The Effect of EGR on Diesel Particulate Emissions

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ABSTRACT

It has been reported that the application of EGR (exhaust gas recirculation) for NO_x reduction, results in soot promotion in diesel engines, and in soot suppression in a steady burner. The soot or particulate, however, was evaluated on the basis of the Bosch Smoke Unit. In this study, the effect of EGR on diesel particulate, dry-soot, and SOF emissions was investigated quantitatively with a CVS mini-dilution tunnel. The engine was run at several EGR ratios over a wide load range with both advanced and retarded injection timings. It was mainly shown that the evident NO_x - particulate tradeoff was observed under those conditions in which the particulate promotion effect of EGR was obtained, and this becomes weak or even favorable under the conditions in which no effect or the suppression effect of EGR was obtained.

INTRODUCTION

With emissions regulations for diesel engines becoming more stringent, much interest has been focused on particulate reduction research. EGR (exhaust gas recirculation) is a method of NO_x reduction known and applied for years.

A number of studies [1], [2], [3], have been made on the application of EGR to direct-injection diesel engines and its effect on exhaust emissions, particularly, NO_x and soot. It was reported in these studies that EGR decreased NO_x emissions, but this resulted in an increase in soot.

One of the authors in a previous study [4], stressed the importance of the operating condition on the effect of EGR on particulate emissions. It was reported that EGR suppressed particulate formation under some engine operating conditions. Furthermore, in that study, a determining factor for the effect on the particulate was suggested to be the combustion pattern defined as the fuel mass-fraction burned during the initial stage or during the subsequent stage of diesel combustion.

However, in all these studies mentioned, particulate or soot was evaluated on the basis of the Bosch Smoke Unit. Thus, there is a need to evaluate the soot or particulate more quantitatively by using a mini-dilution tunnel in conjunction with a constant volume sampling (CVS) system. This study aims to determine the effect of EGR on diesel particulate, dry-soot, and soluble organic fractions (SOF) emission indices.

Several results consistent with the previous findings are reported here, which show the complex behavior affecting the particulate. Thus, the purpose of the present study is to reveal the EGR effect on the particulate emissions quantitatively with sufficient reliability over a wide range of combustion conditions.

EXPERIMENTAL SET-UP

The experimental set-up schematic diagram is shown in Fig. 1. The test engine used was a YANMAR N-22, direct-injection, 4-cycle, single-cylinder diesel engine. Its specifications are listed in Table I. To obtain a quantitative evaluation for the particulate, a CVS mini-dilution tunnel system shown in Fig. 2 was utilized. This system was made to conform with standard EPA and SAE regulations. A butterfly valve controls the dilution ratio, which is defined as the ratio of the CVS volume to the exhaust volume. This was determined by dividing the undiluted exhaust CO_2 concentration by the dilute CO_2 concentration . Dilution air passes through a filter and mixes with the exhaust gas. A sampling probe, located approximately 12 tunnel diameters downstream of the point where the exhaust enters the dilution tunnel, takes a portion of the diluted exhaust and the particulate sample was collected on a 47 mm Pallflex teflon-coated glass fiber filter housed in a filter holder.

Pressure within the cylinder was measured with a piezoelectric type pressure transducer fitted in the engine's cylinder head. The injection nozzle valve lift signal and the crank angle signals were also taken, digitized and processed by a computer system. A valve controls the amount of exhaust gas recirculated. In this study, EGR is defined by the equation:

$$\text{EGR ratio} = (Mo-Megr)/Mo$$

where, Mo is the air mass flow rate without EGR, and Megr is the air mass flow rate with EGR.

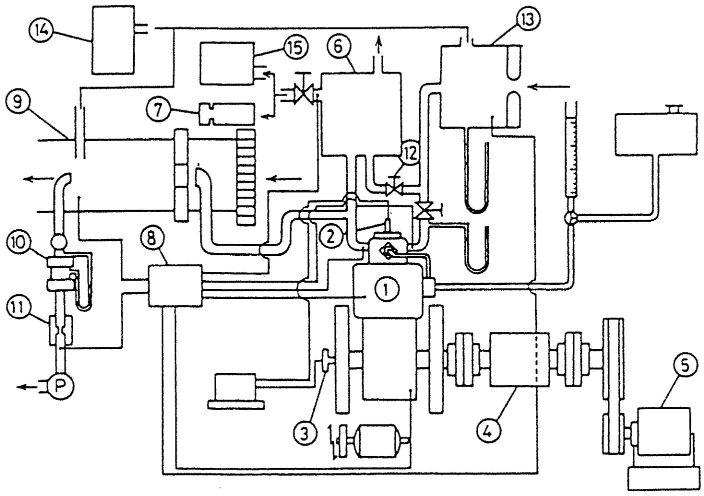


Fig. 1 Schematic Diagram of Experimental Set-up

(1) Engine
(2) Pressure Transducer
(3) Rotary Encoder
(4) Torque Meter
(5) Dynamometer
(6) Exhaust Surge Tank
(7) Bosch Smoke Meter
(8) Digital Thermometer
(9) Dilution Tunnel
(10) Filter Paper Holder
(11) Choke Nozzle
(12) EGR Control Valve
(13) Inlet Surge Tank
(14) Gas Chromatograph
(15) NO_x Analyzer

TEST PROCEDURE

After idling, the engine was pre-conditioned for 1 hour at 900 rpm engine speed and 80% load to stabilize and minimize particulate measurement errors [5]. After setting the engine at the desired condition, particulate sampling followed. Before and after sampling, all particulate filters were placed in an air-conditioned room (25°C, 50% rel. hum.) and allowed to equilibriate for at least 12 hours prior to weighing to eliminate errors in weighing. Extraction solvent used was dicholoromethane $CH_2(CL_2)$. SOF extraction was done by the filter-soak method [6].

In this text, the engine was run at a constant speed of 900 rpm, with the load varied over a wide load range, and EGR ratios of 0, 10, 10, and 30%, and at injection timings of an advance of 21 deg and a retarded timing of 5 deg BTDC.

TYPE	YANMAR N-22
COMBUSTION CHAMBER	DIRECT INJECTION
NUMBER of CYLINDERS	1
VALVE ARRANGEMENT	OHV
CYCLE	4
COOLING SYSTEM	HOPPER TYPE
COMPRESSION RATIO	16
BORE * STROKE	140 * 200 mm
STROKE VOLUME	3.078 l
RATED POWER/rpm	14 kW(19PS)/1000rpm
INJECTION PUMP	BOSCH TYPE
INJECTION NOZZLE	HOLE NOZZLE(4-hole)
INJECTION TIMING	VARIABLE
NOZZLE OPENING PRESSURE	30 MPa

Table I Test Engine Specifications

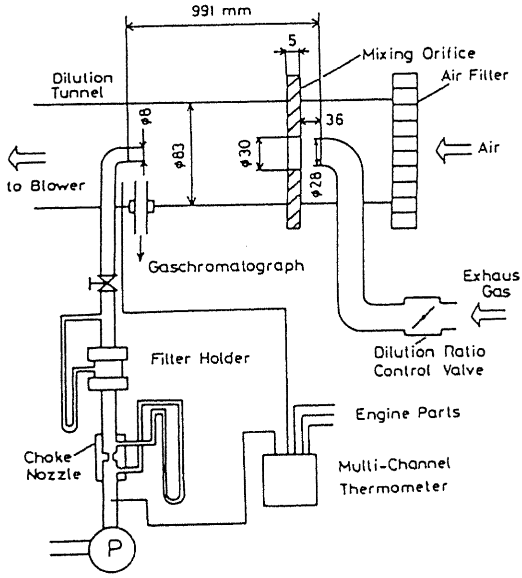


Fig. 2 Detail of Mini-dilution Tunnel System

RESULTS AND DISCUSSIONS

(1) Effect of Dilution Ratio on the Particulate Emission Index

To determine the particulate measurement reliability of the CVS mini-dilution tunnel system, the engine was run at steady state conditions, over a wide load range, and with the dilution ratio set at a range of about 8 to 24. As per EPA regulations, the dilution tunnel temperatures was kept below 52°C. The results as shown in Fig. 3, indicates that the dilution ratio within the tested range had

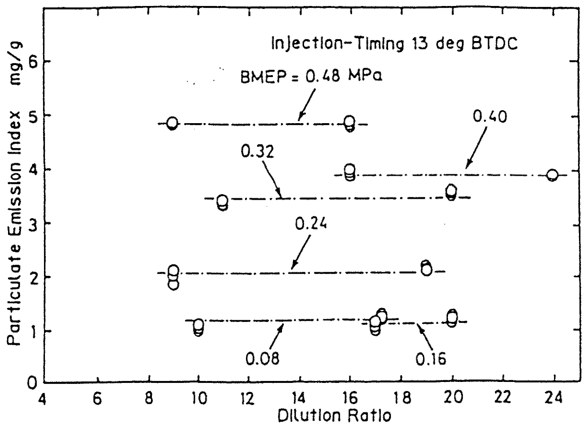


Fig. 3 The Effect of Dilution Ratio on Particulate Emissions (13° BTDC)

no effect on the particulate emissions. This agrees with the findings of previous dilution tunnel studies [7], [8]. Thus the particulate measurement in this study is considered to be reliable.

(2) Effect of Injection Timing, and EGR on the Particulate, Dry-Soot and SOF Emissions

From the engine application point of view, the evaluation of the effect of EGR is better made at the constant load or power. Within the experimental conditions in this study, the specific fuel consumption was little changed by applying EGR. Then, the fuel consumption rate can represent the torque, BMEP (brake mean effective pressure), or the power under the constant engine speed condition.

Figures 4a, 4b, and 4c, show the effect of EGR on the particulate, dry-soot, and SOF emissions for an injection timing of 5 deg BTDC. The emission indices are plotted against the fuel consumption rate and the brake mean effective pressure BMEP which represents a given load, as mentioned above.

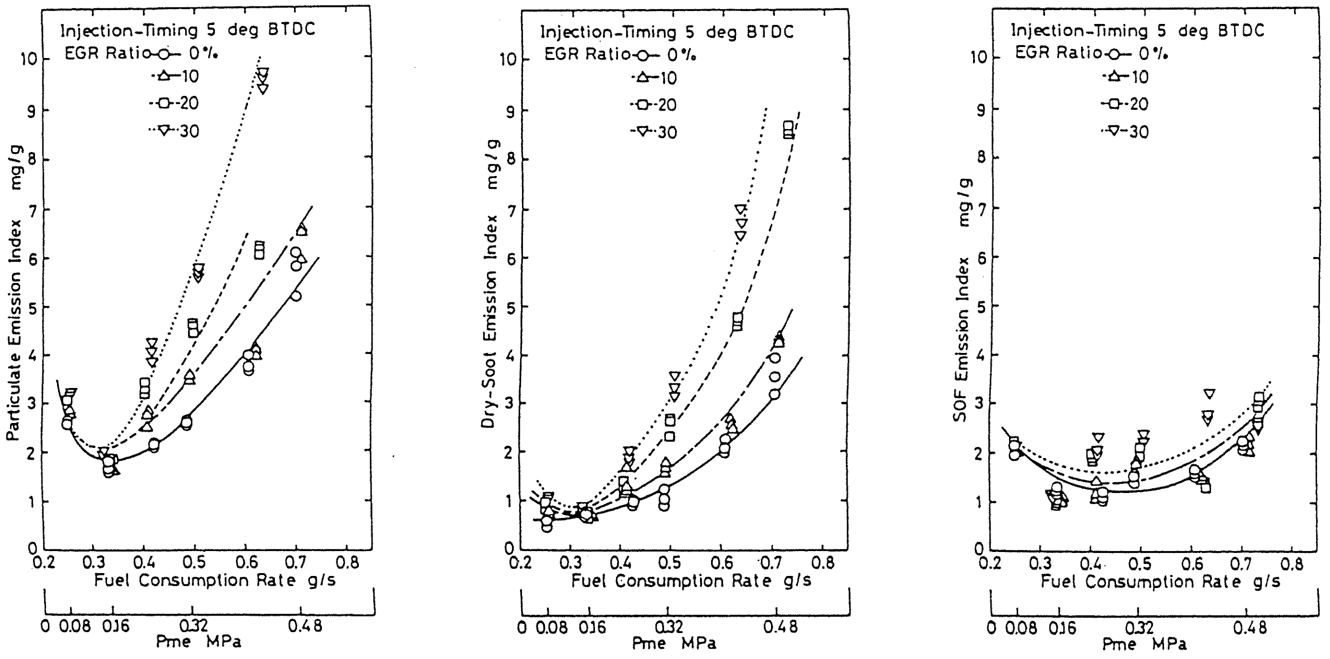
From the results shown in these figures, it is clear that EGR has an effect to promote the particulate and its component emissions. The particulate increase is mostly caused by the increase in the dry-soot component. Thus, at retarded injection timing, EGR does not have a favorable effect from the practical point of view.

As for an advanced injection timing of 21 deg BTDC, the results are shown in Figs. 5a, 5b, and 5c. Here, the behavior of EGR is more complex than the case of retarded timing.

At higher load conditions, EGR at 10 and 20% decreased slightly the particulate which was due to a decrease in the soluble component. However, at 30% EGR, a dramatic increase in particulate is evident. Here, both the dry-soot, and SOF components increased.

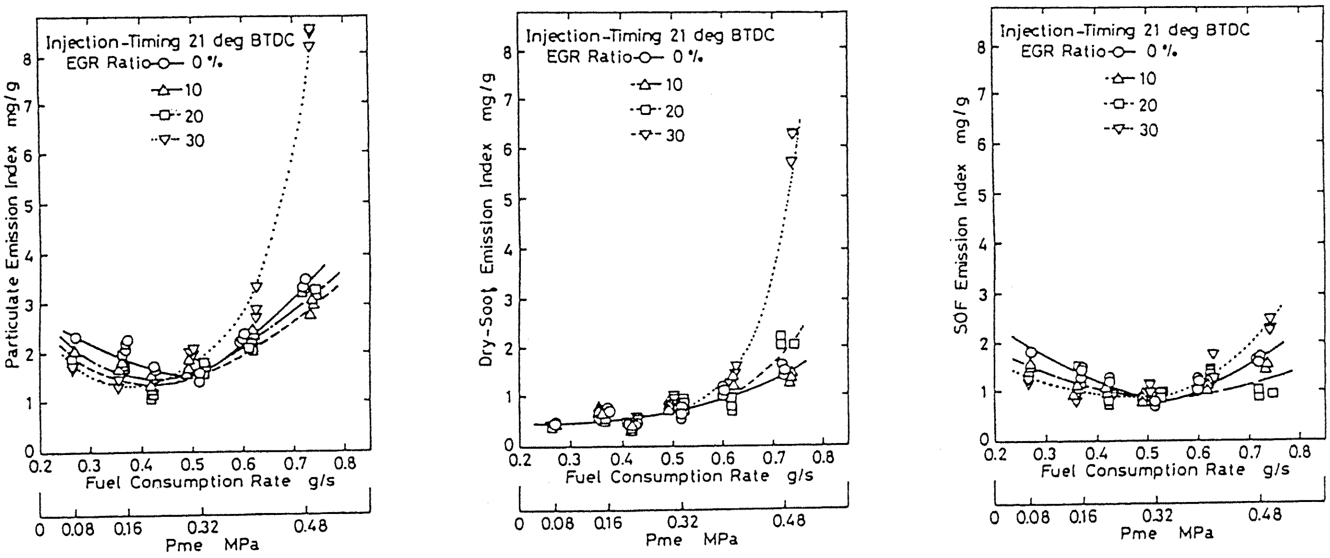
At medium load conditions, EGR had very little effect or no effect at all on the particulate, dry-soot, and SOF emissions. On the other hand, at low load conditions, the dry-soot component did not change, while the SOF component decreased at 10, 20, and 30% EGR, resulting in a decrease in the particulate emissions.

From these results, it can be said that EGR shows a particulate suppressing effect at lower load conditions with advanced injection timing.



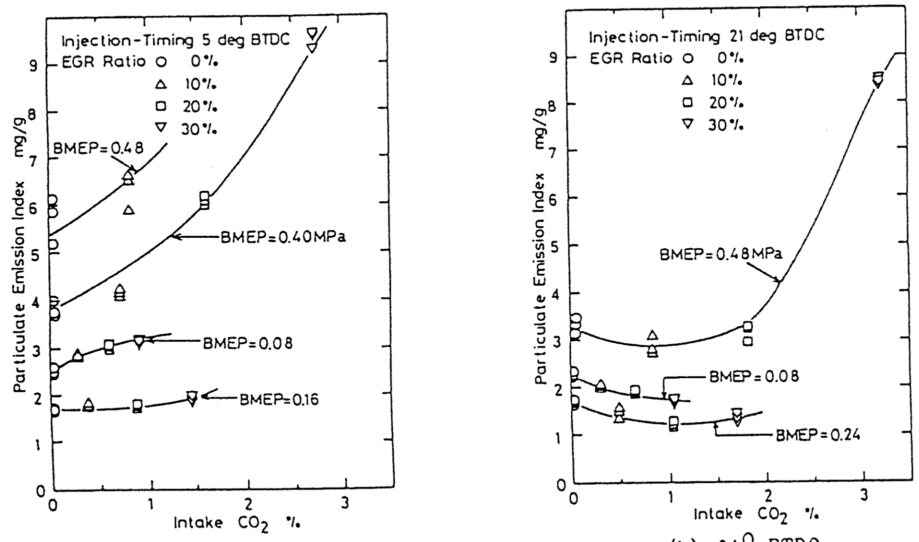
(a) Particulate (b) Dry-soot (c) SOF

Fig. 4 The Effect of EGR on Particulate, Dry-soot, and SOF Emissions (Fuel Consumption Rate Basis, 5° BTDC)



(a) Particulate (b) Dry-soot (c) SOF

Fig. 5 The Effect of EGR on Particulate, Dry-soot, and SOF Emissions (Fuel Consumption Rate Basis, 21° BTDC)



(a) 5° BTDC (b) 21° BTDC

Fig. 6 The Effect of Intake Manifold CO_2 Concentration on the Particulate Emission Index

(3) Effect of Intake CO_2 Concentration on the Particulate Emission Index

The effect of intake CO_2 concentration on the particulate emission index is plotted in Figs. 6a and 6b to show the EGR effect more clearly with a normalized scale.

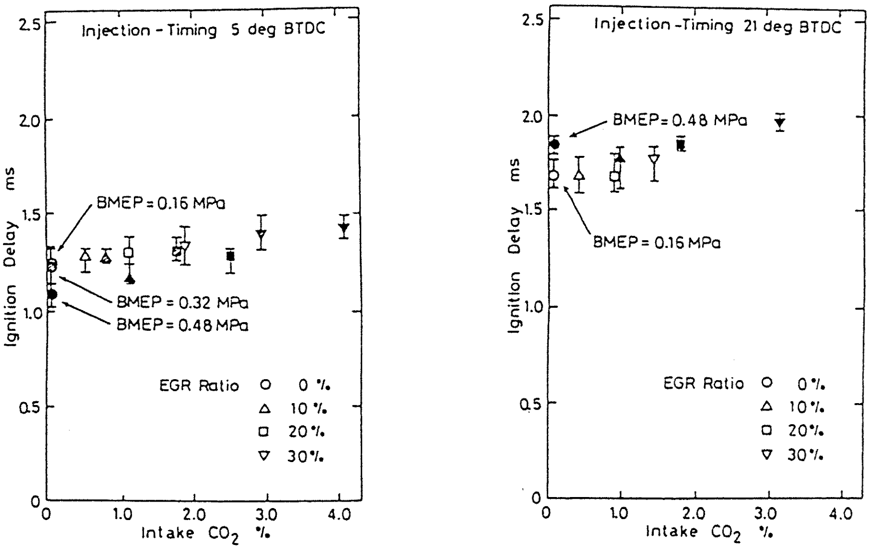
At 5 deg BTDC, for all load conditions, an increase in the intake CO_2 concentration generally shows an increasing tendency in the particulate emission index, though the magnitude is slight at low load conditions.

Whereas, at 21 deg BTDC, the increasing tendency of particulate with the increase in CO_2 is only evident at high load conditions, there seems to be very little effect on the particulate emissions. And at low load conditions, intake CO_2 concentration increases resulted in a decrease in the particulate emissions.

(4) The Effect of EGR on the Ignition Delay

Figures 7a and 7b show the effect of EGR on the ignition delay. Here, the ignition delay is plotted against the intake manifold CO_2 concentration. With increasing EGR, the amount of CO_2 in the intake manifold is increased. The intake manifold temperature is likewise increased.

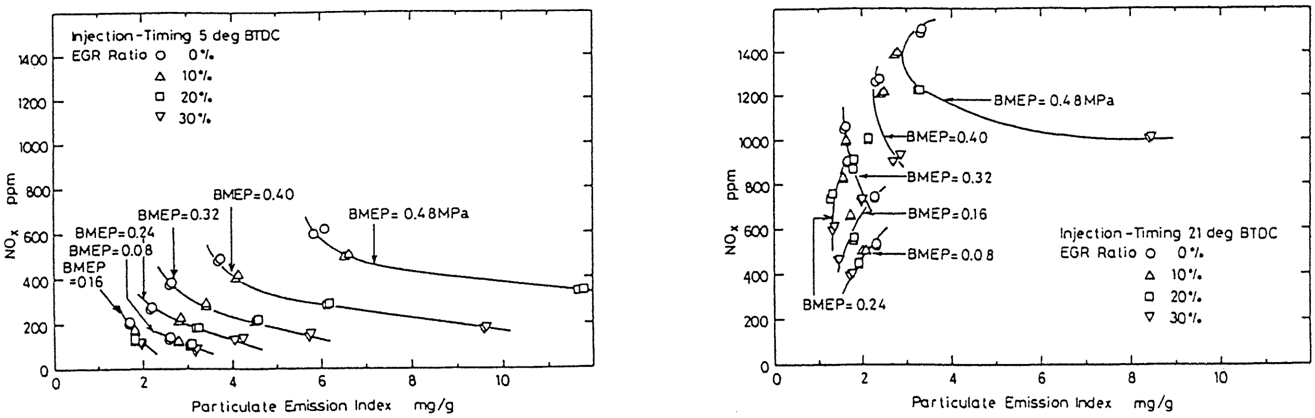
The results show that with increasing EGR, the ignition delay lengthens. Although at 21 deg BTDC injection timing the ignition delay seems to take a slight minimum at about 10% EGR, the results generally show a slight increase in ignition delay with increasing the amount of CO_2 at the intake. The



(a) 5° BTDC

(b) 21° BTDC

Fig. 7 The Effect of EGR on the Ignition Delay



(a) 5° BTDC

(b) 21° BTDC

Fig. 8 NO_x - Particulate Correlation

individual effects of O_2 reduction (CO_2 addition in the intake manifold and manifold temperature increase were studied by Andree et al. [9], Wong [10], and Meguerdichian [11]. From these studies, it was reported that CO_2 addition increased the ignition delay, while an increase in the manifold temperature shortened the ignition delay. The lengthening of ignition delay with EGR will mean that the effect of CO_2 and N_2 dilution predominates over the effect of the manifold temperature increase. Thus, this EGR effect on the spontaneous ignition process suggests that most of the emission results may be caused by the dilution effect of EGR, and not by the slight increase in temperature.

(5) NO_x-Particulate Tradeoff

Figures 8a, and 8b, are plotted to determine the tradeoff relationship between NO_x and the particulate emissions. At a retarded injection timing of 5 deg BTDC, the tradeoff between NO_x and particulate is evident in most conditions. In other words, the application of EGR decreased NO_x but resulted in an increase in particulate emissions.

At 21 deg BTDC, the tradeoff relationship becomes more complex, and it is still recognizable at high load and high EGR ratio conditions but the degree is lesser than at 5 deg BTDC. However, at low load conditions, the tradeoff is almost nonexistent, since at these conditions, NO_x and particulate emissions are both reduced with EGR.

Although it is generally reported that EGR results in an increase in particulates (soot promotion) or smoke, a condition exists where EGR has been found to have the reverse effect, that of particulate suppression.

In a study using a steady spray burner [12], it was reported that nonluminous combustion was achieved through exhaust recirculation, in other words, soot formation was suppressed. A single droplet combustion experiment utilizing a combustion vessel [13] showed that CO_2 suppressed soot formation while N_2 did not. Although the conditions in spray burners and combustion vessels are different from diesel engines, these studies may shed some light as to the soot suppression effect recognized in this study. Some further basic studies need to be done to investigate further this effect of EGR.

CONCLUSIONS

With a direct-injection diesel test engine, the effects of EGR on particulate, dry-soot, SOF, and NO_x emissions were investigated experimentally.

The results are summarized as follows:

1) EGR was found to have two contrary effects on particulate, suppression and promotion, or no effect depending on the operating condition. Now, it is further suggested that the suppression effect is due to the decreased SOF component and can be recognized when the ignition delay is comparatively large.

2) With EGR, the evident NO_x-particulate tradeoff was observed for the conditions under which the particulate promotion effect of EGR was obtained. However, it tends to become weaker, and even shifts to a "favorable" effect for the conditions under which no effect or the particulate suppression effect of EGR was obtained.

3) Applying EGR increased the inert gas concentration and the temperature in the intake manifold. This resulted in an overall increase in the ignition delay. Therefore, the dilution effect of EGR is considered to be predominant over the heating effect for the spontaneous ignition process, and it could suggest that most of the EGR effect reported in this study is due to the effect of dilution.

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NOMENCLATURE

Mo = air mass flow rate without EGR, g/sec
Megr = air mass flow rate with EGR, g/sec

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