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The Characteristics of Fuel Consumption And Exhaust Emissions of the Side Exhaust Port Rotary Engine

Ritsuharu Shimizu, Haruo Okimoto, Seijo Tashima, and Suguru Fuse
Mazda Motor Corp.

ABSTRACT

Mazda has been pursuing the research of side exhaust porting for its rotary engine in an effort to improve the engine's fuel efficiency and exhaust emissions characteristics. The side exhaust porting configuration provides greater flexibility in setting port timing and shape, as compared to the peripheral exhaust porting configuration, which is in use in the current-generation rotary engines; the side exhaust porting configuration enables the selection of a port timing more favourable to reduced fuel consumption and exhaust emissions.

The side exhaust port rotary engine used in this research has its exhaust port closure timing around the top dead centre (TDC) and has no intake – exhaust timing overlap. As a result, burnt gasses entering the next cycle of combustion are reduced, this enhancing combustion stability; also, the air-fuel ratio can be set leaner for improved fuel consumption. In addition, since the trailing-side end of the combustion chamber does not open to the exhaust port. HC exhaust emissions are reduced.

INTRODUCTION

Mazda has long been striving to improve the fuel efficiency and exhaust emissions of the rotary engine (hereinafter referred to as RE). Using the thermal reactor system in the 1970's, and a catalyst-based emissions control system, a fuel injection system, and a six-port induction system after 1981, fuel consumption and exhaust emissions have been significantly improved. In view of the need to conserve resources and to protect the global environment, however, we are now facing social requirements for even more stringent fuel consumption and exhaust emission levels. To reach these goals, there is a great need to improve fundamental engine components, as well as to further develop conventional technologies.

As part of Mazda's effort to improve fuel efficiency and exhaust emissions, we are currently engaged in research on the side exhaust port RE. The side exhaust porting configuration, as compared to the peripheral exhaust porting configuration, provides much greater design flexibility, and enables the setting of port timing and shape in ways that are advantageous to reducing fuel consumption and exhaust emissions. This paper presents results from research on the RE with side exhaust porting configuration, and discusses the basic characteristics of the side exhaust port RE with respect to fuel consumption and exhaust emissions.

FUEL CONSUMPTION AND EXHAUST EMISSIONS CHARACTERISTICS OF THE CURRENT RE

The automotive gasoline RE has, since it was first put into practical use, primarily had a side intake porting and peripheral exhaust porting configurations, with the intent of providing combustion stability. In this research we, therefore, first studied the fuel consumption and exhaust emissions characteristics of this type of an intake/exhaust system.

1. FUEL CONSUMPTION CHARACTERISTICS

THERMAL DISTRIBUTION – Although the current combination of side intake port and peripheral exhaust port ensures overall combustion stability, however, in order to enhance combustion stability under low-speed and light-load conditions, the configuration relies on having a zone that is richer than stoichiometric. Improved thermal efficiency of the RE, on the other hand, dictates having improved

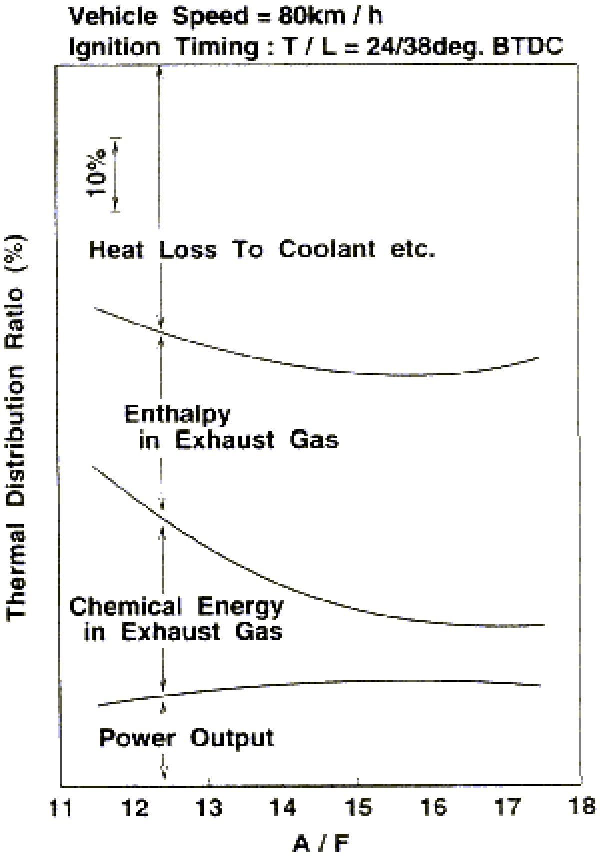

Fig. 1 Thermal Distribution of the Mazda RE

Table 1 Major Specifications of the Tested Engine

Type	**2-Rotor in line**
Displacement (cc)	654 x 2-Rotor
Eccentricity x Generating Radius x Width (mm)	15 x 105 x 80
Compression Ratio	9.7
Combustion Chamber Shape	MDR
Intake Porting	Side Porting
Intake Open / Intake Closed	Pry:32^0 ATDC/40^0 ABDC Sry:32^0 ATDC/30^0 ABDC Aux:45^0 ATDC/80^0 ABDC
Exhaust Porting	Peripheral Porting
Exhaust Open / Exhaust Closed	75^0 BBDC/48^0 ATDC
Fuel Supply System	Electronically Controlled Fuel Injection

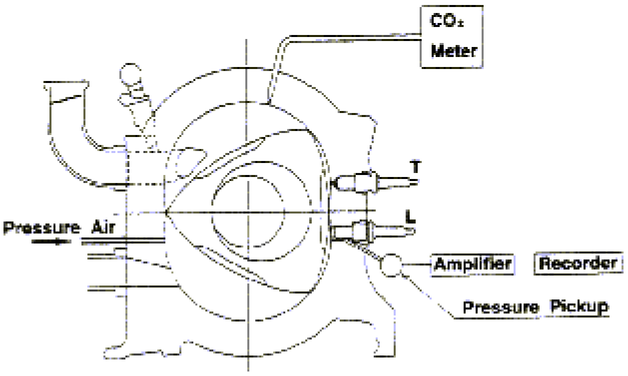

Fig. 2 Test Equipment

combustion stability at the stoichiometric air-fuel ratio.

Figure 1 illustrates an example of the thermal distribution of the Mazda RE. In the over-rich mixture zone, the amount of energy lost as chemical energy of unburned ingredients, such as HC and CO, increases considerably with a resultant significant decrease in thermal efficiency.

IMPROVEMENT IN COMBUSTION STABILITY THROUGH DECREASED INTERNAL EGR RATIO.

To enhance combustion stability, we have investigated several areas including, the optimisation of rotor recess configuration, reduction of the carryover of exhaust has to the intake side (hereinafter referred to as internal Exhaust Gas Recirculation (EGR)) with secondary air, optimisation of intake and exhaust port timings, atomisation of fuel, and enhancement of ignition capability. In this research we focussed on internal EGR, which has a particularly significant effect on combustion instability.

The internal EGR ratio may be defined by the following equation:

Internal EGR Ratio
= (Concentration of CO_2 in the Mixture)
/ (Concentration of CO_2 in the Exhaust Gas)

In order to develop techniques for enhancing combustion stability, we studied the relationship between the internal EGR ration and combustion stability.

Tested Engine and Test Equipment – Table 1 shows the major specification of the tested engine, and Figure 2 illustrates the test equipment. The engine is basically a naturally-aspirated Mazda 13B-type RE. To reduce the internal EGR ratio, pressurised air is supplied into combustion chamber from the intake/exhaust side of the minor axis of the rotor housing. The pressure in the combustion chamber is measured in order to evaluate the combustion stability. The measurement is conducted using a pressure transducer installed on the leading side (hereinafter referred to as L-side) of the ignition plug. The mixture used to measure CO_2 concentrations inside the combustion chamber is taken out of a small hole on the sliding surface of the rotor housing at a point situated between the location where the pressurised air port closes and where the mixture ignites.

Test Results – Shown in Figure 3 is the relationship between CO_2 concentration in the mixture (an alternative parameter for determining internal EGR ratio) and combustion pressure fluctuation. The combustion pressure fluctuation is represented by the standard deviation of the ratio of the pressure variation to the mean value of the maximum combustion becomes stable with decreased internal EGR.

Figure 4 shows CO_2 concentrations in the mixture at idle speed (720 rpm) and fuel consumption at the lean limit. Fuel consumption at the lean limit is defined as the minimum fuel consumed without the generation of any misfire. As internal EGR decreases, the lean limit at idle speed improves, with a resultant reduction in fuel consumption. Probably causes for increased internal EGR under low-speed and light-load conditions include: (a) burned gasses trapped at the exhaust port closing, (b) exhaust has carried over during the intake-exhaust overlap, and (c) other factors, such as blow-by gas. With respect to factor (b), a study has been conducted with different degrees of intake-exhaust overlap through the manipulation of intake-port open timing, and it was reported that internal EGR decreased as the overlap decreased, with a considerable resultant improvement in mixture ignitability.

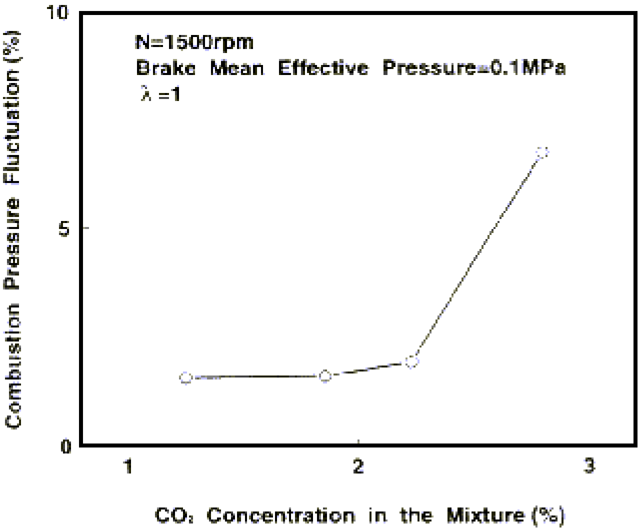

Fig. 3 Relationship Between CO_2 Concentration in the Mixture and Combustion Pressure Fluctuation.

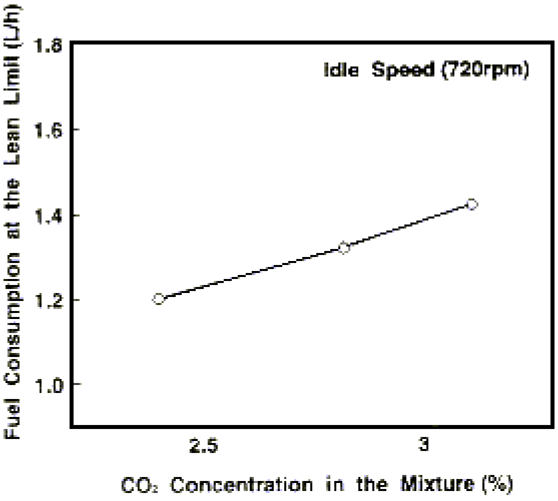

Fig. 4 CO_2 Concentration in the Mixture and Fuel Consumption at the Lean Limit

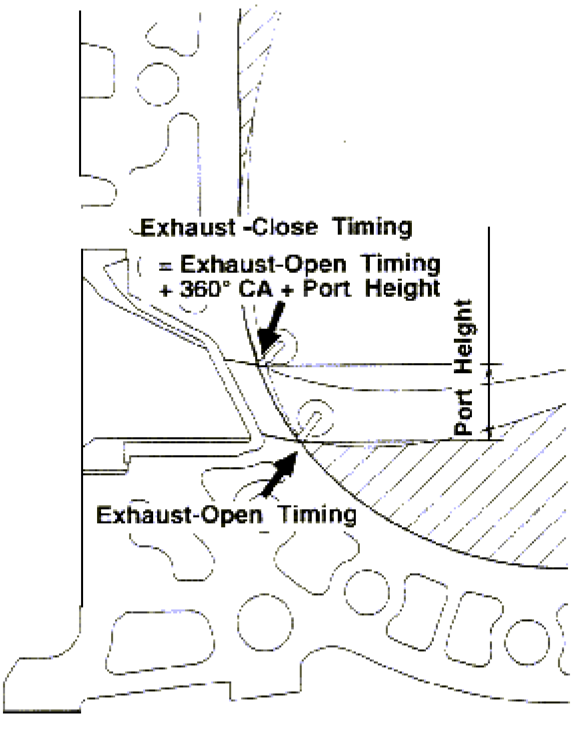

Fig. 5 Geometric Relation Between Exhaust Open and Closure Timings of the Peripheral Exhaust Port RE

As for factor (a), which is considered to be the most significant contributor to increased internal EGR, because the combustion chamber volume is minimised when the exhaust port is closed at TDC, internal EGR ratio can be reduced by setting exhaust closure timing in the vicinity of TDC. On the peripheral exhaust port RE however, it is difficult to advance exhaust closure timing because thermal efficiency factors determine, to a large extent, exhaust open timing, which, in turn, determines the exhaust closing timing by the geometric relation between exhaust open and close timings (Figure 5). If the exhaust open timing exceeds 90 degrees before the bottom dead centre. Although this may reduce internal EGR, it will also reduce thermal efficiency.

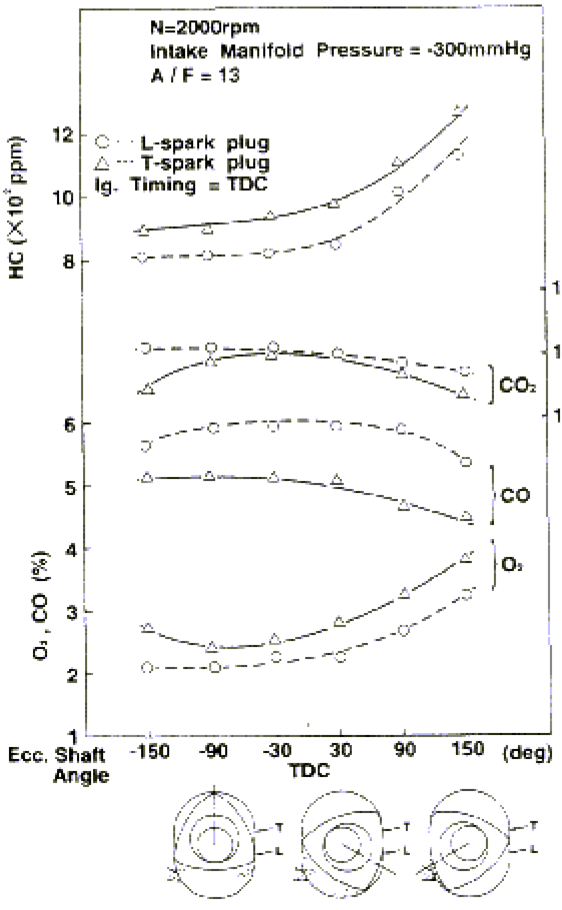

Fig. 6 Concentration of Exhaust Composition at Different Rotor Angles

2. EXHAUST EMISSIONS CHARACTERISTICS

EXHAUST GAS COMPOSITIONAL DISTRIBUTION OF THE CURRENT RE – Exhaust as from the RE includes high levels of HC. Shown in Figure 6 are the results from measurements of the concentration of exhaust composition at different rotor angles. It should be noted here that HC increases sharply as the trailing side (hereinafter referred to as T-side) approached the exhaust port. Since O2 also increases sharply while CO2 decreases, it is reasoned that little combustion occurs around the T-side end of the combustion chamber, thus causing the high levels of HC emissions.

POTENTIAL OF HC REDUCTION WITH PERIPHERAL PORT EXHAUST CONFIGUCATION – Potential approached for reducing HC are: (a) burning the unburned mixture at the T-side end of the combustion chamber and (b) preventing HC from being emitted in the effluent gasses. Concerning the implementation of the first approach, fuel consumption and HC emissions characteristics of different rotor recess shapes, which were studied in the past with respect to optimising the rotor recess shape, are shown in Figure 7. With a rotor recess shape that

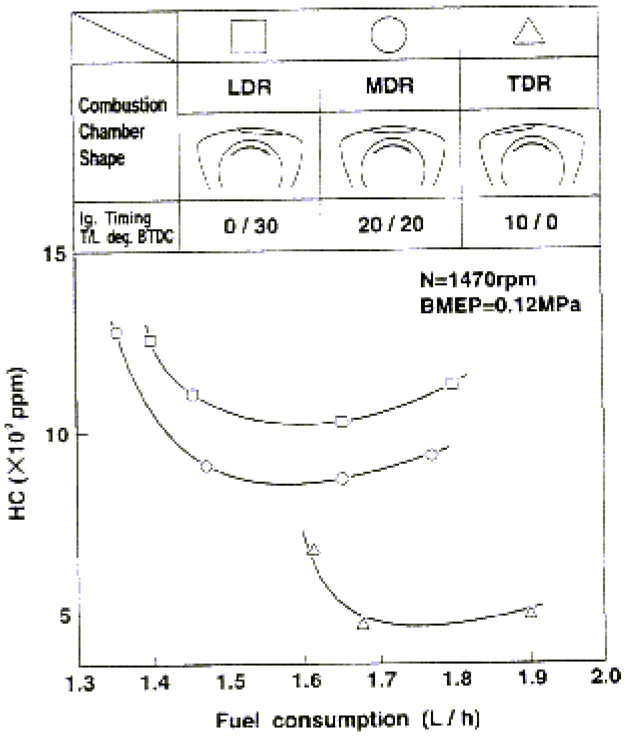

Fig. 7 Effect of Combustion Chamber Shape on HC Emissions

accelerates combustion at the T-side end of the combustion chamber, the HC emission lever decreases albeit with an adverse effect on combustion stability; and, as fuel consumption is decreased, misfire occurs at an early stage, with a remarkable increased in unburned HC. For these reasons, on the current production model, the MDR combustion chamber is used because it has a good balance of fuel consumption and exhaust emissions. Another attempt which was made is the supply of O2 at the T-side end of the combustion chamber to burn HC at that location. As for the second approach, it is considered to be difficult to keep HC from being discharged in the effluent as long as the peripheral porting configuration is used.

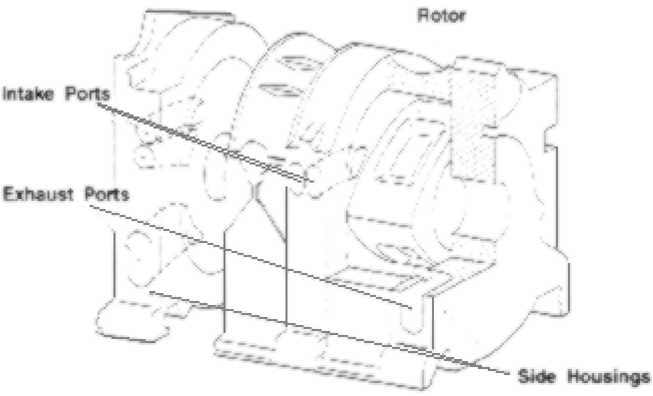

Fig. 8 Basic Construction of the Side Exhaust Port RE

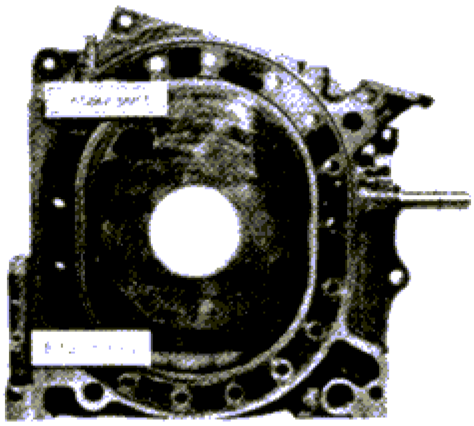

Fig. 9 Photograph of a Side Housing with Side Exhaust Port.

SIDE EXHAUST PORT RE

1. STUDY OF SIDE EXHAUST PORT

To further improve fuel consumption and exhaust emissions characteristics of the RE, we next studied the attributes of side exhaust port RE. For improved fuel consumption, it is required to reduce the internal EGR ratio, to set exhaust closure timing around TDC, and to eliminate intake-exhaust overlap. And, for minimised HC emissions, the configuration should be one in which the T-side end of the combustion chamber does not open to the exhaust port. Using the side-porting configuration for the exhaust port would offer a great degree of freedom in setting the porting timing and shape, and it would help reduce fuel consumption and exhaust emissions.

Shown in Figure 8 is the basic construction of the side exhaust port RE. The exhaust ports are positioned on the sliding surfaces is the front and rear housings, in a manner similar to the side intake ports. Figure 9 is a photograph of a side housing with side exhaust port. Figures 10 and 11.

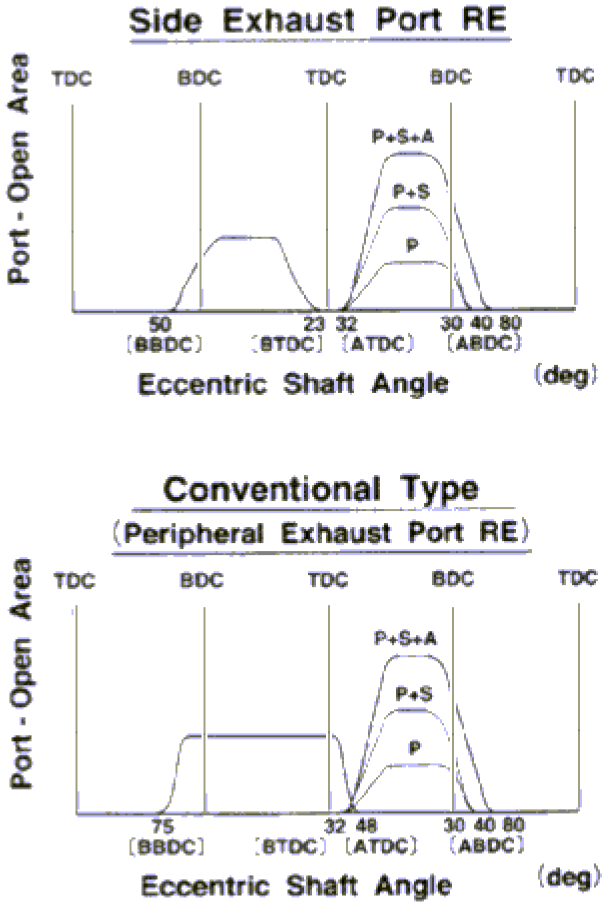

Fig. 10 Port-Open Area Characteristics

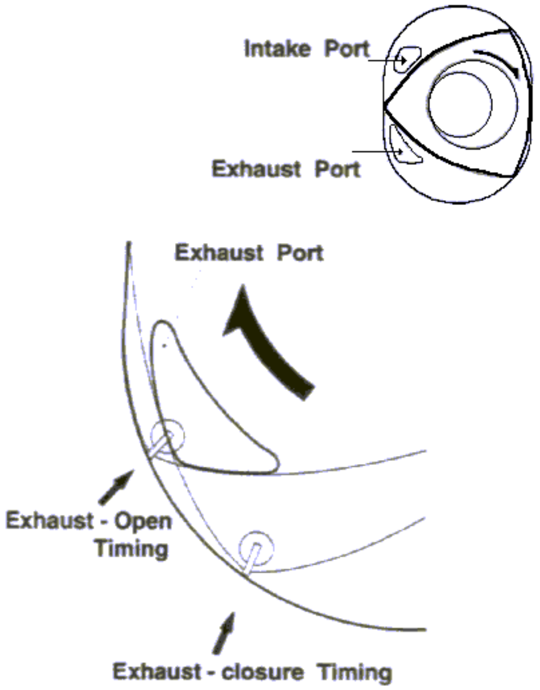

Fig. 11 Detailed Drawing of the Exhaust Port Shape

Figures 10 and 11 show the port-open area characteristics and a detailed drawing of the exhaust port shape, respectively. The closing timing was set around TDC, and that entirely eliminated the intake-exhaust overlap.

2. TESTED ENGINE AND TEST EQUIPMENT

Table 2 shows the major specifications of the tested engine, and Figure 12, those of the test equipment. The engine is based on a naturally-aspirated Mazda 13B-type RE, and has been evaluated in comparison to an engine with the peripheral exhaust porting configuration. The only difference between the two engines is the exhaust port configuration. At idle speed, these two engines are supplied with secondary air by the same secondary air system as used in the current RE. And, both systems are set so that almost the same amount of secondary air enters the combustion chamber in the intake process.

3. TEST RESULTS

FUEL CONSUMPTION CHANACTERISTICS – Figure 13 shows the relationship between engine load and internal EGR ratio at 1500 rpm at stoichiometric air-fuel ratio. The internal EGR ratio is significantly

Table 2 Major Specifications of the Tested Engines

Category	Peripheral Exhaust Port RE	Side Exhaust Port RE
Displacement (cc)	654 ^{x} 2 Rotor	⇐
Eccentricity x Generating Radius X Width (mm)	15 ^{x} 105 ^{x} 80	⇐
Compression Ratio	9.7	⇐
Combustion Chamber Shape	MDR	⇐
Intake Porting	Side Porting	⇐
Intake open / Intake closed	Pry: 320 ATDC / 400 ABDC Sec: 320 ATDC / 300 ABDC Aux: 450ATDC / 800 ABDC	⇐ ⇐ ⇐
Exhaust Porting	Peripheral Porting	Side Porting
Exhaust open / Exhaust closed	75^{0} BBDC / 48^{0} ATDC	50^{0} BBDC / 23^{0} BTDC
Fuel Supply System	Electronically Controlled Fuel Injection	⇐

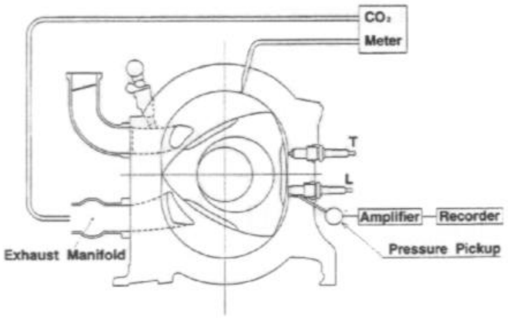

Fig. 12 Test Equipment

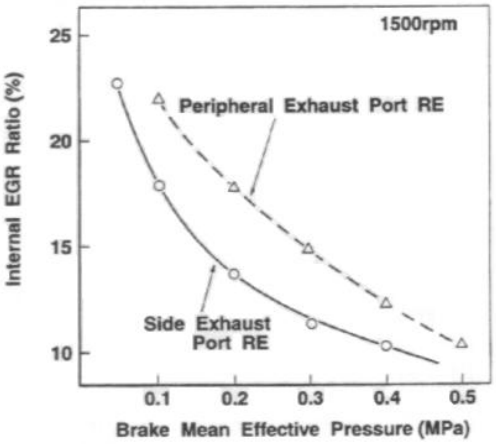

Fig. 13 Relationship Between Load and Internal EGR Ratio

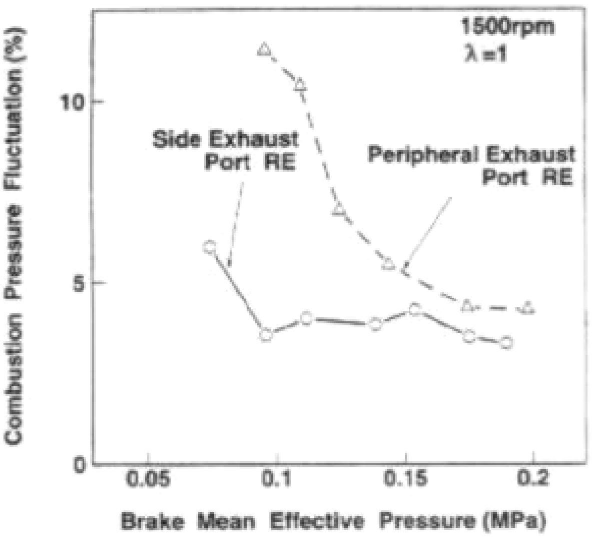

Fig. 14 Relationship Between Load and Combustion Pressure Fluctuation

improved on the side exhaust port RE as compared to the peripheral exhaust port RE. This is thought to be the effect of the reduction in exhaust gasses carried over during the intake-exhaust overlap, as well as that of the reduction in the volume of trapped exhaust gas when the exhaust port is being closed. As shown in Figure 14, the side exhaust port RE has a high degree of combustion stability over the entire load range of the engines when compared to the conventional, peripheral exhaust port type engine at the same air-fuel ratio.

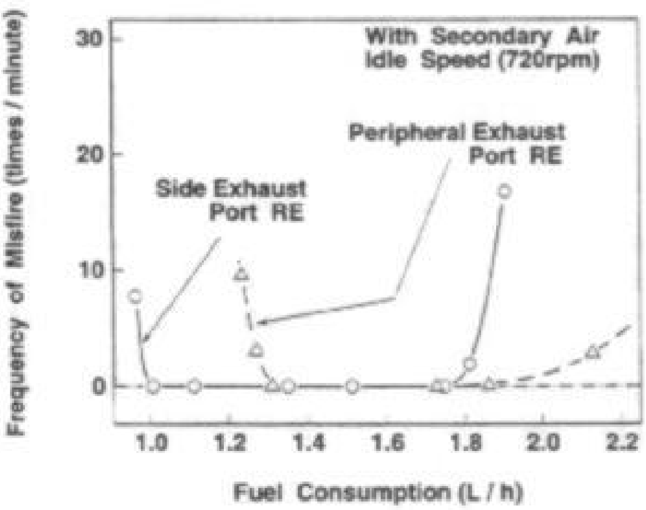

Fig. 15 Relationship Between Fuel Consumption and Frequency of Misfire at Idle Speed.

Figure 15 shows ignitability at idle speed. With little fluctuation in combustion pressure, the side exhaust port RE shows a consistently good mixture-ignitability at idle speed, and it enjoys combustion stability over a wide range of air-fuel ratios.

As a result, in comparison to the peripheral exhaust port RE, the side exhaust port RE can run with lean air-fuel ratio in the low-speed and light-load range, which is the dominant mode for automotive engines, and thus, significantly improves fuel consumption.

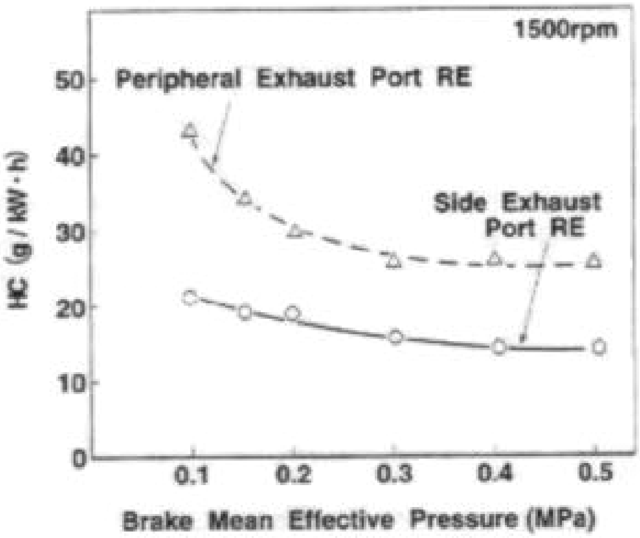

Fig. 16 Relationship Between Load and HC Emissions.

EXHAUST EMISSION CHARACTERISTCS – Figure 16 shows the HC exhaust emissions characteristics for both the side exhaust port RE and the peripheral exhaust port RE. The HC emissions from the side exhaust port RE and 35 to 50 percent less than those from the peripheral exhaust port RE.

The reason for the superiority of the new RE with respect to HC emissions reductions is considered to be its geometry, which prevents gasses around the T-side end of the combustion chamber from being emitted. As illustrated in Figure 17, the peripheral exhaust port RE is constructed so that the T-side end of the combustion chamber opens to the exhaust port, and this allows the emission of the HC gasses around that area. In the side exhaust port RE, on the other hand, the T-side end of the combustion chamber is distant from the exhaust port – even at the time of port closure – and, as a consequence, HC gasses in the vicinity cannot easily escape through the exhaust port, but instead, are retained over for the next cycle of combustion.

Finally, in addition to the above-mentioned effect, another significant reason for the reduction in the HC

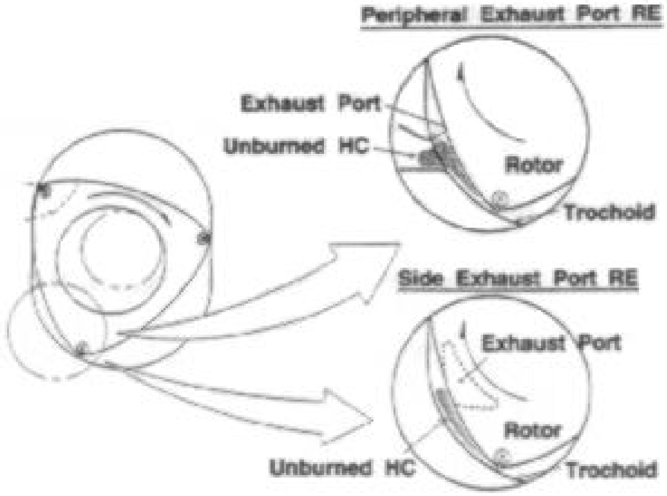

Fig. 17 Mechanism of HC Emission Around T-side End

emissions in side exhaust port RE during operation in the light-load range is the improvement in combustion stability.

SUMMARY

(1) Combustion stability in the RE increases in proportion to the reduction in internal EGR ratio, which extents the lean limit of the air-fuel ratio.
(2) The side exhaust port RE enable the exhaust port closure timing to be set in the vicinity of TDC, with a resultant reduction in internal EGR ratio under low-speed and light-load conditions. Consequently, combustion stability is improved, and a leaner air-fuel mixture setting becomes possible when compared to the peripheral exhaust port RE. These changes also provide a significant improvement in fuel consumption.
(3) The side exhaust port RE can significantly reduce HC emissions when compared to the peripheral exhaust port RE.

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