Effects of Supercharging and EGR on Diesel Combustion and Emissions

Y.Daisho, N.Uchida*, K.Morita**, S.Shimogata *** and T.Saito

Department of Mechanical Engineering
Waseda University
3-4-1 Okubo, Shinjuku-ku, Tokyo 169
Japan
* *Hino Motors, Ltd.*
** *Toyota Motors Co.*
*** *Tokyo Gas Co., Ltd.*

ABSTRACT

Diesel combustion and exhaust emission characteristics influenced by exhaust gas recirculation (EGR) and supercharging are investigated. The engine test results indicate that increasing EGR can significantly reduce NOx. At the same time, increasing the intake boost pressure by supercharging can favorably improve combustion and thermal efficiency deterioration due to EGR, without increasing NOx. A simplified combustion model combined with the extended Zeldovich mechanism explains these NOx emission characteristics.

In addition, diesel sprays and combustion were visualized in a rapid compression and expansion machine by means of a copper vapor laser for a light source synchronized to a high-speed 16 mm camera. The photographs show that supercharging can increase air entrainment in the fuel spray thereby increasing evaporation, resulting in reduced ignition delay and enhanced diffusion combustion.

INTRODUCTION

In recent years, fuel injection timing retardation has been utilized to decrease NOx emissions and meet increasingly stringent NOx emission regulations. However, this approach cannot be the ultimate solution because of deteriorating fuel economy and the exhaust emissions other than NOx. Exhaust gas recirculation (EGR) can achieve more efficient NOx emission reduction, although the range of EGR is restricted for diesel engines only to low load due to increasing smoke emission and in-cylinder abrasion[1]. Thus, to reduce smoke emission and improve fuel economy while using EGR, the effects of supercharging were investigated in a direct-injection diesel engine. The characteristics of diesel sprays and combustion under supercharged conditions were then observed in a rapid compression and expansion machine by means of high-speed photography with a copper vapor laser.

EXPERIMENTAL APPARATUS AND PROCEDURES

Test Engine

The test engine used was a water-cooled, 1.35 l, single cylinder, four stroke-cycle, direct-injection diesel engine having a 20 to 1 compression ratio. For supercharging, a roots blower was utilized to compress the intake air up to 80 kPa gauge pressure. Cylinder pressure diagrams were obtained for heat release analysis.

Rapid Compression and Expansion Machine (RCEM)

To reproduce and visualize diesel sprays and combustion, a rapid compression and expansion machine (RCEM) has been developed. As illustrated in Fig. 1, a heavy cam weighing 180 kg is dropped along the vertical rail and horizontally reciprocates the rod connecting the piston to compress and expand the charge in the cylinder with a sufficiently high reproducibility. Major specifications are as shown in Fig. 1. The piston accommodates a shallow combustion cavity having a 30 mm radius. The cylinder liner was heated to 170℃ and inlet air to 800℃ to reduce heat loss. To perform single fuel-injection, an electronically controlled high-response spool valve was used to supply a predetermined quantity of diesel fuel stored at 40 MPa in an accumulator. An injection nozzle having 4 holes of 0.30 mm diameter was used.

Spray and Combustion Visualization Apparatus

Diesel sprays and combustion were observed through a transparent acrylic cylinder head using high-speed 16 mm camera at 7,000 fps. A copper vapor laser having a 40 ns pulse width, a modulation frequency up to 20 kHz and 40 kw mean power was utilized as a light source to visualize the sprays. Thus, by synchronizing the laser output to the camera shutter, extremely highly time-resolved photography is possible for spray visualization.

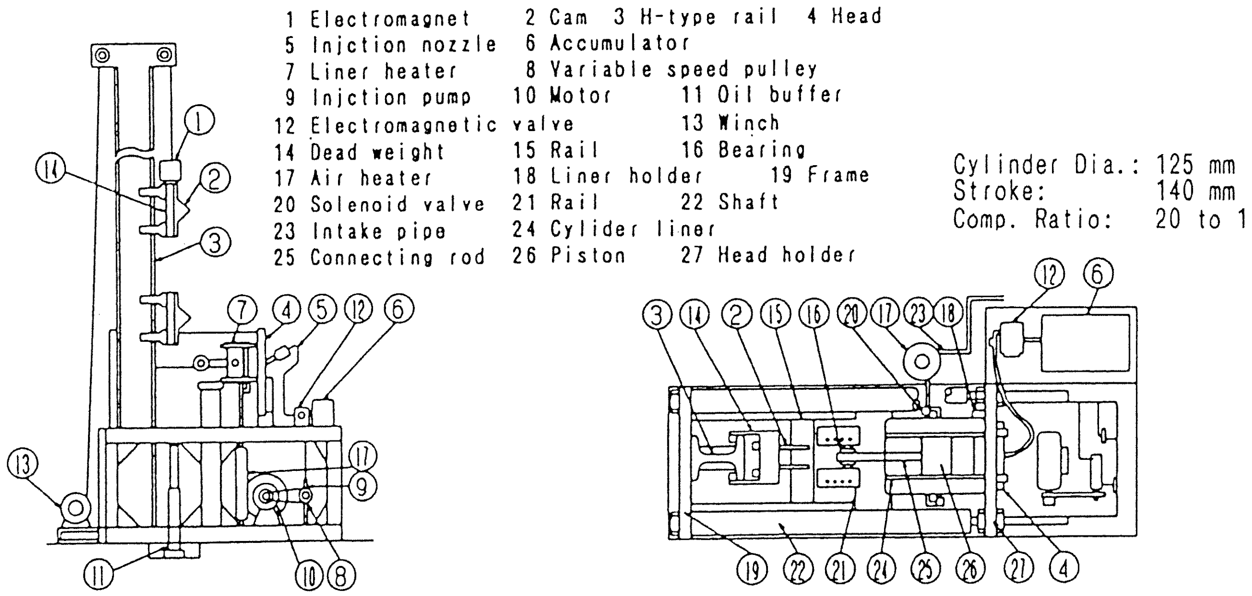


Fig.1 Rapid compression and expansion machine

RESULTS AND DISCUSSION

Engine Test Results

Figure 2 compares the effects of EGR on exhaust emissions at the boost pressures of 39 and 79 kPa gauge. The overall air ratio was 2.8 at 39 kPa and 3.6 at 79 kPa, respectively. In these cases, recirculated exhaust gas and supercharged air were cooled to room temperature by heat exchangers to avoid the effect of an increase in charge temperature. The EGR ratio is defined as the volumetric ratio of recirculated exhaust gas to fresh air. In Fig. 3, the rates of heat release are compared for cases including EGR, supercharging and injection timing retard. Injection timing retard tends to delay the entire combustion process, while EGR tends to increase ignition delay but not change the diffusion combustion process. By contrast, supercharging can reduce ignition delay and the early part of heat release or premixed combustion and also enhance diffusion combustion. This tendency is favorable for improving thermal efficiency. As can be seen in Fig. 2, both THC and NOx emissions are lower at higher boost pressures when EGR ratios are relatively low. This effect is due to the fact that air density increased by supercharging reduces ignition delay, thereby decreasing premixed combustion. Reduced ignition delay will decrease the unburned hydrocarbons resulting from the spreading of the spray and its impingement on the combustion chamber wall. At higher boost pressures, recirculated exhaust gas must be increased to reduce NOx to the same low levels because the recycled gas contains more excessive oxygen.

NOx Formation at EGR and Supercharging

To explain the effects of the above cases on NOx formation, the extended Zeldovich mechanism was applied

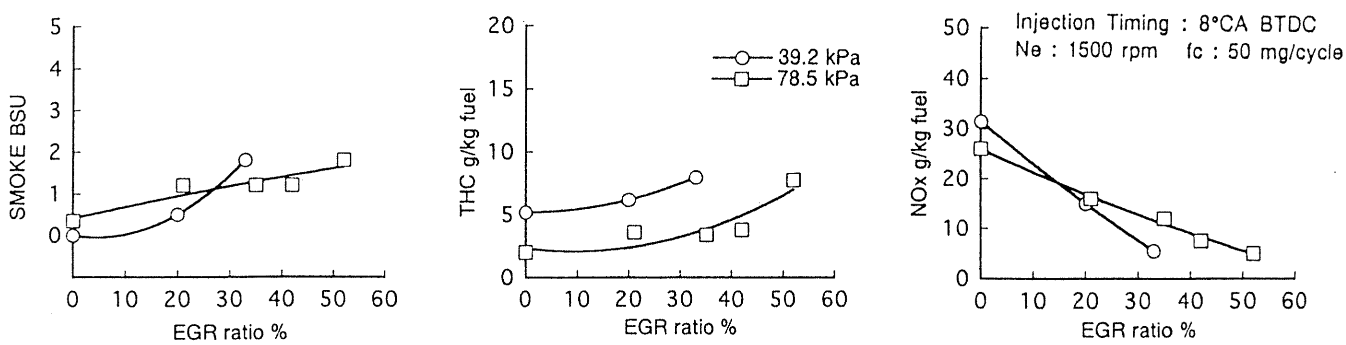


Fig.2 The effects of EGR on exhaust emission

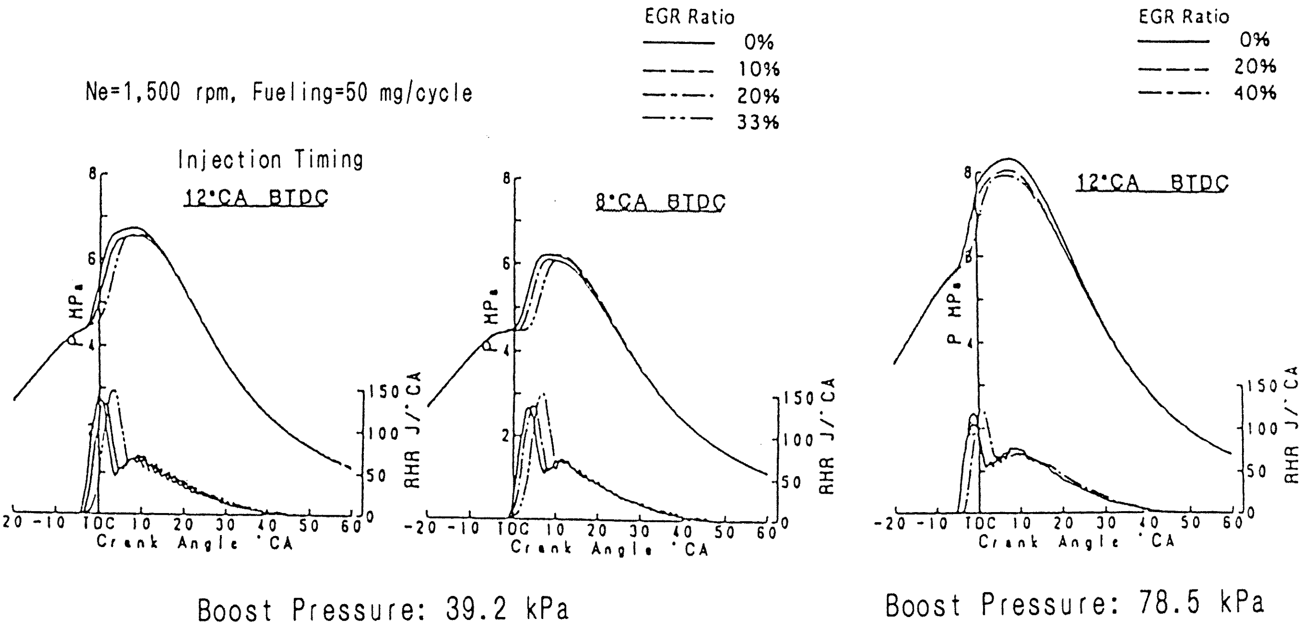


Fig.3 Cylinder pressure and rate of heat release

to a simplified combustion model proposed by the authors[2]. The model assumes that each local fuel-air mixture burns adiabatically at a specific air ratio and then changes isentropically obeying the measured cylinder pressures. Eleven chemical species were taken into account for each burned element. As shown in Fig. 4, indications are that EGR can decrease burned gas temperature, resulting in reducing NO formation. Figure 5 indicates that with supercharging, NO is not increased despite the enhanced air density since burned gas temperatures are not raised due to the reduced premixed combustion.

The predicted effect of EGR and supercharging on NOx emissions are shown in Fig. 6 where the local air ratio is simply assumed to be 1.0. At the lower boost pressure, predicted results agree well with those measured. At the higher boost pressure, however, calculated NOx levels are

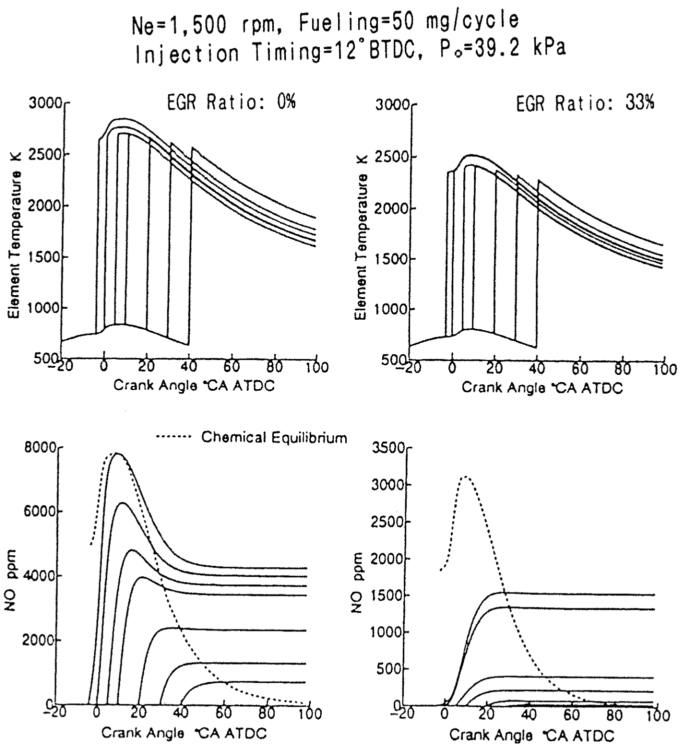


Fig.4 The effect of EGR on NO formation

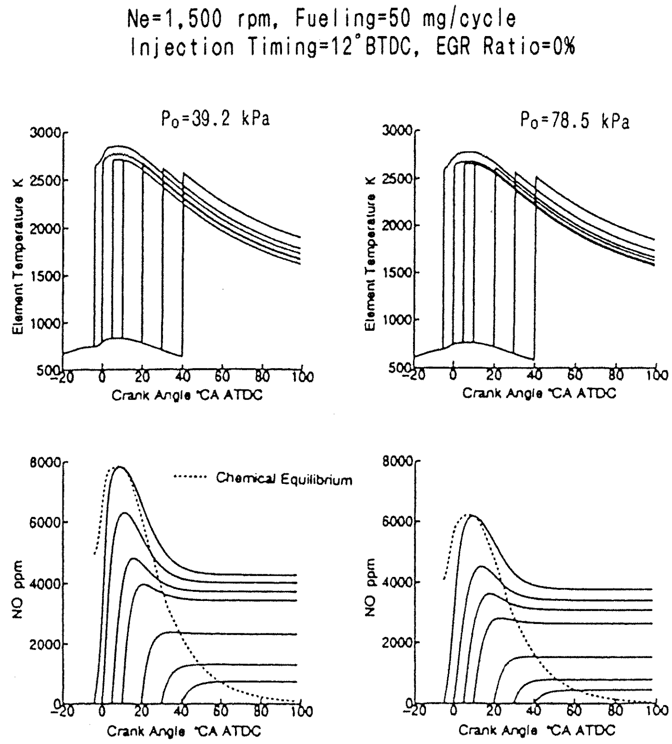


Fig.5 NO formation with supercharging

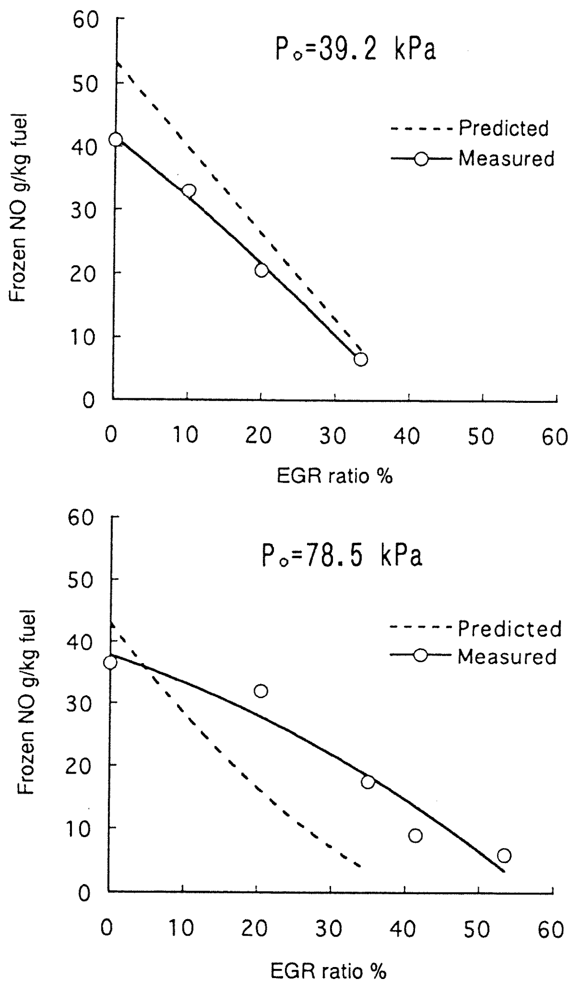


Fig.6 Comparisons of measured and predicted NO emissions

lower than the measurements. Better agreements with the measurements will be possible if a higher air ratio is assumed.

Fuel Sprays and Flame Observed

First, the effect of surrounding gas density on fuel spray formation was investigated in the RCEM under non-evaporative conditions. For this purpose, the piston of the RCEM was fixed and used as a constant-volume vessel. Nitrogen gas was charged in the vessel and kept at room temperature. Figure 7 compares the penetration and volume calculated for observed non-evaporative sprays injected at various surrounding gas pressures. The results indicate that even in the case of supercharging, the spray volume itself is changed only slightly whereas the spray penetration is greatly reduced. Thus, the gas entrained in the spray is almost proportional to the gas density or boost pressure.

Then, combustion experiments in the RCEM were performed for natural aspiration and supercharging cases. Evidently from Fig. 8, by supercharging, a fuel spray evaporates more rapidly due to the reduced fuel droplet size and increased heat transfer between the gas and droplets. The volume of evaporative and non-evaporative sprays are compared in Fig. 7. Thus, with supercharging, the spray does not reach the cavity wall, resulting in reducing hydrocarbon emissions associated the wall impingement as mentioned earlier. The combustion pressures and rates of heat release for the two cases are shown in Fig. 9. These figures show that supercharging can reduce ignition delay and premixed combustion, and enhance diffusion combustion. This conclusion is supported by the high-speed direct photographs shown in Fig. 10, which illustrate that a visible flame appears earlier with supercharging.

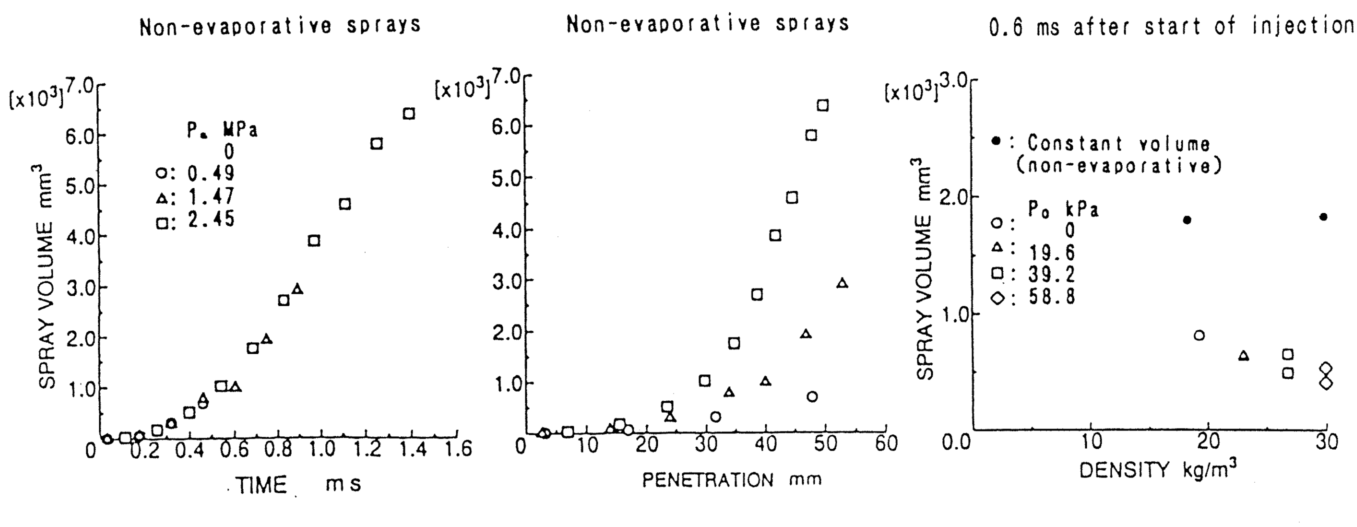
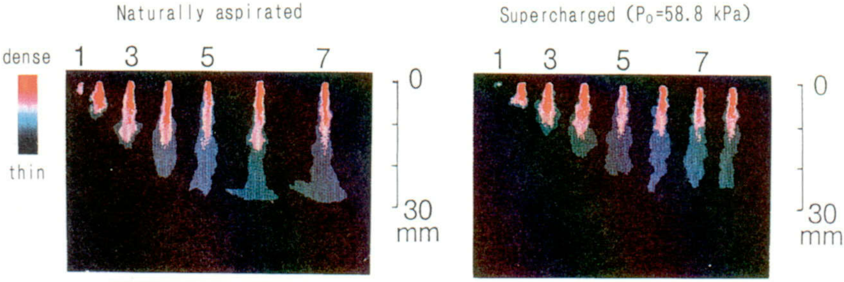


Fig.7 The effect of densitiy on spray volume



Naturally aspirated

No.	Time ms	Injected fuel mg
1	0.07	2.8
2	0.21	9.4
3	0.36	16.1
4	0.50	23.0
5	0.64	29.7
6	0.78	36.1
7	0.93	41.9

Supercharged (P_0=58.8 kPa)

No.	Time ms	Injected fuel mg
1	0.02	0.7
2	0.17	7.3
3	0.31	14.0
4	0.45	20.8
5	0.60	27.6
6	0.74	34.1
7	0.88	40.1
8	1.02	45.4

Fig.8 Liquid fuel densities in evaporative sprays with and without supercharging

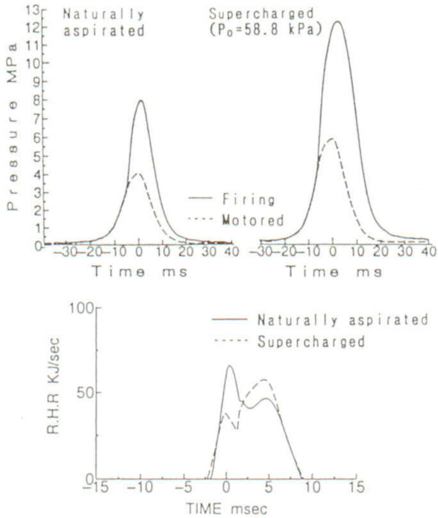


Fig.9 Cylinder pressure and rate of heat release with and without Supercharging

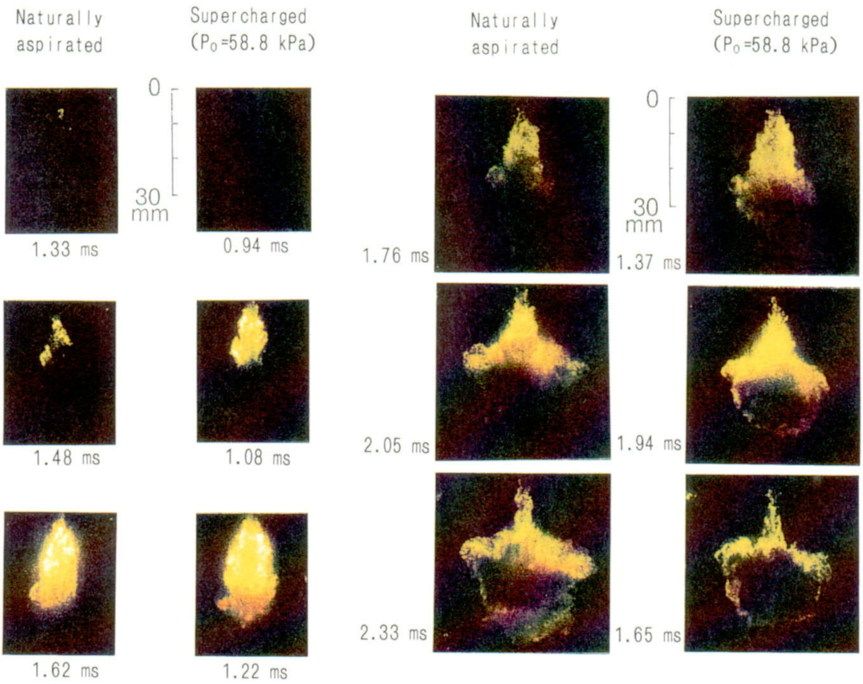


Fig.10 Flame photographs during early part of combustion

CONCLUSIONS

The engine test results indicate that in diesel combustion, increasing EGR can significantly reduce NOx, while increasing intake boost pressure by supercharging can favorably improve combustion and thermal efficiency deteriorated due to EGR without increasing NOx. A simplified combustion model combined with the extended Zeldovich mechanism explains these NOx emission characteristics.

In addition, diesel sprays and combustion were visualized in a rapid compression and expansion machine by means of a copper vapor laser for a light source. The photographs show that supercharging can increase air entrainment in the fuel spray thereby increasing evaporation, resulting in reduced ignition delay and enhanced diffusion combustion.

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