# Combustion Performance of a Fuel Spray Combined with a Water Spray in a Diesel Engine

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ABSTRACT

To reduce exhaust smoke and NOx, the technique of combining a water spray with the fuel injected into the cylinder of a diesel engine was applied to a large diesel engine using a side injection type system.

When the water/fuel volume ratio is 50%, the exhaust NOx is reduced by 50% but the fuel consumption is increased by 2%.

INTRODUCTION

Recently, from the point of view of air pollution, it has become very important to reduce NOx levels in diesel engine exhaust. To this point, most methods of reducing NOx have concentrated on reducing combustion gas temperature, using such techniques as retarding the fuel injection timing and lowering the intake air temperature of diesel engines.

The most effective method of reducing NOx emissions from diesel engines is to inject water into the combustion flame.

As the water injection is independent of the fuel injection, this injection system, which combines the fuel spray with the water spray, is effective for combustion in diesel engines. The water spray is combined with the fuel spray near the exit of the nozzle hole, increasing the total momentum of the spray, especially improving the after burning stage of the combustion process.

It is thought that water injection should precede fuel injection to reduce exhaust NOx effectively. However, it is thought that exhaust smoke is better reduced if fuel injection precedes water injection. In the future, electrically controlled injection systems will be effectively applied for variable injection timing of the fuel spray and the water spray to provide an optimum combustion process.

This paper presents the combustion performance of this injection system.

Meanwhile, aiming at a reduction in the NOx emitted by diesel engines, the development of a stratified fuel-water injection (SFWI)[1] system is now under way at MHI with a new water addition system that will replace the previous water addition system, which used an emulsified fuel oil. This new system injects fuel and water in a stratified system by feeding water into the fuel valves during the period when fuel injection is not taking place. Since ignitability is insured by the injection of fuel oil, a considerable quantity of water can be added, and therefore a considerable reduction in NOx emissions can be expected.

As a result, the combustion characteristics of this system have been clarified, and a large reduction in the emission of NOx, without worsening fuel consumption, has been confirmed.

FUEL SPRAY COMBINED WITH WATER SPRAY

Aiming at a reduction in the NOx emitted by diesel engines, the development of a combined fuel-water injection system, with a new water addition system, is now under way. This system injects fuel and water together near the exit of each nozzle hole.

Since ignitability is insured by injecting an independent fuel spray, a large quantity of water can be added and, therefore, a considerable reduction in NOx emissions can be expected.

Fundamental combustion tests of the injection system have been conducted on a single-cylinder test engine typifying a large, low-speed, 2 cycle diesel engine.

The evaporating latent heat and high specific heat of water together lower the gas temperature. Combining the fuel spray with water increases the momentum of the total spray mass, and the large momentum of the combined spray accelerates mixing with air. This injection system has consistently good ignition and combustion.

The Injection System

Fig. 1 shows the injection system. Fuel goes through an injection pipe under pressure from a fuel injection pump, which is activated by a cam

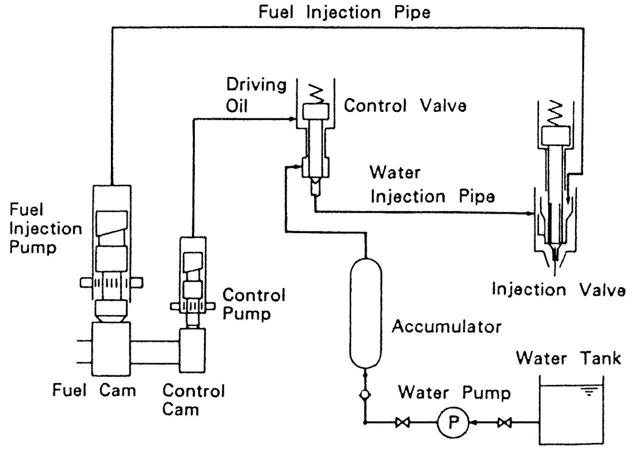



Fig.1 Injection system

on the main engine shaft. Water goes through another injection pipe from an accumulator tank, which is supplied by a high pressure water pump. The injection period is controlled by a valve which is operated by oil pressure. The oil pump is driven by a cam shaft geared to the main engine shaft.

The control valve is opened by oil pressure, which determines the delivery time. High pressure water from the control valve reaches the injection nozzle through the water injection pipe.

Fig. 2 shows the structure of the control valve. The oil from the oil pump enters the bottom of the plunger and the rising oil pressure opens the valve.

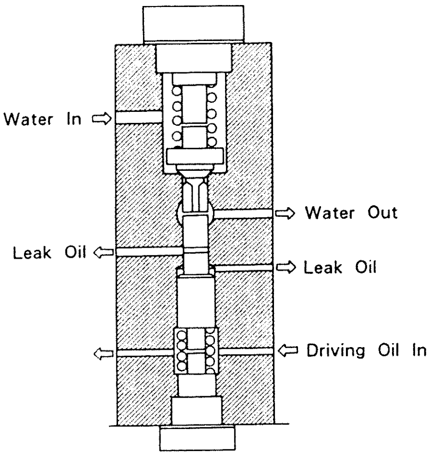



Fig.2 Control valve

The high pressure water from the accumulator goes through the control valve to the injection nozzle. The water injection stops when the control valve closes because the oil pressure drops.

Fig. 3 shows the injection valve which combines the fuel nozzle holes with water nozzle holes.

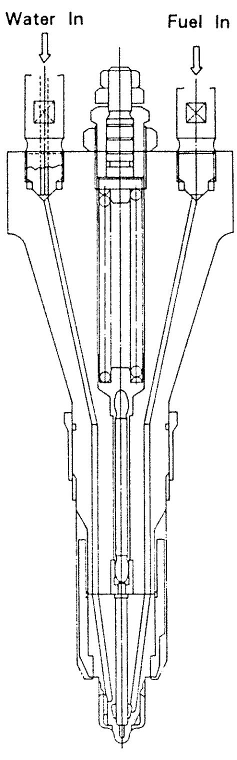
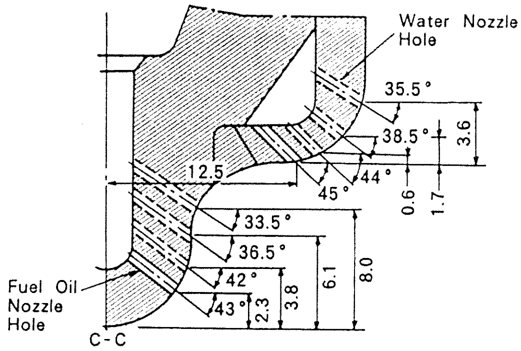
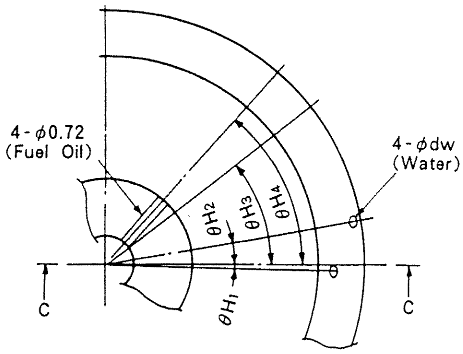



Fig.3 Injection valve

Fig. 4 shows the injection nozzle. There are four holes each for water and fuel, with a 2 degree angle between each pair of holes.




Vertical section of nozzle tip




Horizontal section of nozzle tip

Fig.4 Injection nozzle

<u>Injection Test</u>

An injection test was conducted to measure injection performance. Fig. 5 shows the effect of water pressure on the water injection.

Fig. 6 shows the effect of water volume on the water injection.

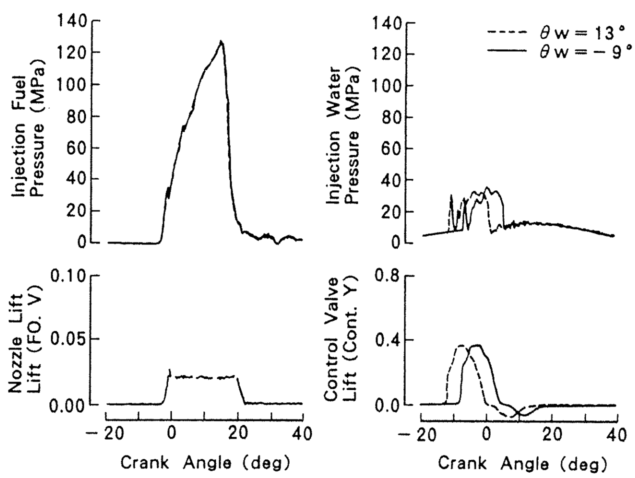



Fig.5 The timing of the water injection

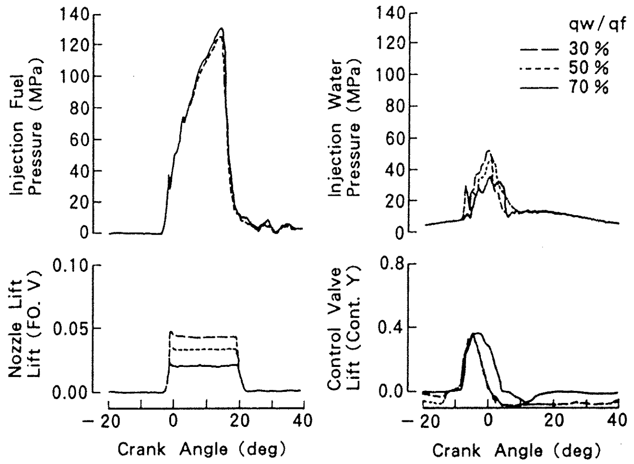



Fig.6 The variable volue ratio of qw/qf

COMBUSTION TEST OF A SINGLE CYLINDER TYPE DIESEL ENGINE

A combustion test was conducted to investigate combustion performance and NOx emission levels.

Fig. 7 shows the test engine.

Table 1 shows the specifications of the test engine.

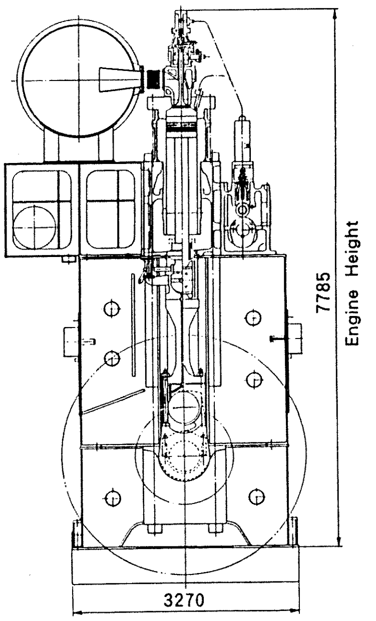



Fig.7 Test engine

Table 1 Type of test engine

| Type | Diesel Engine of 2 Stroke Crosshead Type | | |
|---|---|---|---|
| Cylinder No. | Z | | 1 |
| Cylinder Dia. | D | mm | 450 |
| Stroke | S | mm | 1400 |
| Output | Le | kW | 1184 |
| Revolution | N | rpm | 172 |
| Mean Effective Pressure | P me | MPa | 1.88 |
| Mean Piston Speed | C m | m/s | 8.03 |
| Max. Pres. in Cylinder | Pmax | bar | 160 |
| Length | | mm | 4075 |
| Width | | mm | 4415 |
| Height | | mm | 8285 |

Fig. 8 shows the special combustion chamber, which is of the ball type for minimum heat loss. The piston surface is shaped to create the ball-shaped combustion chamber. The outer diameter of the piston is raised, to create squish flow in the combustion chamber at the top dead center of the crank cycle.

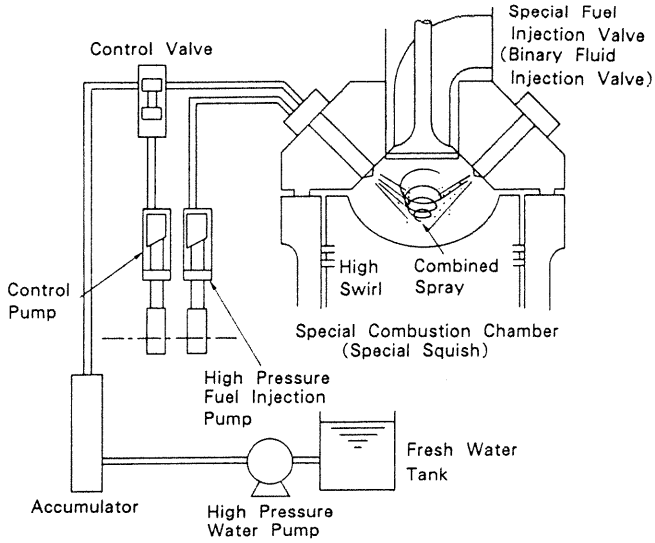



Fig.8 Matching test system of test engine with optimum combination

RESULTS OF THE ENGINE TEST

Engine Performance

The authors succeeded in burning low grade fuel oil with optimum matching of the engine. Performance, including smoke density, was better than that when heavy fuel oil was burned under normal operating conditions, thus achieving the object of this development. (Fig. 9)[2]

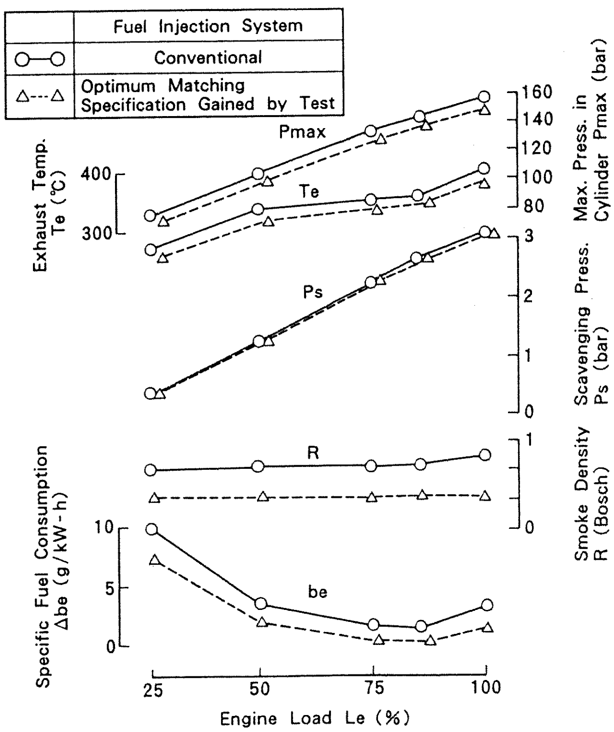



Fig.9 Comprehensive evaluation for influence of high pressure water injection on engine performance

The newly developed high pressure water injection increases the momentum of the fuel spray. In particular, the injection of high pressure water in the latter part of the fuel injection period effectively reduced the smoke density, due to improvement of after burning, by forming a combined spray of fuel oil and water.

The technologies developed through this study could improve (reduce) smoke density by more than 50%, compared with conventional technology under the same conditions.

The reason for the improvement in engine performance is thought to be the increase in spray momentum caused by the addition of the water spray.

The averaged air excess ratio, $\lambda_m$, in the spray is shown in the next formula.

$$\lambda_m = \frac{G_a}{L_{th} \cdot G_f} \qquad (1)$$

In the time $(to)$ under constant injection conditions, $G_a$ is proportional to $G_f$.

$$G_a \propto K(to) \cdot G_f \qquad (2)$$

When the fuel spray is combined with a water spray. $L_{th\text{-}e}$ deceases as water is increased.

$$L_{th\text{-}e} = L_{th} / (1+\varepsilon_w) \qquad (3)$$

Therefore, the air excess ratio $\lambda_m$-e is as shown in the next formula.

$$\lambda_{m\text{-}e} = \frac{G_a(1+\varepsilon_w)}{L_{th} \cdot G_f} \qquad (4)$$

In the combined spray, the air weight/unit of fuel is increased. As the formation of combustible mixture is increased, better engine performance is obtained.

Reduction of NOx

To reduce exhaust smoke and NOx, the fuel spray combined with water is injected into the cylinder.

Fig. 10 shows the reduction of NOx at a water/fuel ratio of 50%. The NOx decreases from 1400ppm to 700ppm.

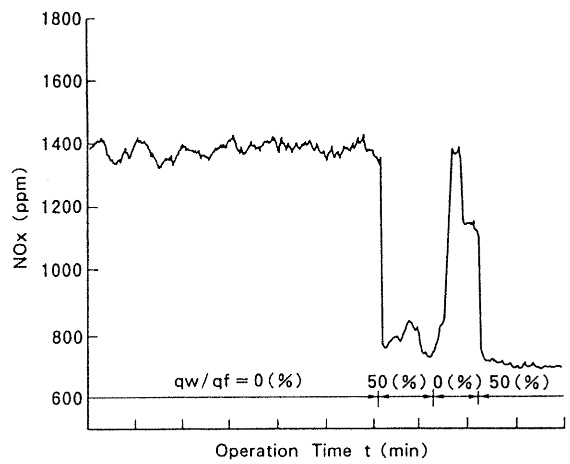



Fig.10 Reducing NOx by fuel oil spray combined with water spray

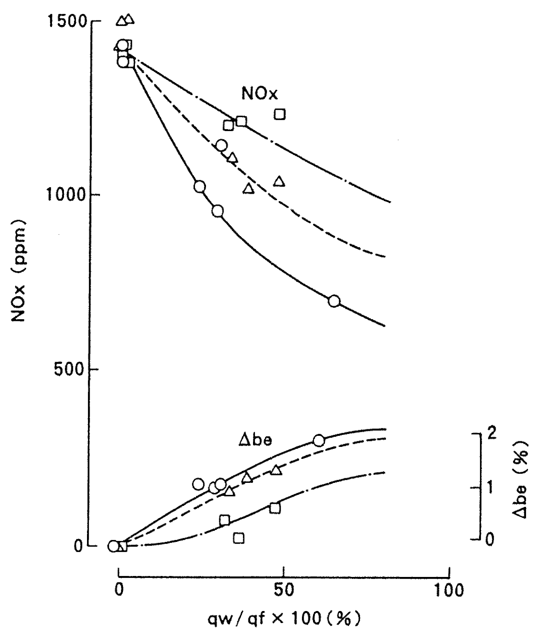



Fig.11 Reducing NOx by increasing water/fuel ratio

Fig. 11 shows the reduction of NOx achieved by increasing the water/fuel ratio. However, the fuel consumption increases against the reduction of NOx.

When the water/fuel volume ratio is 50%, NOx is reduced by 50%, but fuel consumption is increased by up to 2%.

Fig. 12 shows the effects of water/fuel injection timing on combustion performance. To reduce NOx, it is better that the water injection precede the fuel spray. However, to reduce exhaust smoke, it is better that the fuel injection precede the water spray. The results

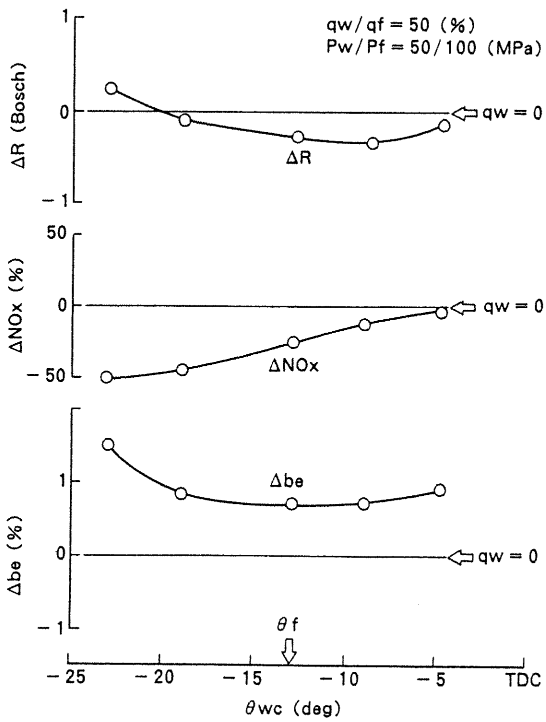



Fig.12 Effects of water/fuel injection timing on combustion performance

suggest that NOx is generated at the point the spray flames, and that smoke is generated during after burning.

CONCLUSION

To reduce exhaust smoke and NOx, the technique of combining a water spray with the fuel injected into the cylinder of a diesel engine was applied to a large diesel engine using a side injection type system. As the water injection system is independent of the fuel injection system, the total injection system can be stabilized for optimum performance of the engine. At the nozzle exit, the water injection spray is combined with the fuel spray through an additional nozzle hole.

since combining the water spray with the fuel spray increases the total momentum of the spray, the after burning stage of the combustion process in improved. The following results were obtained:

1) To reduce exhaust NOx, it is better that the water injection precede the fuel spray.

2) When the water/fuel volume ratio is 50%, exhaust NOx is reduced by 50%, but fuel consumption is increased by 2%.

3) But, to reduce exhaust smoke, it is better that the fuel injection precede the water spray.

4) The fuel spray combined with water injected into the cylinder makes an effective system for reducing exhaust, NOx and smoke.

In the future, an electrically controlled injection system will be effectively applied for variable injection timing of the fuel and water sprays, providing an optimum combustion process.

NOMENCLATURE

$\lambda$ = air excess ratio
$G$ = liqid weight in the spray, $kgf/m^3$
$L$ = air/fuel ratio
$K(to)$ = function with $(to)$
$\varepsilon_w$ = weight ratio of water/fuel

Subscripts
$m$ = mean
$a$ = air in the spray
$f$ = fuel in the spray
$th$ = theoretical
$e$ = in the combined spray
$w$ = water/fuel

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