system which was effective in improving the cold starting characteristics was adopted to achieve NO_x reduction. By this system the mass emissions of NO and unburned hydrocarbon was cut to half without the sacrifice in fuel economy.

To reduce the smoke density when TSCE was running, the compression ratio of the second stage cylinder was reduced. With this pressure reduction it is possible to use the TSCE system up to a load of 0.3 MPa BMEP, without negative effects.

Key Words: Combustion, Internal Combustion Engine, Power, Automobile, Diesel Engine, Exhaust, EGR, BMEP

1. Introduction

The previously reported TSCE system, a unique EGR system in diesel engines, showed remarkable reductions in unburned hydrocarbons and exhaust odor at cold starting because an increase in intake gas temperature is promoted just after starting.

This also gives the reduction in NO_x emissions as obtained with the standard EGR system, because only half the cylinders operate with normal combustion and the other half of the cylinders are charged with the exhaust gas of the other cylinders.

In a direct injection diesel engine using this system, NO and unburned hydrocarbon mass emissions were reduced to half the amount produced by a standard engine. Since the smoke level increases with an increased load, the available load range is restricted to about 0.2 MPa BMEP when the smoke limit is 3 (Bosch number). Such an increase in smoke level came from the high intake gas temperature or insufficient oxygen in the second stage cylinders. An improvement in the smoke level was attempted by lowering the compression ratio in the second stage cylinders. This reduced the smoke level sharply and the available range of the BMEP in the TSCE system could be increased to 0.3 MPa.

Moreover, the operation method of the control valves of the TSCE system attached to the intake and exhaust lines was changed to decrease the intake gas temperature and

increase the oxygen in the second stage cylinders. However the reduction in smoke level was insignificant.

2. Experimental Apparatus and Methods

Table 1 shows the specifications of the tested engine and Fig. 1 is a schematic drawing of the experimental apparatus.

A strain gauge type pressure indicator was adopted on cylinder No. 4 and used considering the combustion process under various conditions. The injection timing was

Table 1 Engine specifications

No. of cyl.	4
Bore X Stroke (mm)	102 X 110
Swept volume (l)	3.6
Comp. ratio	17.5
Injection press. (MPa)	18.5
Nozzle hole	4 X 0.32 ^φ

Fig. 1 Schematic drawing of the experimental apparatus

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measured by a needle valve lift of the injection nozzle picked up by an electromagnetic displacement meter. The crank marks for each angle were detected by a photo transistor and a slit disk.

These data were recorded once on a data recorder and an average pressure diagram was selected from the diagrams monitored on a synchroscope. This average diagram was converted to digital values corresponding to each crank angle through an A-D converter.

Exhaust emissions were measured by NDIR for NO, FID for unburned hydrocarbon, and a Bosch type smoke meter for smoke density.

The operation of the TSCE system is as follows. When the firing order of the engine is 1-3-4-2, the exhaust gas of cylinders No. 2 and 3 is stopped by the valve A as shown in Fig. 1 and conveyed to the intake port of cylinders No. 4 and 1 where the next charge is stopped by the valve C. Since the exhaust strokes of cylinders No. 2 and 3 and the suction strokes of cylinders No. 4 and 1 overlap each other about 180° crank angle as shown in Fig. 2, the pumping loss at the suction and exhaust strokes is reduced by this system.

Fig. 2 Overlap between the intake and the exhaust of each cylinder with the TSCE system

In the TSCE system, cylinders No. 2 and 3 operate normally and cylinders No. 1 and 4 which are charged with the exhaust gas of cylinders No. 2 and 3 operate as in an engine with an EGR system.

The compression ratio of the second stage cylinders was lowered to improve the smoke level. The pistons were modified as shown in Fig. 3, that is, the compression ratio was varied only by an exchange of piston crowns. Therefore, the configuration of the combustion chamber is slightly changed.

Fig. 3 The piston to change the compression ratio

3. Experimental Results and Considerations

3.1. Engine performances at the standard compression ratio

3.1.1. Engine performances under the application of the TSCE system

Fig. 4 shows a comparison of engine performances of the TSCE engine with those of the standard engine. As described about the operation of the TSCE, only cylinders No. 1 and 4 emit exhaust gas directly into the atmosphere and the mass emission from the TSCE system is about half that of the standard engine.

Fig. 4 The engine performances in the TSCE system

As shown in the figure, the NO mass emission from the TSCE system is only 50 % lower than that of the standard engine at tested load. That is, NO concentration emitted from cylinders No. 1 and 4 is almost equal to that from an engine without the TSCE system. From this, it appears that the NO reduction by the TSCE system is based on the mass reduction of exhaust gas. Although the oxygen concentration in cylinders No. 1 and 4 in the TSCE system becomes lower with an increase in load like a standard EGR engine, the NO reduction in the TSCE system does not correspond to the decrease in the oxygen concentration like that in the standard EGR engine. The reason is as follows. The NO concentration in the intake charge for cylinders No. 1 and 4 becomes higher with a higher load because these cylinders are charged with the exhaust gas from cylinders No. 2 and 3. On the other hand, only

about 50 % of the NO in the intake charge is decomposed in the combustion chamber. Thus, even when the oxygen concentration in the intake charge becomes lower in the TSCE system, the NO concentration is not reduced like in the standard EGR engine.

The smoke density in the TSCE system increases with an increase of load and its increase is steeper than that in the standard EGR engine. For this reason, the TSCE system cannot be used at more than 0.2 MPa BMEP when the smoke density is restricted to about 3 (Bosch number). Such an increase in smoke is mainly caused by a decrease in the excess air factor. Moreover, the increase in smoke density is influenced by the diffusion combustion period, that is, when the intake charge temperature in cylinders No. 1 and 4 became higher, the ignition lag became shorter and the diffusion combustion period that produced the smoke became longer.

The difference in fuel consumption between the TSCE system and the standard engine is negligibly small. The fuel consumption in diesel engines usually becomes higher with an increase in smoke density, but in the TSCE system half of the cylinders operate under normal combustion and the valve overlap between the exhaust strokes of cylinders No. 2 and 3 and the suction strokes of cylinders No. 4 and 1 is large. Therefore the energy of the exhaust gas in cylinders No. 2 and 3 offsets the pumping loss of the suction strokes of cylinders No. 4 and 1. Thus, the thermal efficiency does not drop, though nevertheless the smoke density is increased with the application of the TSCE system.

3.1.2. Effect of injection timing on the engine performances in the TSCE system

Fig. 5 compares the influence of injection timing on the engine performance between the TSCE engine and the standard engine.

In this figure, the NO mass emission in the TSCE system is 50 % lower than that in the standard engine at all injection timings. In the TSCE system the increase of unburned hydrocarbon under an advanced injection timing is larger than that in the standard engine, for 0.3 MPa BMEP. Though the advanced injection timing is effective for the reduction of smoke density, it is limited by the increase in unburned hydrocarbons.

Fig. 6 shows the ignition lag and the rate of pressure rise measured from the combustion pressure diagram. As shown in this figure, the ignition lag in the TSCE system is 2° to 3° crank angle shorter than that in the standard engine. However, the optimum injection timing for both engines is almost equal to 15° BTDC.

As shown in Fig. 6, the rate of pressure rise in the TSCE system is lower than that in the standard engine. Moreover, the rate of pressure rise in the standard engine increases with an increase of load, but that of the TSCE system is almost constant at the tested load conditions. Therefore, when the TSCE system is applied to a four-cylinder engine, a lower rate of pressure rise, that is, more quiet combustion can be expected in

Fig. 5 The relation between the injection timing and the engine performances in the TSCE system

Fig. 6 The ignition lag and the rate of pressure rise with the TSCE system

half of the cylinders.

3.1.3. Comparison of exhaust emissions between the TSCE and the standard EGR system

Fig. 7 shows a comparison of exhaust emissions between the standard EGR engine

Fig. 7 Comparison between the TSCE system and the standard EGR system

and the TSCE system.

As shown in this figure, since the rate of NO reduction in the TSCE system is about 50 %, the EGR rate in the standard EGR engine which indicates the same NO reduction as that in the TSCE is about 40 % at 0.1 MPa BMEP and about 20 % at 0.3 MPa.

The smoke density in the standard EGR engine when the reduction rate of NO emission is about 50 % shows only a slight increase compared with the standard engine without EGR even under 0.3 MPa BMEP. Therefore, the smoke level in the TSCE system is inferior to that of the standard EGR engine, and improvements in the smoke level are necessary.

Fig. 8 compares the combustion pressure diagram for a standard EGR system with that for the TSCE system at the condition of similar NO emissions. A characteristic feature of the TSCE system is that the ignition lag is shorter and the combustion temperature at high loads is lower than those of the standard EGR system. This feature leads to an increase in smoke level because the diffusion combustion period which mainly controls the smoke level is longer and the reburning of the smoke is not sufficiently promoted

Fig. 8 Differences in combustion pressure diagrams between the TSCE system and the standard EGR system

because of low combustion temperature.

3.2. The engine performances at the low compression ratio

3.2.1. The reduction in smoke level at low compression ratio

When the TSCE system at the standard compression ratio is used, the available load range is limited to about 0.2 MPa BMEP by the increase in smoke density. To improve this disadvantage, we tried to reduce the compression temperature by lowering the compression ratio of cylinders No. 1 and 4 in the second stage of the TSCE system from 17.5 to 16.

Fig. 9 shows the engine performances at these compression ratios.

As shown in this figure, even at the low compression ratio the smoke level increases when the TSCE system is used. However, the smoke level at the low compression ratio of the TSCE system was remarkably lower than that of the TSCE system with the standard compression ratio at 0.3 MPa BMEP. That is, the smoke level decreases from 6.5 (Bosch number) at the standard compression ratio to 3.5 at the low compression ratio.

Since the fuel consumption of the TSCE engine is nearly equal to that of the standard engine and NO and unburned hydrocarbon emissions are half of those of the standard engine, the merits of the TSCE system are retained even at the low compression ratio.

As a result of this, at the lower compression ratio in the second stage cylinders the effective load range of the TSCE system can be expanded to 0.3 MPa BMEP.

In passenger cars, 0.3 MPa BMEP

Fig. 9 The engine performance at the low compression ratio in half the cylinders

corresponds to a constant speed of about 80 km/h, and so, the TSCE system reduces the toxic exhaust gas without any sacrifice in fuel economy from cold start to warming up and at normal car speed.

Fig. 10 is a pressure indicator diagram which compares the influence of a lowered compression ratio between the TSCE system and the standard engine under 0.1 MPa BMEP. As shown in Fig. 10(a) which is a pressure diagram for the standard engine, the cylinder gas temperature just before ignition at the low compression ratio is 50 to 70 °C lower than at the standard compression ratio. This tendency is the same as in Fig. 10(b) for the TSCE system. Moreover, at the low compression ratio in the TSCE system, the combustion temperature of the expansion stroke becomes high. That is, since the compression temperature drops at the low compression ratio and the ignition lag increases, the pre-mixture combustion rate increases and the combustion temperature in the expansion stroke increases. Thus the reduction of smoke density is realized.

3.2.2. Startability at the low compression ratio

In this experiment, the application of the low compression ratio in half the cylinders was expected to prevent a deterioration of cold startability. When the first

Fig. 10 The combustion pressure diagram at the low compression in half the cylinders

stage cylinders which have the ordinary compression ratio reach the firing condition, the second stage cylinders which are charged with the exhaust gas of the first stage cylinders can operate even at the low compression ratio.

To confirm this, we attempted a comparison of the startability between the standard engine and the TSCE one at the low compression ratio in cylinders No. 1 and 4. The startability was evaluated by the changes in the battery voltage at the engine starting. Since the battery voltage increases when firing starts, the combustion state can be judged by the level of battery voltage.

Fig. 11 shows the test results. In the

Fig. 11 A comparison of the battery voltages at starting

TSCE system, the initial firing occurred just after starting, but, eighteen seconds are needed for complete combustion. In the standard engine, the first complete combustion is established early, but the engine stalls just after the throttle return. Therefore, the complete combustion requires 26 seconds when re-starting is included. Even when the compression ratio is low, the startability advantage of the TSCE system is maintained.

3.3. The relationship between the exhaust smoke and the valve operation in the TSCE system

In the TSCE system, the increase in smoke level may come from high intake gas temperatures or lack of oxygen in cylinders No. 1 and 4.

One cause of this was assumed to be that the volumetric efficiency of cylinders No. 2 and 3 which operate under normal conditions dropped with the use of the TSCE system.

Fig. 12 shows the test results about the volumetric efficiency. As shown in this figure, the volumetric efficiency of cylinders No. 2 and 3 did not drop with the use of the TSCE system.

Fig. 12 The volumetric efficiency of the first stage cylinders in the TSCE system

The intake gas temperature of cylinders No. 1 and 4 in the TSCE system is about 120 °C higher at 0.1 MPa BMEP and 170 °C higher at 0.3 MPa than that in standard engine.

To prevent an increase in intake gas temperature and lack of oxygen, we tried to change the operation of the valves adopted to realize the TSCE system.

Fig. 13 shows the control methods of the valves and Fig. 14 indicates the engine performances. In Fig. 13, the type I is the

Type Valve	I	II	III	IV
A	Close	Close	Open	Open
B		Open		
C	Close	Open	Open	Close

Fig. 13 The changes in the operation of the valves adopted for the TSCE system

Fig. 14 The engine performance in the changed operation of the valves which were adopted for the TSCE system

standard TSCE system, and the type II is the TSCE system operated with B and C valves open. In the type II, the exhaust gas of cylinders No. 2 and 3 is emitted into the atmosphere through the intake pipes of cylinders No. 1 and 4 and the oxygen in cylinders No. 1 and 4 decreases. Thus, the smoke density of this type increases as compared with the standard TSCE system. This tendency is the same as in the type IV which has the A and B valves open.

The smoke density in the type III which has the A and C valves open decreases slightly, because a part of the exhaust gas from cylinders No. 2 and 3 is emitted into the atmosphere through these exhaust pipes and cylinders No. 1 and 4 are charged with fresh air of about 10 % of the cylinder volume compensating for the exhaust gas volume which is emitted into the atmosphere. In this type, NO and unburned hydrocarbon are as much reduced as in the standard TSCE system.

4. Conclusions

We could obtain the following results through the experiments aimed at an overall improvement of exhaust emissions under application at the road load condition of the TSCE system which has been effective to improve the cold startability.

(1) When the TSCE system is applied to a standard compression engine, the available load condition is limited to about 0.2 MPa BMEP for smoke levels below Bosch No. 3. On the other hand, NO and unburned hydrocarbon mass emissions are reduced to half without any sacrifice of fuel efficiency.

(2) The load range of the TSCE system at the low compression ratio is extended to about 0.3 MPa BMEP because the ignition lag becomes longer and the part of pre-mixture combustion increases. Therefore the reduction in smoke density is possible.

The load of 0.3 MPa BMEP corresponds to a constant speed of 80 km/h in a passenger car. Thus the TSCE system can halve the levels of NO and unburned hydrocarbons without any sacrifice in the fuel efficiency in this load range.

(3) The rate of pressure rise of the second stage cylinders in the TSCE system does not increase even at high loads. Moreover, the rate of pressure rise in the TSCE system is lower than that of the standard engine, and silent combustion may be expected.

(4) When the control methods of the valves which are adopted in the intake and exhaust lines for operation of the TSCE system are changed, the smoke density can be slightly reduced due to an increase in oxygen and a drop in intake gas temperature.

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