Diesel Combustion and Emission Study by Using of High Boost and High Injection Pressure in Single Cylinder Engine

- The effects of boost pressure and timing retardation on thermal efficiency and exhaust emissions -

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ABSTRACT

The heavy duty diesel engines have adopted many technologies for clean emissions and low fuel consumption, such as direct fuel injection combined with high injection pressure and adequate in-cylinder air motion, turbo-intercooler system and highly strong steel piston. By these technologies the diesel engines have achieved the one of the lowest CO_2 emission as prime mover. However the heavy duty diesel engines are strongly expected lower NOx and PM emission levels than today.

In this study the high boost and lean diesel combustion has been attempted by a single cylinder engine in order to obtain a good engine performance and clean exhaust emission. The experiment has been done under the conditions of intake air quantity up to 5 times of naturally aspirated (NA) engine and 200 MPa injection pressure. The adopted pressure booster is external supercharger, which can control intake air temperature. In this engine the maximum cylinder pressure will increase and new technologies have been adopted, such as the monotherm piston for the endurance of Pmax 30 MPa and also every engine part is designed newly.

As the boost pressure increase, the rate of heat release is resemble to the injection rate and becomes sharper and combustion improves and also the brake thermal efficiency becomes better. The high boost and lean diesel combustion results in low smoke, ISCO and ISTHC without the ISNOx increase and gives good thermal efficiency.

INTRODUCTION

Heavy-duty diesel engines have performed continuous improvement in fuel consumption and exhaust emissions through the changing from the pre-chamber type to the direct-injection type, the combustion modification by the high-pressure injection and swirl air motion [1], the adoption of turbo-intercooler [2,3], and the changing the materials of piston from aluminum to iron [4]; they have attained the well-established reputation worldwide as the prime movers of low CO_2 emission [5]. However, at present the reduction of exhaust emissions such as NOx and PM is required urgently [6].

The improvement of exhaust emissions is now proceeding by the adoption of the newly developed common rail fuel injection system that makes high pressure injection possible and the turbo charging system that provides the air in large amount to the cylinder. The furthermore improvement will be carried out in this same way in the future [7,8,9,10,11]. Although the catalyst is indispensable for the reduction of exhaust emissions from diesel engines, it is necessary to minimize the amount of exhaust emissions and also it is important use the after treatment efficiently. In this study, the engine performance and exhaust emissions were measured, under the condition that the fuel injection pressure was raised up to 200MPa using the single cylinder engines, and the amount of intake air was raised to 5 times of NA engine by the high boost pressure.

EXPERIMENTAL CONDITION

Experimental single cylinder engine

The specification of the used engine is shown in Table 1. This single cylinder engine was designed to make it bearable against the maximum cylinder pressure of Pmax=30MPa. The piston used in this experiment is the monotherm piston made of steel which is bearable against Pmax=30MPa. The shape of the cross section of the piston and the combustion chamber are shown in Fig.1. Most of the parts of the engine such as the piston pin, conrod, crank shaft, metal materials, intake and exhaust valves, cylinder head, head bolt, head gasket, cylinder block, as well as the piston were designed to be bearable against Pmax=30MPa.

In the high boost experiment, it was considered that Pmax would rise higher than 30MPa and the compression ratio ε=15.0 was chosen in order to reduce the Pmax. The regular compression ratio was ε=16.5.

Table 1 Engine specifications and test conditions

Item	Specifications
Engine type	DI single cylinder
Bore and stroke	135 × 140 mm
Displacement	2004 cm^3
Cylinder head	4 valve
Comb. chamber	D = 98 mm, shallow dish
Compression ratio	15
Swirl ratio	0.6
Air charging	External super charger with cooler, Max 501.3 kPa
Injection system	Accumulator type
Injector	Hole nozzle, 0.17 × 6
Injection pressure	200 MPa
Engine speed	1000 - 2000 rpm
Fuel	Diesel fuel JIS No.2 (Sulfur 400 ppm)

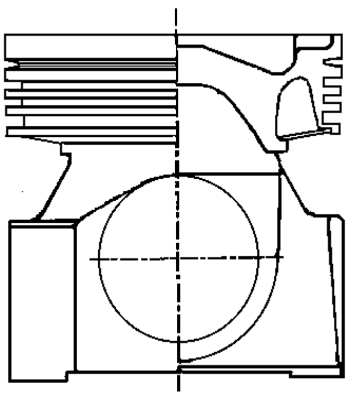

Fig.1 Combustion chamber shape and monotherm steel piston for Pmax 30 MPa

The fuel injection pressure at the performance test was 200MPa, and the regular JIS No.2 diesel fuel (Sulfur 400ppm) was used.

Experimental system and conditions

The external high pressured fuel injection system was used in this study. The injection timing was set to ignite at TDC in real time by monitoring the heat release rate. The duration of the ignition delay was short under the condition of supercharging, and the injection timing was just before few degrees of TDC. The supercharging system in this engine was the external super charge system driven by a motor and the exhaust pressure was set to the same as the atmospheric pressure. Consequently, as the pumping work of the engine becomes a great extent to the plus work, the pumping work on the pressure diagram was excluded from IMEP, regarding only the work of the combustion area as IMEP (indicated mean effective pressure kPa). BMEP (brake mean effective pressure kPa) of the single cylinder engine was obtained from IMEP of the results of this experiment by using the motoring friction of the multi cylinder engine.

Observation of combustion

As there are only a few cases of the observation of combustion under the condition of supercharging, we used the results of high-speed photography of diesel combustion from the past as reference data for the examination of the same single cylinder engine [12]. The engine specification of the condition of combustion observation is slightly different from that of performance test. The different points are shown in Table. 2.

As the combustion chamber on the piston was observed from the bottom of the piston cavity, the combustion chamber shape was flat and shallow dish, the diameter of the cavity was 100mm, the bottom of the piston cavity was made of quartz glass and its compression ratio at observation test was ε=16.
The load was equivalent to 60%, the injection pressure Pinj=100MPa under the constant condition of air excess ratio λ=3.5 and the boost pressure varied from

Table 2 Test conditions for combustion high speed photography

Item	Specifications
Comb. chamber	D = 100 mm, flat shallow dish with transparent bottom
Compression radio	16
Charging conditions	from NA to 341.3 kPa
Injection pressure	100 MPa
Air excess ratio	3.5 constant
Engine speed	1000 rpm

Pb=101.3kPa, which is NA condition, to Pb=341.3kPa, which is the critical pressure for the strength of quartz.

EXPERIMENTAL RESULTS

Pressure diagram and variation of heat release rate

Fig.2 shows the results when changing the boost pressure Pb (kPa) under the constant conditions of the injection quantity q=250mm^3/st and Ne=1000rpm. The amount of air is twice of the NA condition under Pb=201.3kPa. The heat release rate of the figure shows good burning and that the burning becomes even better by increasing Pb, and the heat release rate approaches nearly the injection rate.

Fig.3 shows the results when changing the injection quantity from q=150 to 350mm^3/st, under the constant condition of the boost pressure Pb=501.3kPa and Ne= 1000rpm. As the amount of air in the cylinder was large under this condition and the injection duration was as long as 30deg.CA at q=350mm^3/st, it is necessary to expand the total nozzle area in order to shorten the injection duration.

Fig.4 shows the results when changing the engine speed from Ne=1000, 1500 to 2000rpm under the constant conditions of the boost pressure Pb=301.3kPa and the injection quantity q=250mm^3/st. The injection duration at injection quantity q=250mm^3/st at Ne= 2000rpm was as long as 40deg.CA and, as given by the heat release rate, the burning duration was as long as up to 60deg.CA. Since this is not good combustion, some improvement is needed.

Low engine speed (1000 rpm)

Fig.5 shows the relationship of the brake thermal efficiency and Pmax, increasing the boost pressure set as parameter to IMEP. Fig.6 shows the exhaust gases under the same condition. IMEP can be increased up to 3000kPa under the injection quantity 350mm^3/st. and the output power is equivalent to 282kW(383PS) of 6-cylinder engine at 1000 rpm, taking the friction into consideration.

The brake thermal efficiency reached its maximum at 48% under the condition of IMEP 2000kPa. It is an effective way to raise IMEP by boosting pressure in order to improve the fuel consumption. When the boost pressure was increased, the brake thermal efficiency rose gradually. However, as the brake thermal efficiency increased slowly at more than Pb=401.3kPa, the effective quantity of air sent to cylinder is expected to be up to 4 times of NA engine.

Furthermore, ISNOx (indicated specific NOx) per output power was 8-10g/kWh approximately, and it did not change to a large extent by increasing boost pressure

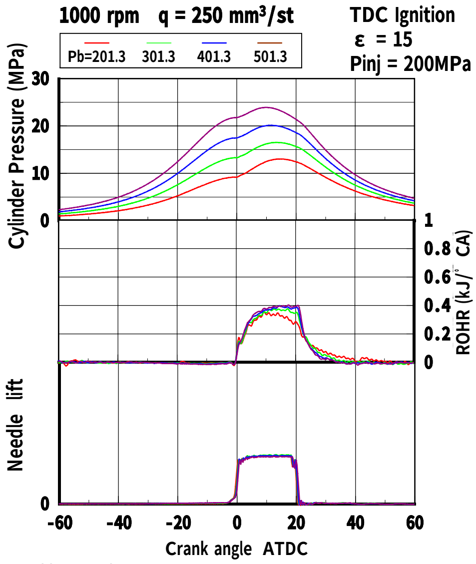

Fig.2 Effect of boost pressures on cyl. press. and ROHR

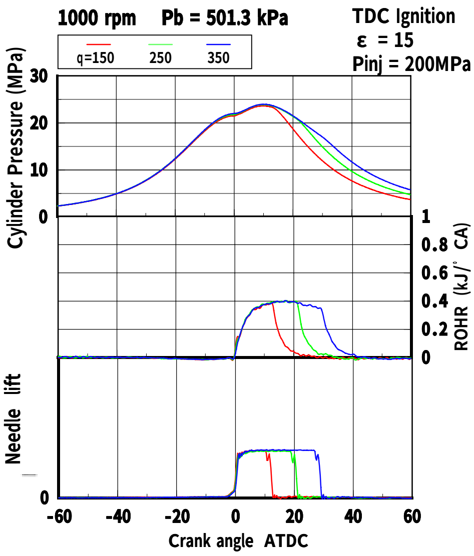

Fig.3 Effect of fuel quantity on cyl. press. and ROHR

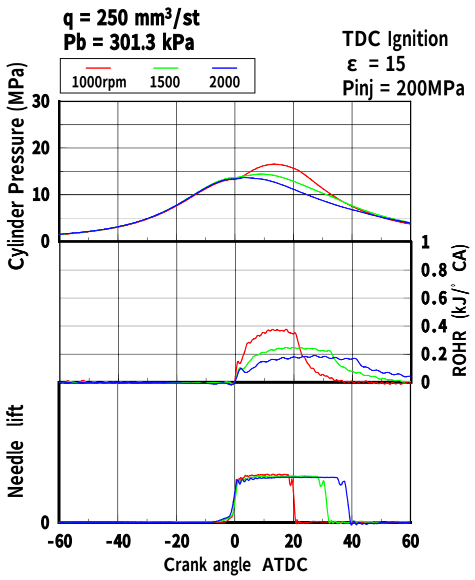

Fig.4 Effect of engine speed on cyl. press. and ROHR

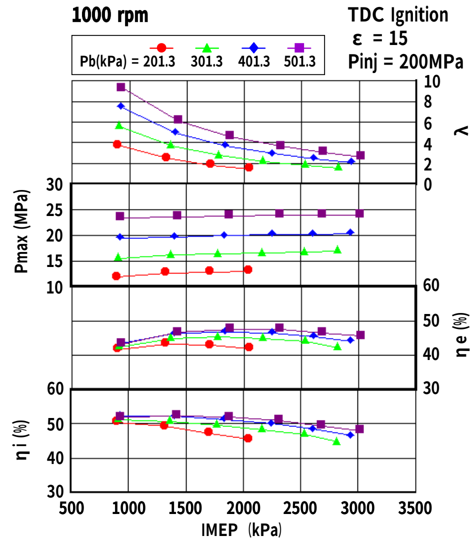

Fig.5 Effect of boost pressures on Pmax and thermal efficiency (Ne = 1000 rpm)

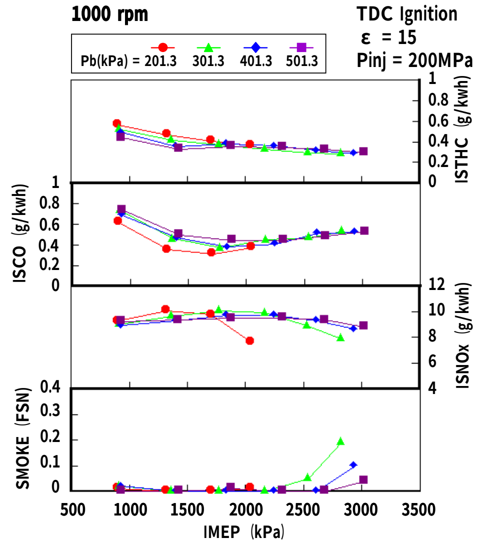

Fig.6 Effect of boost pressures on exhaust emissions (Ne = 1000 rpm)

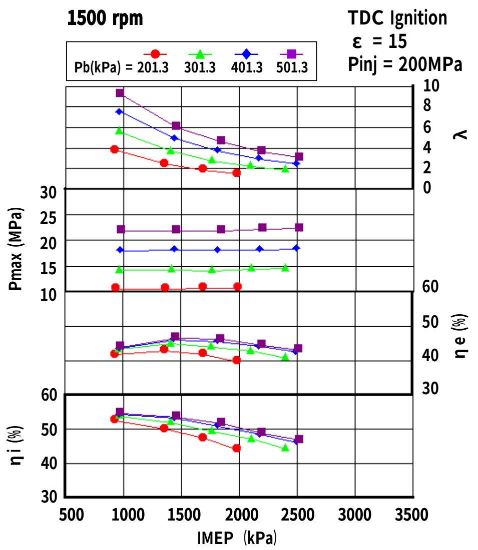

Fig.7 Effect of boost pressures on Pmax and thermal efficiency (Ne = 1500 rpm)

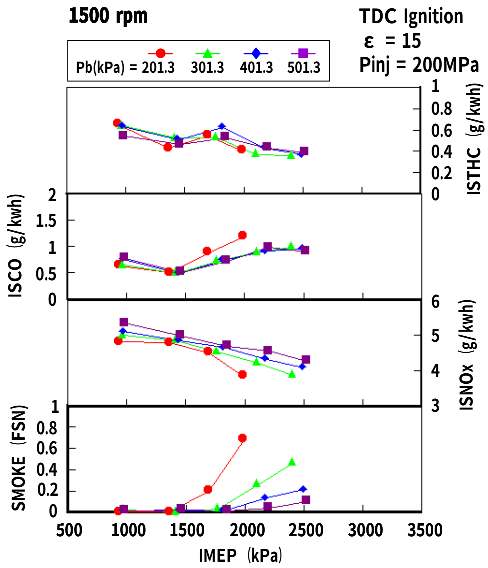

Fig.8 Effect of boost pressures on exhaust emissions (Ne = 1500 rpm)

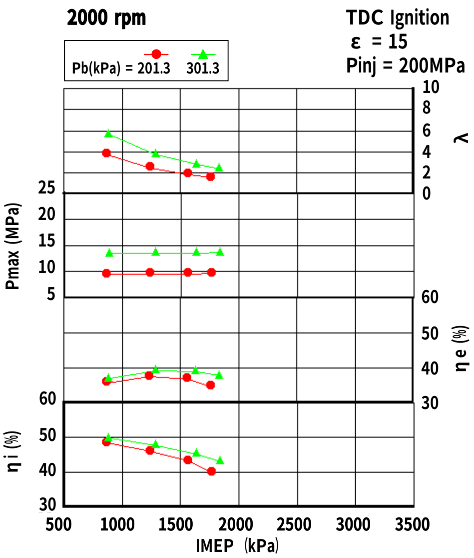

Fig.9 Effect of boost pressures on Pmax and thermal efficiency (Ne = 2000 rpm)

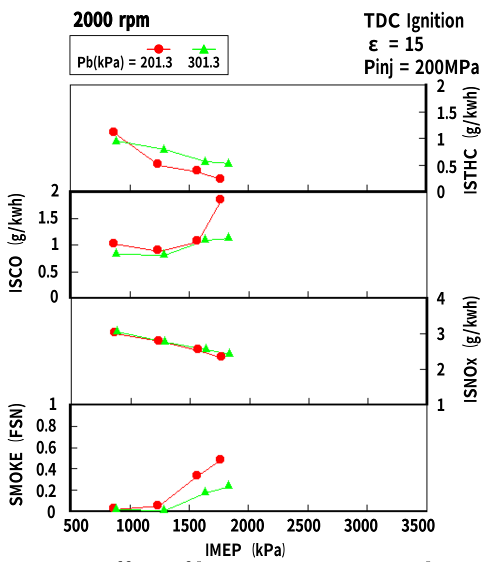

Fig.10 Effect of boost pressures on exhaust emissions (Ne = 2000 rpm)

or fuel injection quantity. At the beginning of this experiment, there was an anxiety that the boost pressure would increase and the oxygen concentration would also increase at the lean combustion and that would lead to the increase of oxygen concentration and ISNOx, but in actuality ISNOx did not increase. This result was very interesting. On the other hand, ISNOx tends to decrease when IMEP increases because it causes the decrease of λ. Especially under Pb=201.3kPa, ISNOx decreased at the maximum value of IMEP, and the combustion was good without deterioration of smoke even at λ=1.5.

Although the levels of ISCO and ISTHC per output power were low, it is necessary to lower the level of ISTHC even more, taking the required PM in the future into consideration.

Under the much air the level of smoke was very low because this experiment was performed by supercharging and it can be seen that the combustion was good. Although explained before that under Pb=201.3kPa the combustion was good without deterioration of smoke even at the small value of λ=1.5 at the maximum value of IMEP, the air excess ratio may lower to λ=1.5-2.0 at the condition of more than Pb=301.3kPa, and the smoke would tend to increase at the maximum value of IMEP. Since the injection quantity was as large as 350mm^3/st as never before under the condition that IMEP increased by increasing boost pressure, as the injection duration becomes very long and during that time the piston would come down, it is assumed that the fuel will spread out from the piston cavity and deteriorate the combustion and cause the smoke generation. It is necessary to find the combustion which does not yield smoke at the level of λ=1.8.

Medium engine speed (1500 rpm)

Fig.7 and Fig.8 show the results of Ne=1500rpm. IMEP is 2500kPa at the injection quantity q=305mm^3/st, and the output power is 343kW as equivalent to 6-cylinder engine at 1500 rpm. The pattern of the test result is resemble to the case of Ne=1000rpm, and the maximum brake thermal efficiency at 46% can be obtained at IMEP=1500-2000kPa. As ISNOx has a decreasing tendency against the increase of IMEP, the increase of IMEP is preferable. However, as the decrease of ISNOx is supposed to be caused by the decrease of λ and involves the increase of smoke, it is necessary to find the method to decrease the smoke.

High engine speed (2000 rpm)

Fig.9 and Fig.10 show results of Ne=2000rpm. IMEP was 1850kPa at the injection quantity q=240mm^3/st, and the output power 317kW equivalent to 6-cylinder engine. Because of the specification of the existing nozzle, the injection duration was long, and as the injection quantity was limited, the maximum value of IMEP was 1850kPa. As the frictions increased when the speed increased, the maximum value of the brake thermal efficiency was 39%.

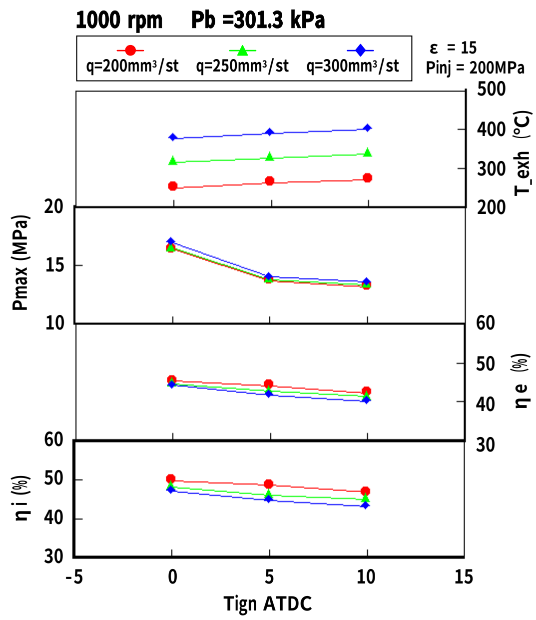

Fig.11 Retardation of combustion timing effects on Pmax and thermal efficiency η e

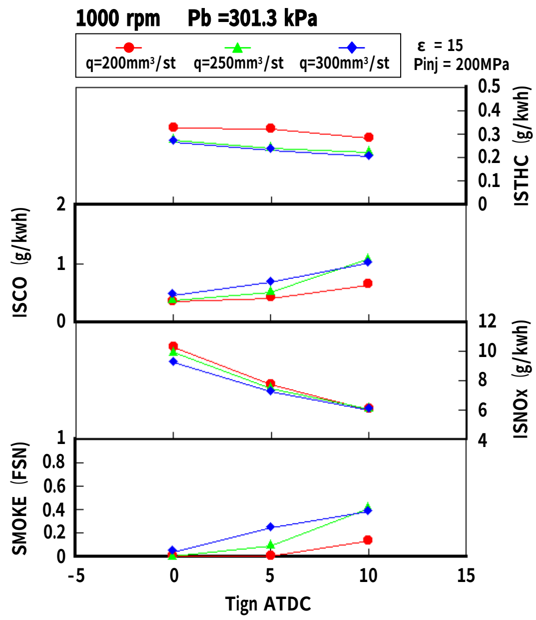

Fig.12 Retardation of combustion timing effects on exhaust emissions

On the other hand, the level of ISNOx was low, and ISNOx decreased against the increase of IMEP. As the injection duration became long at a high speed, the smoke increased remarkably when the injection quantity increased. Accordingly, high BMEP engine should have the good injection characteristics of both high speed & high load point and low speed & low load point, and the injection quantity should cover the large range from idling to 350mm^3/st.

Combustion retardation (1000 rpm)

The effects of combustion retardation by fuel injection timing retarded on engine performance and exhaust emissions in 1000rpm are shown in Fig.11 and Fig.12 respectively. In these Figures the parameter is fuel injection quantity, which is varied from 200 to 300 mm^3/st. The purpose of combustion retardation is the reduction of ISNOx and the reduction of ISNOx is 40% by 10deg of combustion retardation. The demerits in exhaust emissions are increases of ISCO and smoke concentration. Considering future restrict emission regulation, the concentration of smoke should be depressed its increase in order to reduce the mass of PM. For keeping low smoke level, the limit of combustion start is 5deg. ATDC and the limit of fuel quantity is 250mm^3/st in Pb= 301.3kPa condition and at keeping these conditions the reduction of ISNOx can be 25% due to the 5deg. combustion retardation. Keeping high boost pressures ISNOx can be reduce largely by combustion retardation. On the contrary the brake thermal efficiency in q=250mm^3/st deteriorates 2.5% by 5deg. combustion retardation and this means, namely, 5% of deterioration in fuel consumption.

By the combustion retardation Pmax reduces 3.5MPa from TDC to 5deg.ATDC of ignition but Pmax does not change after 5deg.ATDC of ignition because the Pmax changes to the peak of compression pressure from the peak of combustion pressure.

CONSIDERATION

Pmax and brake thermal efficiency

While supercharging boosts the intake air, Pmax is increased and at the same time the brake thermal efficiency is also improved. By increasing Pmax the brake thermal efficiency shown in Fig.13 was obtained by boosting Pmax and increasing IMEP. From this result, the thermal efficiency, namely, fuel consumption can be improved by extending Pmax to 20-25MPa and by using the high thermal efficiency range of IMEP=1.5-2.0MPa as the running range in vehicle.

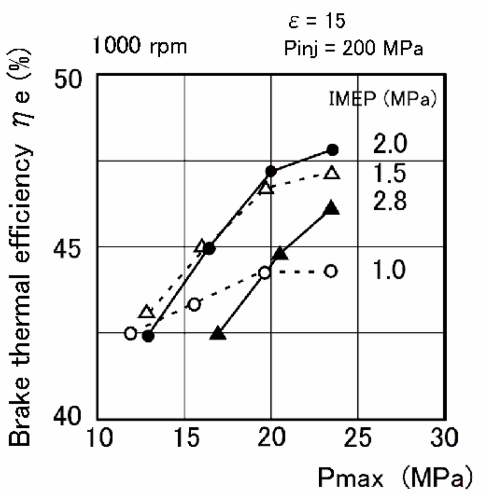

Fig.13 Improvement in brake thermal efficiency by Pmax increase (Ne = 1000 rpm)

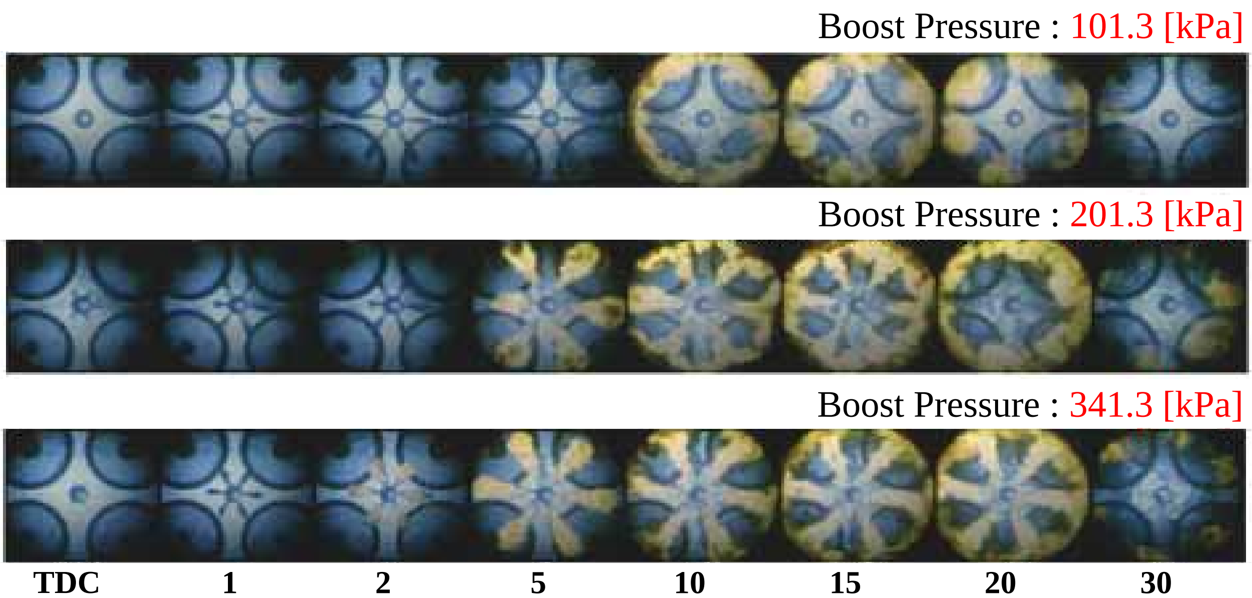

Fig.14 High-speed photographs of diesel combustion (Pinj = 100 MPa, λ = 3.5, ε = 16, Ne = 1000 rpm)

Reduction of exhaust emissions

Pb=201.3 and 301.3kPa obtained from this experiment, the value of NOx without after treatment is the same to that of the current regulation. It is necessary to decrease NOx value in future by means of the large volume of EGR because there is the limit of combustion retardation.

Furthermore, the increase of the air amount by raising the boost pressure has a good effect on reducing the smoke. However, in the case where Pb=201.3kPa at Ne=1500rpm, NOx decreases, but smoke increases when IMEP exceeds 1500 kPa. It is due to the decrease of excess air ratio caused by the increase of IMEP. It is necessary to find the combustion where the smoke does not arise at the level of λ=1.8.

Observation of combustion

Fig.14 shows the results of the combustion observation by the single cylinder engine. This observation was conducted under the same condition to the performance test but the injection pressure was 100MPa and the boost pressure was increased to Pb=341.3kPa from the level of NA. The results of the combustion observation provided many facts useful for consideration. If the boost pressure increased, ignition would occur extremely fast. The spray enters the flame and the density difference between the flame and the air becomes greater. The combustion duration in high pressure condition becomes longer due to large amount of fuel and furthermore it is necessary to promote the mixing of fuel spray and air by new method.

Improvement items

Under the engine speed of Ne=2000rpm in this test the injection duration was too long and in order to shorten the duration it is necessary to increase the total nozzle area. It is important to consider the existing desirable balance of combustion lest the total nozzle area should be increased too much. Moreover, as the excess air ratio decreases and involves the increase of smoke when the injection quantity increases. It is necessary to find the combination of the injection system and the combustion chamber where the smoke will not arise under the level of the air excess ratio λ=1.8.

SUMMARY

The engine performance and the characteristics of exhaust emissions were examined by inducing the amount of intake air up to 5 times of NA engine and by increasing the injection quantity up to 350mm^3/st under the condition of the injection pressure 200MPa.

1. By increasing the amount of intake air, combustion has been improved and as a result the sharp heat release has been obtained and thermal efficiency has improved. By increasing the amount of air and by increasing Pmax, brake thermal efficiency has been improved.

2. In case of the high boost diesel combustion, by increasing the air amount, NOx weight per output power did not increase. Furthermore the smoke has been reduced greatly by increasing the air amount. It has proved experimentally that the reduction of both NOx and PM is effective by high boost and lean combustion.

ACKNOWLEDGMENTS

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NOMENCLATURE

BMEP	:Brake mean effective pressure	kPa, MPa
IMEP	:Indicated mean effective pressure	kPa, MPa
Ne	:Engine speed	rpm
Pb	:Boost pressure	kPa
Pinj	:Injection pressure	MPa
q	:Injection fuel quantity	mm^3/st
ROHR	:Rate of heat release	kJ/°CA
ISNOx	:Indicated specific NOx	g/kWh
ISCO	:Indicated specific CO	g/kWh
ISTHC	:Indicated specific THC	g/kWh
SMOKE	:Smoke FSN	
ε	:Compression ratio	
λ	:Air excess ratio	
ηe	:Brake thermal efficiency	%
ηi	:Indicated thermal efficiency	%

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