Effect of Water Induction on the Performance and Exhaust Emissions in a Diesel Engine (II)

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This study was to investigate the effects of water induction through the air intake system on the characteristics of combustion and exhaust emissions in an IDI diesel engine. The fuel injection timing was also controlled to investigate a method for the simultaneous reduction of smoke and NOx when water was injected into the combustion chamber. The formation of NOx was significantly suppressed by decreasing the gas peak temperature during the initial combustion process because the water played a role as a heat sink during evaporating in the combustion chamber, while the smoke was slightly increased with increased water amount. Also, NOx emission was significantly decreased with increase in water amount. A simultaneous reduction in smoke and NOx emissions was obtained when water was injected into the combustion chamber by retarding more 2°CA of the fuel injection timing than without water injection.

Key Words : Water Injection, Fuel Injection Timing, Diesel Engine, Intake Port, Smoke, NOx

Nomenclature

BSFC : Brake specific fuel consumption
BTDC : Before top dead center
$dP/d\theta$: Pressure rise rate
$dQ/d\theta$: Heat release rate
NOx : Oxides of nitrogen
NOx^* : Oxides of nitrogen without water injection
NOx^0 : Oxides of nitrogen with water injection
P : Combustion pressure in the cylinder

1. Introduction

Technologies to obtain power from water have been studied ever since the internal combustion engine was devised (Dryer, 1993). However, there have been no significant results in obtaining power using neat water without any fuels. Previous experimental studies on the effect of introducing water in diesel engines were carried out with mixtures or emulsions of water and fuel (Ishida et al., 1997 ; Jacques et al., 1977). There is a little comprehensive information on the relative advantages of various methods of injecting water into diesel combustion systems.

There are three ways to supply water to an internal combustion system : 1) via the air inlet manifold, 2) directly into the cylinder through a separate injection pump and injection nozzle, and 3) directly into the cylinder with the fuel (emulsified fuel) through the fuel injection nozzle.

In the first method, the water injection is phased to occur at top dead center of the non-firing stroke and tests have examined a range of water/fuel ratios up to the misfire limit. With the second method, the phasing of the timing of water injection with respect to the timing of fuel injection

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has been varied, as well as the water/fuel ratio. Many researchers (Jacques et al., 1977 ; Sjoren, 1977 ; Greeves et al., 1977 ; Murayama et al., 1998) have studied the effects of adding water using the third method because it eliminates the need for a water tank. However, it has been reported that mixtures of water and fuel are not uniform (Sjoren, 1977).

Greeves et al.(1977) reported the effects of water injection on fuel economy, ignition delay, and exhaust emissions of smoke, CO, NO, and HC (hydrocarbons) in a DI (direct injection) diesel engine. Compared with fuel injection only, NO was reduced up to 70% by injecting water in the air inlet or with the fuel. Nevertheless, while water injected via the air inlet manifold increased smoke and CO, water injected with the fuel reduced smoke and CO up to 50% and provided small improvements in specific fuel consumption. With an increase in HC beyond a water/fuel ratio of 0.6, however, the NO reduction was limited to 50% when injecting water with the fuel. In addition, a computer model of the diesel combustion process showed that, in addition to the thermal effect of water injection, water injection affected the rates of air entrainment and fuel/air mixing. Particularly, water injected with the fuel was an additional source of injected momentum for fuel/air mixing. It has also been reported that water/fuel emulsions were very effective in reducing NOx and smoke (Dryer, 1993 ; Sjoren, 1977 ; Murayama et al., 1998).

Murayama et al.(1998) reported that a large reduction in NOx concentration was obtained over a wide range of engine operations with emulsified fuel in a single DI diesel engine, in spite of the increased ignition lag and rapid combustion. Furthermore, economy was improved and smoke was reduced. The reductions in NOx concentration, fuel consumption, and smoke were even more remarkable when compared with operating the same engine with water fumigation.

Miyamoto et al.(1998) also reported that water injection into the air inlet manifold or directly into the cylinder reduced NOx emissions without any sacrifice of specific fuel consumption. Jurng et al.(1989) reported that with emulsified fuel, ignition delay lagged and NOx and smoke were reduced.

A new way of reducing exhaust emissions by injecting water and solutions into the combustion chamber through the intake port was studied (Ryu et al., 2002). However, NOx was greatly reduced with water injection through intake port, but smoke was not improved more than without water supply. In addition, there are few reports on the effect of various solutions in reducing NOx and smoke and improving engine performance. Thus, this study considered the water injection through intake port and the fuel injection timing for simultaneously reducing NOx and smoke in an IDI diesel engine.

This study focused on the effects of water injection on exhaust emissions. Engine performance and exhaust emissions with water injection were compared with conventional diesel fuel. Moreover, an improved method for simultaneously reducing NOx and smoke by varying the timing of fuel injection is explored in this study.

2. Experimental Apparatus and Method

2.1 Test engine and apparatus

This study considers a water-cooled, 4-cylinder, 4-stroke, commercial indirect injection diesel engine without any modifications. The principal specifications of test engine are provided in Table 1. The test engine was started by a starting motor and manually controlled by an eddy current engine dynamometer (HW130) that was capable of maintaining a constant engine speed and absorbed 130 kW of the engine output power.

Table 1 Specifications of test engine

Item	Specification
Engine model	HD D4BA
Bore × Stroke	91.1 × 95 (mm)
Displacement	2476 (cm^3)
Compression ratio	21
Combustion chamber type	Pre-combustion
Injection timing	Variable
Coolant temperatue	80±2℃

To investigate exhaust emissions, a Bosch type smoke meter (HBN-1500) and an exhaust gas analyser (Green line MK) employing the electrochemical cell type detector were installed at the position of 300 mm down the exhaust pipe from the exhaust manifold. The fuel consumption rate was also measured with a 150 cc measuring gauge and a stop watch. To analyze the combustion characteristics of the diesel engine with water induction, a piezoelectricity pressure sensor (Kistler 6061B) with a water-refrigerated adaptor was mounted on the pre-chamber of the fourth cylinder, and the pressure data generated from the sensor were sent to a date acquisition system through the pressure transducer (Kistler 5011).

2.2 Experimental method

The experiments were conducted with water injection at engine speeds of 1000, 1500, 2000, and 2500 rpm, and at engine loads of 0, 25, 50, 75, 90, and 100%.

The test engine was operated with 80±2℃ cooling water under all experimental conditions. After completing test work on a selected test condition, the fuel filter and engine oil were exchanged with new ones in order to avoid any effect on the next test.

To effectively supply water into the cylinder, two-hole gasoline injectors were installed on the intake manifold of the IDI diesel engine. The first distilled water was used in these tests. The injection pressure and temperature of water were 0.2 MPa and 20℃, respectively. The amount of water injected was 10, 20, 30, and 40 mg for most test conditions, but 10 mg water was injected for the tests of fuel injection timing. To investigate the effects of fuel injection timing on the exhaust emissions, fuel was injected by retarding the injection timing from BTDC 10℃A to BTDC 0℃A at 2℃A interval.

Figure 1 shows a schematic diagram of the water injection system. The timing and duration of each injector in the system were controlled by the A and Z pulses generated by the encoder driven by the engine crankshaft. Figure 2 gives the locations of the water injectors.

Figure 3 shows the timing and duration of the water injections. The start of the injection occurred at 10℃A after the intake valve was opened. The amount of water was controlled by changing the pulse duration width of the injector for each test condition.

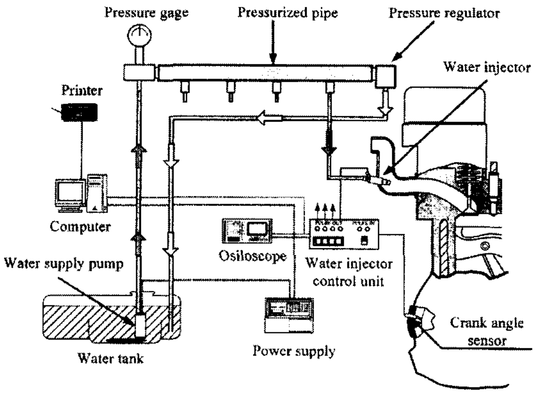

Fig. 1 Schematic diagram of experimental apparatus

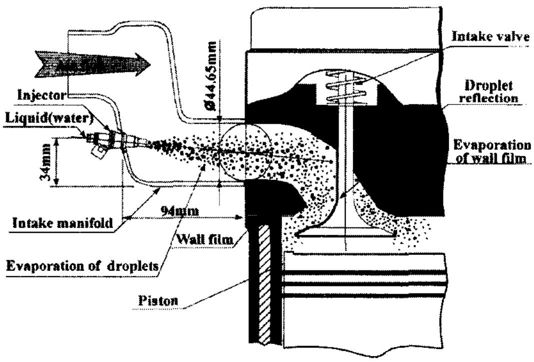

Fig. 2 Location of water injector

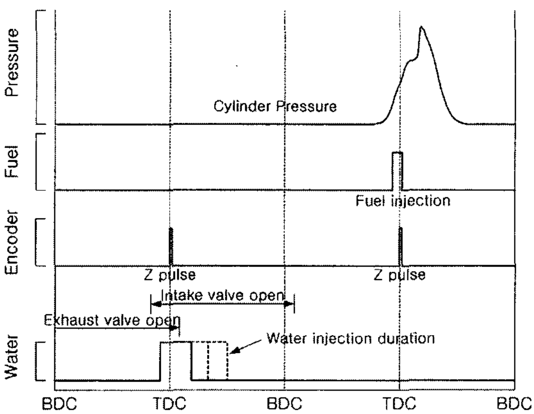

Fig. 3 Timing and duration of water injection

3. Results and Discussion

3.1 Effects of water induction

Figure 4 shows the effects of water injection on the exhaust emissions as a function of the engine load at an engine speed of 2000 rpm. For all fuels, there is a traditional BSFC trend for variations in the engine load: BSFC slightly increases for all loads with water injection rates of 10, 20, and 30 mg, and greatly increases with a water injection rate of 40 mg. This may be caused by the reduction of peak pressure and temperature in cylinder due to water injection.

For all fuels, the NOx emissions increase with increasing engine loads up to 75%. The NOx emissions then decrease with further increases in the engine load. The NOx emissions are lower with water injection than without, and decrease with increasing rates of water injection. The greatest reduction of NOx emissions in terms of the absolute amounts occurs for medium loads. The smoke and CO concentrations increase with the engine load, and slightly increase with the water injection rate.

Figure 5 shows the cylinder pressure, rate of pressure rise, and heat release rate at an engine speed of 2000 rpm for a full load. The peak pressure is reduced and the auto-ignition timing is delayed as the water injection rate increases. This is caused by the temperature reduction in the cylinder due to water induction, and explains the decreased engine performance shown in Fig. 4. Ignition delay increases slightly with the amount of injected water as seen in the pressure rise rate and heat release rate curves in Fig. 5. The heat release rate of early premixed combustion region increases due to the increase in ignition delay as the amount of injected water increases.

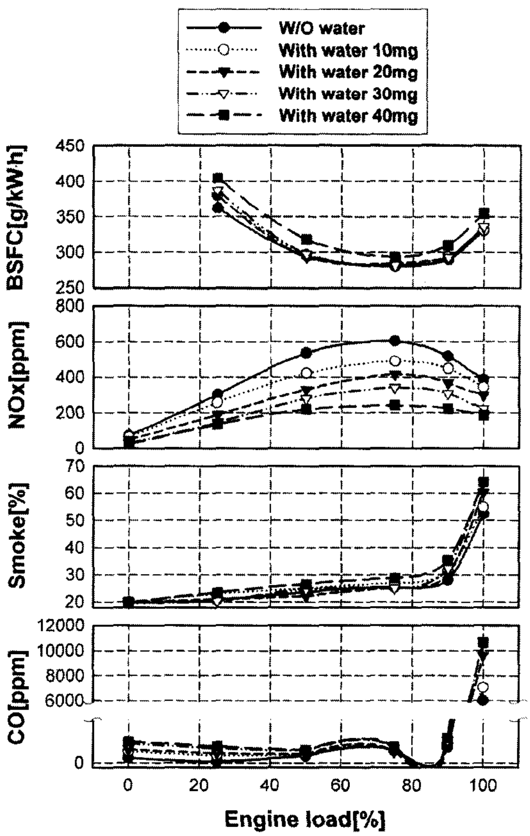

Fig. 4 Exhaust emissions versus engine load at an engine speed of 2000 rpm

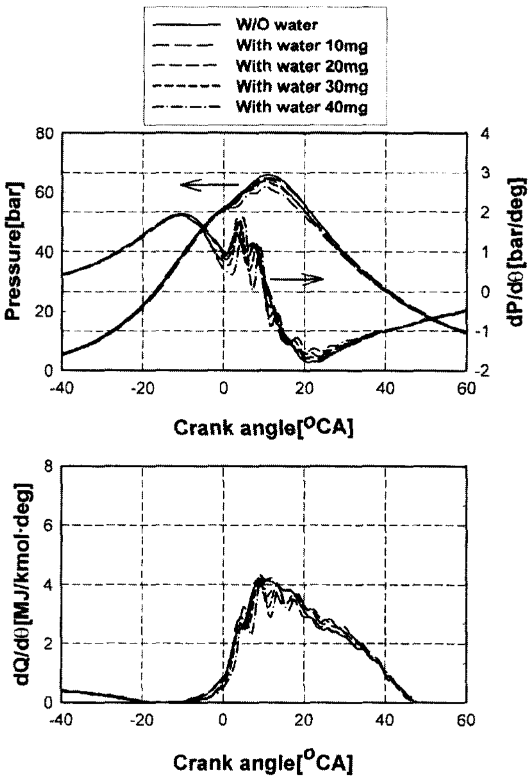

Fig. 5 Pressure, $dP/d\theta$ and $dQ/d\theta$ at an engine speed of 2000 rpm and an engine load of 100%

Figure 6 shows the exhaust emission characteristics with water injection as a function of engine speed at the engine load of 75%. NOx is reduced with increasing rates of water injection at all engine speeds, due to the reduction in the cycle temperature. Figure 7 shows the cylinder temperature at an engine speed of 2000 rpm and a load of 100%. The cylinder peak temperature decreased with increase in water injection rate through into the intake port. This result may cause the reduction of NOx as shown in Figs. 4 and 6. With increasing rates of water injection, however, the smoke and CO concentrations slightly increase and the BSFC was increased as shown in Fig. 4. Also, the smoke emissions with water injection are greater at lower engine speeds than at higher engine speeds.

Figure 8 shows the effect of the water/fuel ratio on the NOx characteristics. The ratio of NOx with

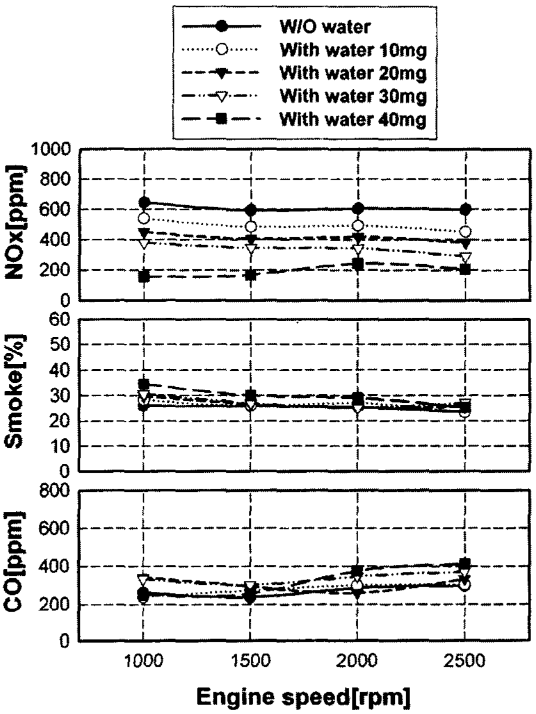

Fig. 6 Exhaust emissions versus engine speed at an engine load of 75%

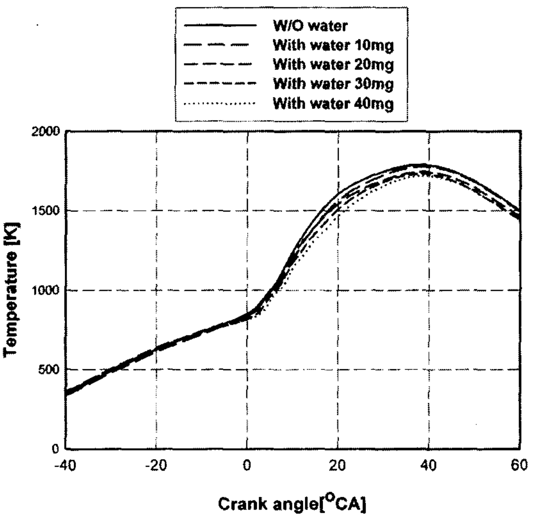

Fig. 7 Cylinder temperature at an engine speed of 2000 rpm and a load of 100%

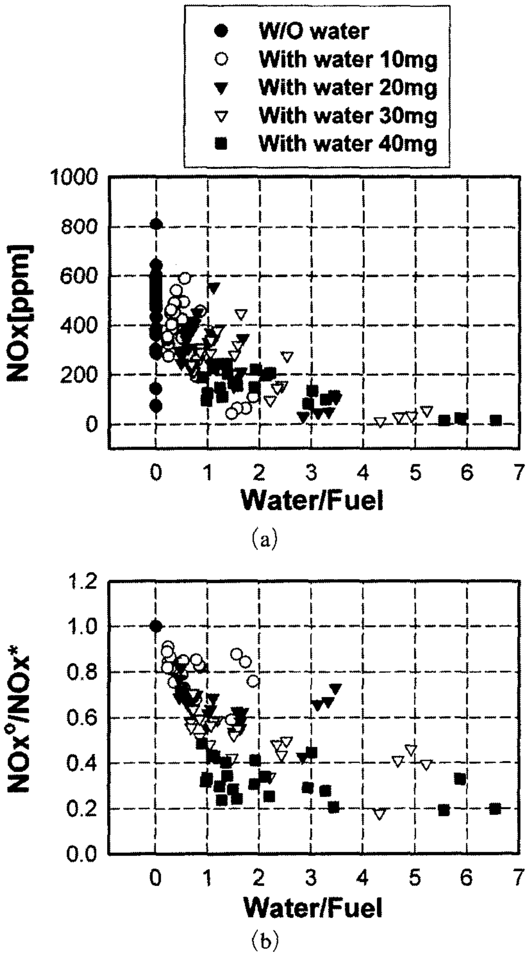

Fig. 8 Variation of NOx emissions versus water/fuel ratio

water injection to that without water injection is also expressed as a dimensionless profile. It can be seen that peak NOx emissions are reduced with an increased water/fuel ratio, but in the case of dimensionless profile in NOx emission shown in Fig. 8(b), NOx are reduced more with an increase in the amount of water injected than with an increase in the water/fuel ratio. The reduction in NOx emissions is therefore affected more by the absolute quantity of injected water than by the water/fuel ratio.

3.2 Effects of fuel injection timing

Figure 9 shows the BSFC, smoke, and NOx at various engine loads and fuel injection timings for diesel fuel without water injection, at 2000 rpm. The lowest BSFC value is obtained for a timing of BTDC 4℃A at the engine load of 25%. At other engine loads except the engine load of 25%, the lowest BSFC value is obtained for a timing of BTDC 6℃A. However, the smoke and NOx concentrations decrease when the fuel injection timing is retarded.

Figure 10 shows the BSFC, smoke, and NOx at various engine loads and fuel injection timings for diesel fuel with 10 mg of water injection at 2000 rpm. The lowest BSFC value is different from that shown in Fig. 9. At a timing of 2℃A, there is a simultaneous reduction of smoke and

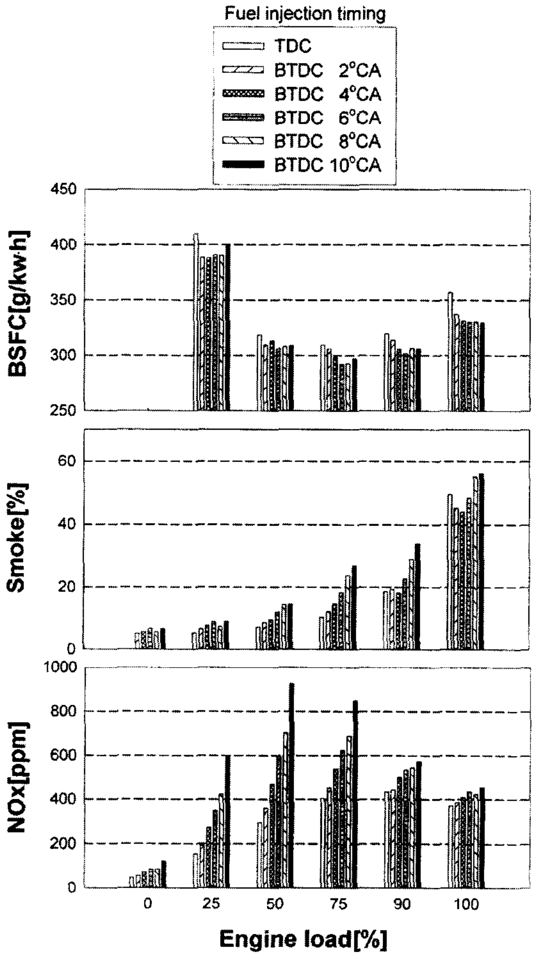

Fig. 9 BSFC, smoke, and NOx versus engine load and injection timing with diesel fuel

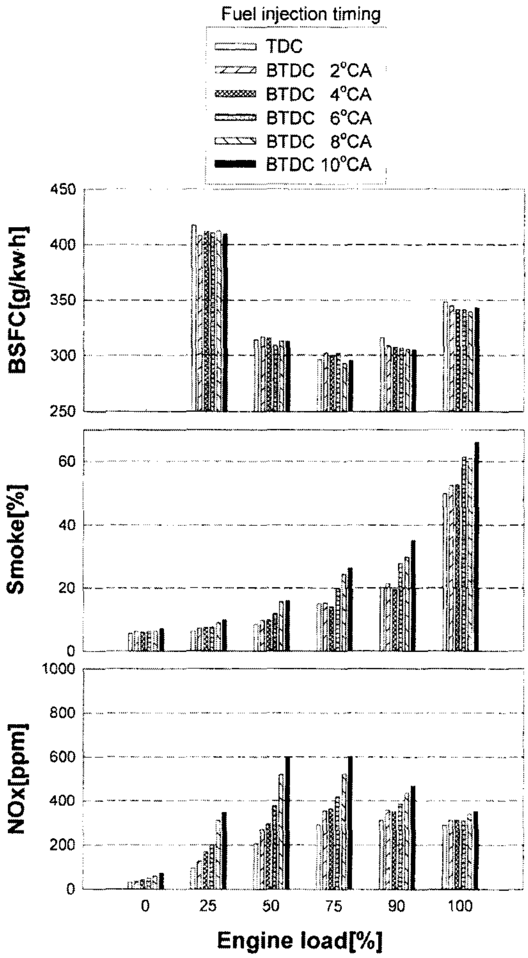

Fig. 10 BSFC, smoke, and NOx versus engine load and injection fiming with water injection of 10 mg

NOx, even though the BSFC slightly increases. Therefore, if the fuel injection timing was controlled over the practical application range, the smoke and NOx concentrations could be simultaneously reduced without any engine modifications.

The optimum fuel injection timing in the practical application range with water injection is shown in Fig. 11. The optimum fuel injection timings with diesel fuel only are BTDC 4℃A and BTDC 6℃A respectively at low loads and high loads. With water injection via intake port, however, the optimum fuel injection timings for exhaust emissions are BTDC 2℃A and BTDC 4℃A respectively at low loads and high loads. Therefore, if the timing of fuel injection with 10 mg of water injection is retarded more 2℃A than without water injection, smoke and NOx emissions could be simultaneously reduced at all engine loads except 100% load with a little sacrifice of the BSFC values.

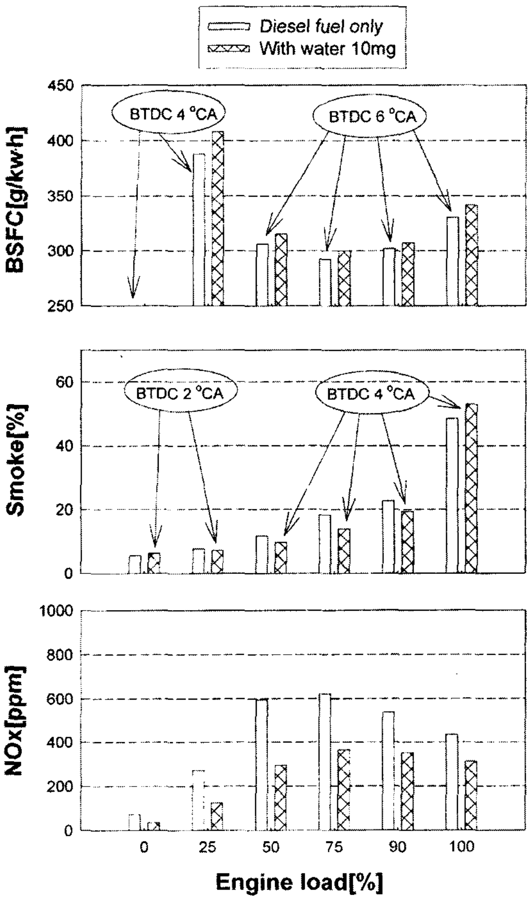

Fig. 11 BSFC, smoke, and NOx versus engine load at optimum injection timing with and without water injection

4. Conclusions

The method of water injection through intake port for simultaneously reducing NOx and smoke in an IDI diesel engine was considered. Especially, an improved method for simultaneously reducing NOx and smoke by varying the timing of fuel injection was explored in this study.

The formation of NOx was significantly suppressed by decreasing the gas peak temperature during the initial combustion process because the water played a role as a heat sink during evaporating in the combustion chamber, but the smoke was slightly increased with increased water amount. The reduction in NOx emissions is also affected more by the absolute quantity of injected water than by the water/fuel ratio.

However, a simultaneous reduction in smoke and NOx emissions was obtained when water was injected into the combustion chamber by retarding more 2℃A of the fuel injection timing than without water injection. Therefore, if the fuel injection timing was controlled over the practical application range, the smoke and NOx concentrations could be simultaneously reduced without any engine modifications.

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