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Effect of nano air-bubbles mixed into gas oil on common-rail diesel engine

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ABSTRACT

The nano air-bubbles mixed into gas oil are used for the energy saving and environmental load reduction of diesel engine. The nano air-bubbles were mixed into the fuel line continually by a super miniature ejector-type mixer (outer diameter: 20 mm, length: 34 mm) which can make nano and micro sizes. After the micro air-bubbles were separated with the nano air-bubbles in a mixing tank, diesel engine performance test with a common-rail injection system was experimented. The results showed that 3% reduction in break means specific fuel consumption, 1% rise in charging efficiency and a slight reduction in the density of exhaust smoke etc. These were caused by mixing the nano air-bubbles into gas oil. It is confirmed that the nano air-bubbles had advanced and activated combustion by a physical and chemical action.

1. Introduction

Recently, improvement in fuel efficiency of vehicles has been drastically required due to the aggravation of problems of the environment and energy, such as global warming, tight oil demand, etc. The demand for diesel passenger cars that are fuel-efficient and emit less greenhouse gases has increased centering around west Europe, where the sales share accounted for more than 56% in 2011 [1]. Meanwhile, in order to cope with the emission control regulations becoming more severe, the increase in the after treatment cost of gases emitted from diesel engines has become a large task. One of its solutions is a fuel pretreatment, that is to say fuel reforming.

Conventionally, various studies are being done on fuel additives to improve diesel combustion and decrease harmful emissions. In-cylinder strategy to reduce local temperatures and consequently the NOx production rate is the injection of water in emulsion with the fuel [2–16]. Most engine experiments and numerical studies using water emulsion fuel technique show that the NOx reduction is accompanied with a large reduction of PM and soot emissions. At a given fuel injection rate, the use of WDE leads to an increase of the total injected mass, of which a consequence is an increase of the mixing rate between fuel and air, thus reducing local fuel–air ratios and consequently PM production [3,10,12]. Author et al. have proceeded with research on simultaneous reductions of fuel consumption and poisonous exhaust gases by mixing gas oil with air-bubbles micronized using air as a means of fuel improvement [17–20]. As a result, the fuel consumption was reduced by 2–14% and reductions of exhaust smoke and NOx were also confirmed, by mixing the gas oil with micronized bubbles, or nano bubbles, to the extent where stable driving is possible without air entrainment in the engine.

As the diesel engine which was used in this research was a jerk fuel injection type, it is unknown whether the gas oil mixed with nano air-bubbles favorably affects the common-rail injection system that is most commonly used now.

Therefore, in this research, a new common-rail injection system was introduced and its effect on the high pressurization of gas oil mixed with nano air-bubbles was discussed experimentally.

2. A summary of micro and nano air-bubbles mixed into gas oil

Practical applications of micro and nano bubble technology have recently become to attract people's great concerns in wide variety of areas in advanced and conventional science and technologies, such as energy conversion and heat removal devices, diagnosis by

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ultrasound echo due to micro and nano bubble collapse, drug delivery systems, cleaning and sterilization by shock waves due to the collapse of high-pressure micro and nano bubbles, production of ozone water, mining using physical absorption at gas–liquid interfaces, purification and improvement of oil-contaminated soil and polluted water by air supply (sea, lake, river etc), absorption of carbon dioxide gas, fish culture, etc [21].

Fig. 1 shows (a) photograph of the device and (b) internal structure of an ejector-type micro and nano air bubble mixture device. The size of this mixture device was 20 mm in outer diameter and 34 mm in length, and the material was brass [22]. The left side of the figure is the inlet for fuel (hereafter referred to as gas oil) and the right side is the outlet of the gas oil mixed with nano air-bubbles.

The mechanism of mixing nano air-bubbles by this mixture device is as follows: 1) It injects the gas oil pressurized by a pump at a high speed using an injection effect or a nozzle, selfprimed air by the negative pressure generated in the neighborhood of the outlet, and form a film-like gas–liquid interface. 2) The absorbed air is separated and bubbled by the separation, turbulent mixing and shearing action of the gas oil. 3) The air-bubbles are further refined by the separation area formed in the sudden expansion region.

This is a method to prompt the atomization of the gas oil spray by mixing nano air-bubbles into gas oil as nano air-bubbles [18], and accelerate the combustion by increasing the amounts of dissolved oxygen and ions [18–20]. As the size of the nano air-bubble mixture device of this method is extremely compact, it is possible to retrofit it to existent diesel engines.

When air-bubbles of the macro or micro-size entered in fuel, a fuel injection pump and a nozzle caused an air entrainment and used only air-bubbles of the nanosize here to become unstable in an engine.

3. Experimental setup

3.1. Experimental apparatus

Fig. 2 shows the schematics of the experimental apparatus used in this experiment, Fig. 3 shows a photograph of its appearance, and Table 1 shows the test engine specifications. The engine load and rotation speed of this experimental apparatus can be controlled from a PC by software for the dynamometer (FC-design Co. Ltd. DA50-UW [23]). Vital engine factors, such as fuel consumption and intake air mass, can be directly obtained and stored by PC.

A commercially available Yanmar Diesel NFD150-E remodeled into a common-rail fuel injection system was used as the test engine (Table 1). As for the test fuels, ordinary gas oil (JIS No.2 gas oil, Table 2, hereafter referred to as control) and gas oil mixed with nano air-bubbles were separately used through a three-way valve fixed in a part of the fuel pipe. In order for the effect of the amount of mixed nano air-bubbles to be measured, two devices, nano air-bubble mixture device I and mixture device II, were fixed on the line of the gas oil mixed with nano air-bubbles.

Fuel flow rate was measured by a 213 type of Max Machinery Inc, smoke in exhaust gas by an opacimeter (light transmission type smoke meter, MEXA-600SW of HORIBA), O_2 concentration by LM-1 of Grid, and noise by a CEM DT-8851 noise meter. In addition, the noise meter was put in the distance of 1 m from engine side, and the setting assumed a properties (a weighted sound pressure level).

3.2. In-line type nano air-bubbles mixture device

In this experiment, two In-line type nano air-bubble mixture devices were fixed on the line supplying gas oil from the fuel tank to the engine. Fig. 4 shows a photograph of the mixture device. For the purpose of measuring the amount of nano air-bubbles mixed into the gas oil, two mixture devices were used.

The gas oil that flowed from the fuel tank and was pressurized by the nano air-bubble mixture device I selfprimes the air at the ejector part, which is sent to a mixing tank installed on the fuel line, as shown in Fig. 5. The ultra fine bubbles formed in this mixture device include micro bubbles and nano bubbles. Therefore, after the bubbles of micro-size were separated at the mixing tank, the gas oil mixed with nano bubbles is supplied to the engine. The gas oil mixed with ultra fine bubbles is referred to as “nano bubble gas oil” hereafter in this research. When the fluid level in the mixing tank rises and switches on a liquid level indicator, the flow is switched to the circulation line of the mixing tank. With this circulation, the efficiency of mixing nano bubbles is raised by increasing the number passing through the injector part. Mixture device II plays the role to raise the amount of bubbles mixed into the gas oil by circulating the gas oil in the mixing tank.

The amount of dissolved oxygen in the mixing tank was measured by a DO meter B-507 for organic solvent of Iijima Electronics Corporation.

3.3. Common-rail type fuel injection system

Fig. 6 shows a photograph of the common-rail fuel injection system. This system was assembled with commercially available components. Table 3 shows the main specifications of the common-rail fuel injection system (FC-design Co. Ltd., Fi-CMR [23]). This system has the ability of multiple injections up to 7 point injections at the maximum injection pressure of 200 MPa.

3.4. Experimental method

A partial load experiment was conducted at a constant rate of 2000 rpm. The total performance of the engine, the smoke in exhaust gas and remaining O_2 were measured, when the brake mean effective pressure of atmospheric correction is 200 ~ 550 kPa.

The time of fuel injection was set as a single point injection 17° before top dead center, which was the rating before the engine was modified to a common-rail type, and the injection pressure was

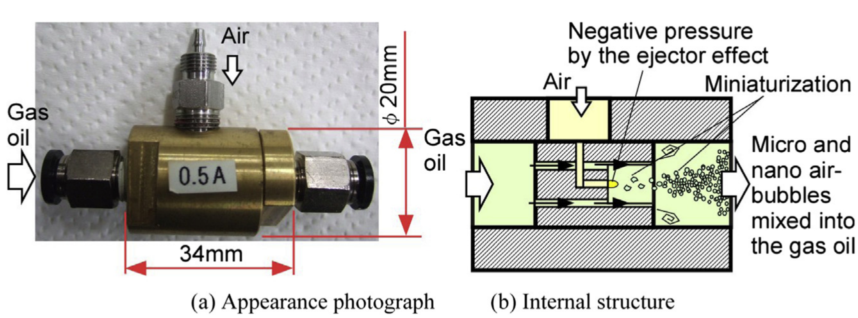

Fig. 1. Ejector-type micro and nano air-bubbles mixture device.

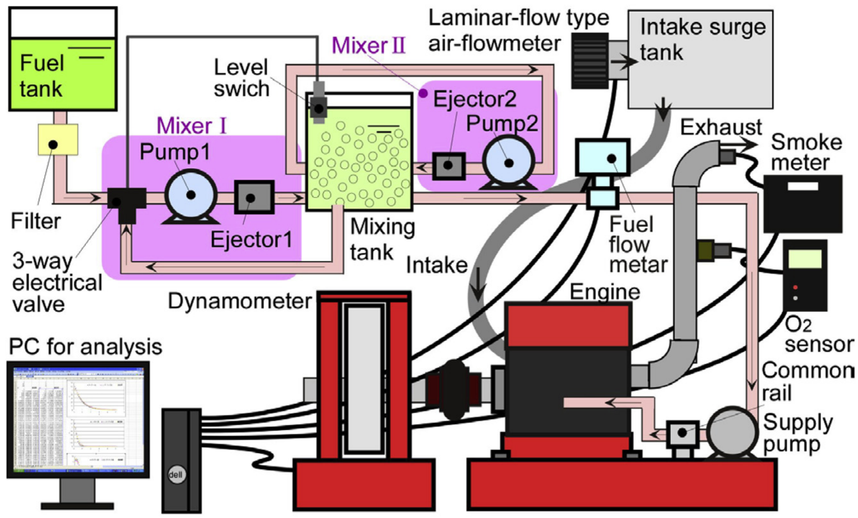

Fig. 2. Schematics of experimental apparatus.

increased to 80 MPa from 20 MPa of before modification. The injection time of fuel for the above load was approximately 0.40–0.85 ms.

3.5. Error analysis

The measurement errors for the fuel flow rate, engine torque, and engine speed are estimated to be about 0.5%, 0.2% and 0.1%, respectively. Total error for brake specific fuel consumption is estimated to be about 0.55%, and is calculated by taking the square root to add the square of three errors. Therefore experimental data were sampled five times, and calculated approximate curves such as the brake specific fuel consumption in the same load condition.

4. Experimental results and discussions

4.1. Nano bubble gas oil

4.1.1. Bubble size

Fig. 7 shows the distribution of the particle sizes in gas oil measured by a NanoSight M-10 of Quantum Design Japan, Inc. Two peaks were observed in the control (309, 649 nm), possibly caused by additive agents and coloring agents originally included in gas oil. Nano bubble gas oil was analyzed after it was mixed for 10 min by a bubble mixture device and extracted from it. In the figure, nano bubbles in gas oil are distributed in the range from 100 nm to 200 nm. It is reported that nano bubbles in water are distributed around 100 nm [17]. So the distribution of particle size of nano bubbles are resemble in water and gas oil. As the number of particles of the control was 0.52×10^8 particles/mL and that of the nano gas oil was 1.07×10^8 particles/mL, the result of the calculation shows that around 0.5×10^8 bubbles/mL of nano bubbles were mixed. This amount of bubbles means that no nano bubbles were included in a drop of fuel spray. If the amount of bubbles is increased to more than 10^{10} bubbles/mL, more than one bubble will be included in every drop of spray, and therefore better fuel efficiency and further decreases in environmental burdens can be expected by using nano bubble gas oil. In the case of common-rail injection system, the spray is more atomized compared with jerk fuel injection system, it is necessary to take measures to increase the amount of mixing nano bubbles furthermore.

4.1.2. Dissolved oxygen

The characteristics of micro and nano air-bubble mixed gas oil become different according to not only the kinds of mixing device and operating conditions, but also the time they are mixed (that is the discharge rate (circulation) against container size and the lapse of time after the mixing stopped.) Therefore, an in-line type micro and nano air-bubble mixture device to be installed in the fuel line

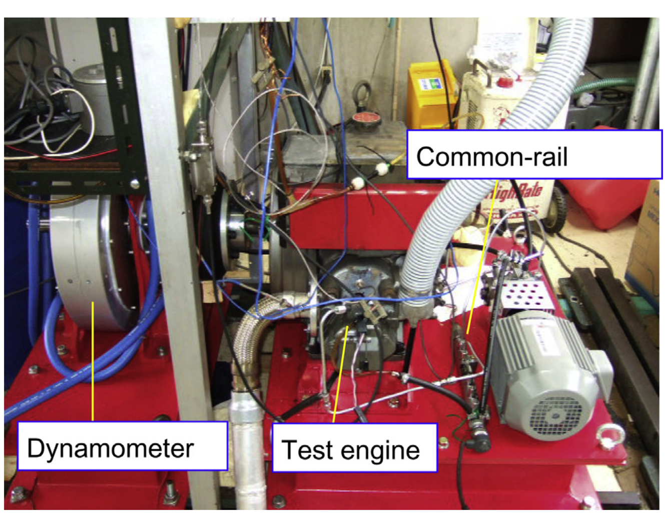

Fig. 3. Snapshot of experimental apparatus.

Table 1
Test engine specification.

Engine model	Remodeled Yanmar Diesel NFD150-E
Type	Water cooled 4-stroke
Combustion	Direct injection
Combustion cavity	Toroidal type
Number of cylinders	1
Bore × Stroke	$\phi 96 \times 105$ mm
Displacement volume	760 cc
Compression ratio	16.5
Max power	11.0 kW/2400 rpm
Injection timing	BTDC 17°
Injector	Common-rail system
Hole diameter × number	$\phi 0.12$ mm × 5
Injection pressure	80 MPa

Table 2
Properties of JIS No.2 gas oil.

Cetane number		56
Net calorific value	MJ/kg	43.12
Density@288 K	kg/mm^3	830
Viscosity@313 K	mm^2/s	2.5
Pour point	°C	−17.5
C	mass %	87.3
H	mass %	12.5
O	mass %	–
Sulfer	mass ppm	< 10
Water	mass ppm	382
50% Distillation temp.	°C	278

was experimentally produced for mounting on a real vehicle, and the chemical characteristics of the micro and nano air-bubble mixed gas oil produced by the device were examined.

Fig. 8 shows the changes with time of the amount of dissolved oxygen in the mixing tank in the cases where the control, only one nano bubble mixture device, and two nano bubble mixture devices was/were used. As the degree of saturation of dissolved oxygen changes depending upon temperature and the amount of saturated dissolved oxygen in gas oil is unknown, the vertical axis of the graph shows the volume of relative dissolved oxygen (DO_R) in gas oil non-dimentionalized by the volume of saturated dissolved oxygen in water, of which the temperature dependence is known.

The DO_R in the case of the control is stable at around 50%. Furthermore, because the DO_R at the time when the nano bubble mixing started was around 70%, the DO_R of the control is presumed to be in the range of 50–70%. The DO_R became stable at 92% in around 20 min when only one nano bubble mixture device was used, and it became stable at 98% in around 10 min when two nano bubble mixture devices were used. These values are thought to be limited by the conditions of the mixture device and mixing in this experiment.

Shortening of burning time is predicted by increase of a partial excess air factor because the amount of dissolved oxygen in fuel increases.

4.1.3. GC/MS measurement

Fig. 9 shows the results of analyses of the control and nano bubble gas oil using a GC/MS (Gas chromatograph-Mass spectrometer). The horizontal axis shows the time and the vertical axis shows the ion intensity. The upper side shows the control and the lower side shows the nano bubble gas oil. As gas oil is the mixture of carbon hydrides, substances with different numbers of carbon

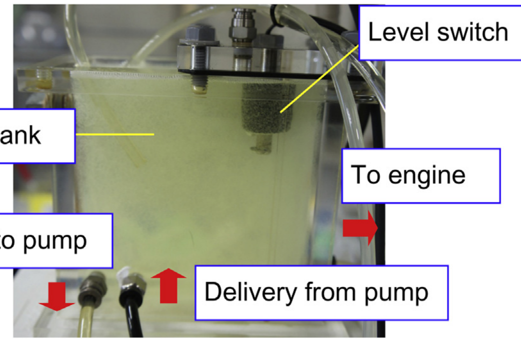

Fig. 5. Micro and nano air-bubbles mixed into the gas oil.

and of saturated and unsaturated bindings are mixed. The large peaks of the graph show saturated hydrocarbon of the main components, e.g. C9 to C26 appear in proportion to carbon number, and bristle-like projections between these peaks are considered to be chemical compounds replaced with unsaturated hydrocarbon, sulfur, nitrogen and other molecules as non-main components. Although there is not enough energy to cut the carbon bond of the main chain cable corresponding to the large peaks, by mixing nano bubbles, it is possible that a replacement reaction reducing the functional group at the end to hydrogen occurs, and as a result, minor components decrease and the bristle-like non-main components decreases. As a result, improvement in the burning reaction of nano bubble gas oil can be expected by hydrogen atoms and oxygen atoms being added. Furthermore, if nitrogen atoms are replaced by hydrogen atoms, its contribution to the reduction of Fuel-NOx can also be expected.

4.2. Engine performance test

Fig. 10 shows the results of the engine performance test. The horizontal axis shows a brake mean effective pressure, P_{mec} [kPa], which is the engine load, and the vertical axis shows unit output, BSFC (brake specific fuel consumption)[g/kWh] or fuel consumption volume per unit time, charging efficiency η_c[%], smoke in exhaust gases or smoke [BSN], noise [dB] and temperature of exhaust gases or T_{eg} [°C] in the order from the bottom.

4.2.1. Fuel consumption rate

The fuel consumption rate was reduced by nano bubbles being mixed into the fuel. The comparison of the case of the control and that of nano bubble gas oil using one mixture device shows that the

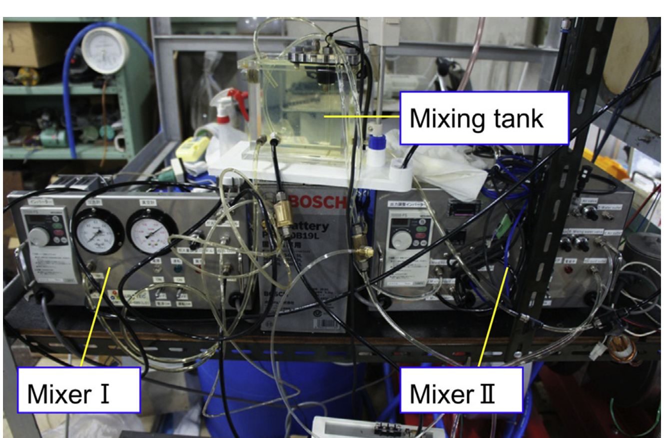

Fig. 4. Ejector-type nano air-bubbles mixer.

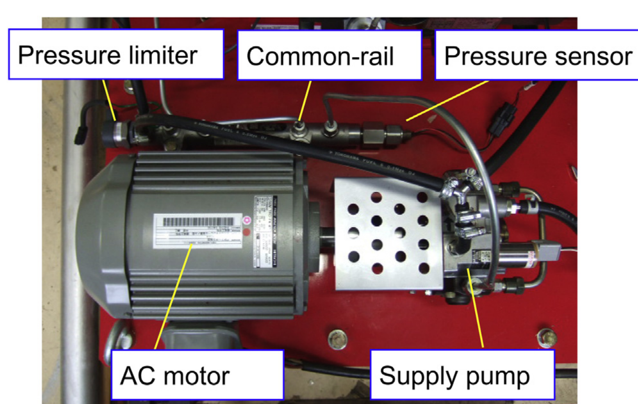

Fig. 6. Appearance of common-rail system.

Table 3
Specification of common-rail fuel injection system.

System model	FC-design Fi-CMR [5]
Injector driver and pressure sensor	DENSO common-rail system (max. 200 MPa)
Common-rail system and pressure regulator	BOSCH common-rail system
Supply pump	BOSCH CP3
Supply pump motor	AC200 V 1.5 kW 4P
Fuel cooling method	Air-cooling fuel conditioner in a coolant tank
Injection timing	Multiple injections (max.: 7 point inj.)

fuel consumption was reduced by 1.1% at the load average, and 2.7% at the maximum. The comparison of the case of control and that of nano bubble gas oil using two mixture devices shows that the fuel consumption was reduced by 3.2% at the load average, and 6.2% at a low load time.

The reasons why the reductions of fuel consumption were larger when the load was low or medium and two mixture devices were used are as follows: The fuel consumption was from 0.013 to 0.033 L/min. at the load for the range from low load (200 kPa) to high load (500 kPa), and the calculation from the discharge quantity of the pump of the mixing tank (0.7 L/min) showed the gas oil was circulating in the mixing tank approximately from 50 times (at low load) to 20 times (at high load). When two mixture devices were used, the number of circulation times became twice, and as a result, the amount of nano bubbles mixed into the gas oil increased and the fuel consumption was further reduced. This result suggests the method of mixing bubbles and optimization of various conditions for the practical use of this system.

As the reasons why fuel consumption can be reduced by nano bubble gas oil, a chemical action can be presumed that the rate of combustion advances due to the increase in local air-fuel mixing ratio and the concentration of ion, and owing to the increase of dissolved oxygen [18–20]. A physical effect can also be considered as the advanced combustion speed caused by further micronization of atomized gas oil due to the mixture of bubbles.

4.2.2. Others performance

The charging efficiency of the control is nearly constant in the neighborhood of 78% in all loading ranges. Meanwhile, in the case of nano bubble gas oil, the charging efficiency tended to be slightly improved, and compared with the control, was improved by approximately 1%. It is considered that the combustion speed was improved due to the effect of bubbles mixed into the gas oil, that is, from both chemical and physical actions, and as a result, the

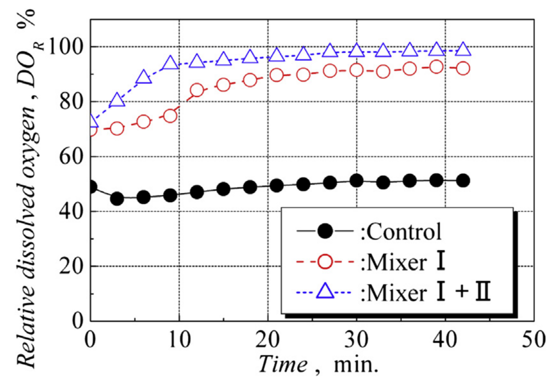

Fig. 8. Comparison of the dissolved oxygen content in control and nano bubbles gas oil versus mixing time.

effective work ratio increased and the heat loss from the cylinder wall was reduced. From the results of this research, reduction of brake specific fuel consumption in the high loading range is expected. However, the fuel consumption decreased in the low loading range instead. These points are considered to be improved by optimization of the bubble mixing method.

As one of the improving effects of fuel by bubble mixing, although the reduction of smoke generated in the high loading range was expected, no difference was observed between the control and the gas oil mixed with bubbles. This is because the fuel consumption was greatly decreased in the low loading range and also because almost no improvement in the combustion effect by bubble mixing was observed in the high loading range, as described previously.

Reduction in engine noise can be expected from the improvement of ignition delay by the nano bubble gas oil. The larger P_{mec} became, the more noise was gradually reduced, and it was reduced by approximately 3 dB for the change of $P_{mec} = 200–550$ kPa. This is considered to be because the formation of pre-mixed gas was prompted with lean mixer in a low load period caused by the micronization of atomized gas oil and the rate of pressure rise increased. The comparison between the control and nano bubble gas oil showed that the engine noise decreased by 0.5 dB at a maximum in the low load range when nano bubble gas oil was used, compared with control. However, no significant difference was recognized.

The temperature of the exhaust gas when nano bubble gas oil was used was low, by approximately 20 °C at a maximum compared

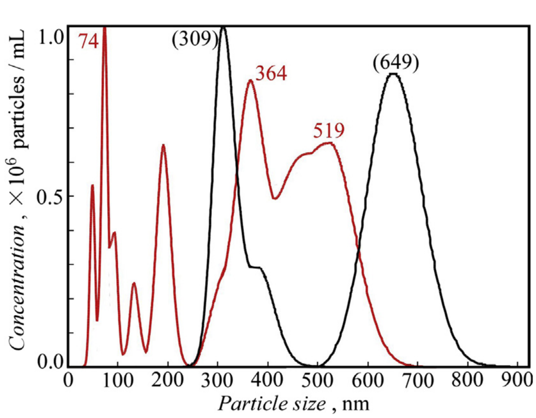

Fig. 7. Particle/bubble size distribution in control and nano bubbles gas oil.

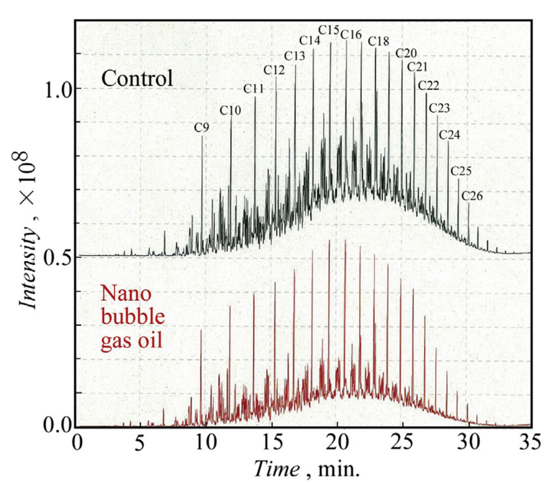

Fig. 9. GC/MS analysis of control and nano bubbles gas oil.

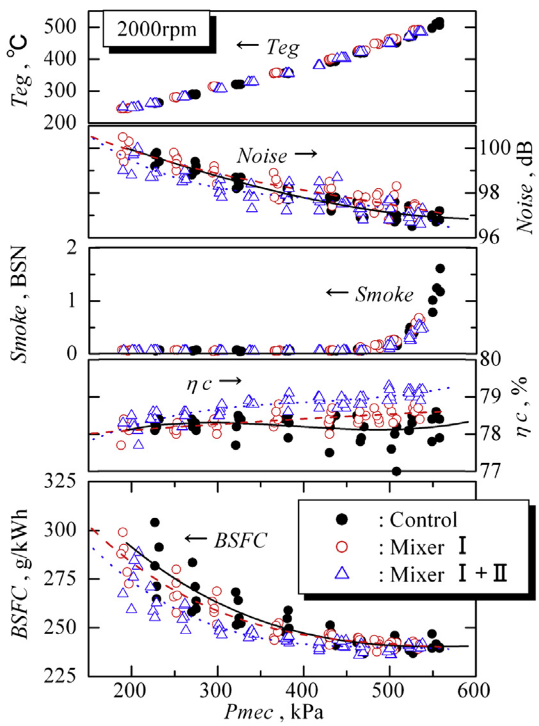

Fig. 10. Engine performance.

with the control. This is considered to be because the combustion speed increased caused by the effect of bubble mixing the same as for the charging efficiency described above, and as a result, the heat loss from the cylinder wall reduced and the temperature of the exhaust gas was also reduced.

In addition, also in the experiment using nano bubble gas oil, unstable phenomenon or unusual noise etc. of the diesel engine were not observed.

4.3. Combustion characteristics

The comparison of heat release rate (HRR) and cylinder gas pressure for control and nano bubble gas oil at 200 kPa load condition is shown in Fig. 11. In the performance test of the preceding paragraph, the effect of fuel consumption reduction performed comparison of control and nano bubble gas oil at 200 kPa load condition which appeared most notably. There are no clear differences between them and both are almost the same. This is because the effect of fuel consumption reduction was very small, to effect HHR and incylinder pressure. However, the fuel consumption improving effect was accepted.

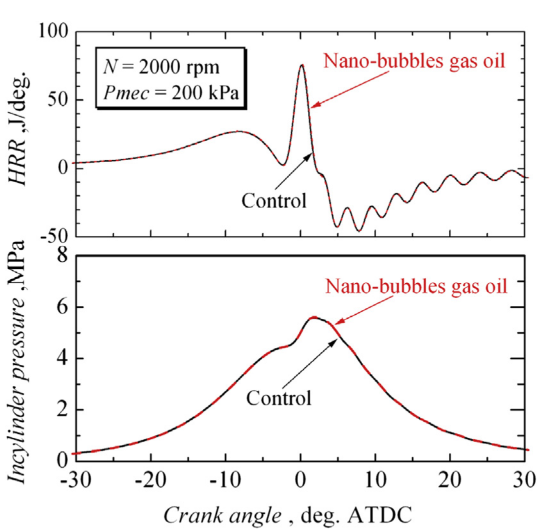

Fig. 11. Heat release rate and cylinder gas pressure with crank angle at 200 kPa load condition.

5. Conclusions

The engine performance caused by the difference of nano bubble mixing conditions using a newly introduced common-rail injection system was experimentally discussed. The findings obtained through this experiment are as follows:

1) The bubble mixing effect by common-rail high-pressure fuel injection system contributes to a reduction in fuel consumption in the ranges of medium and low loads, and when nano bubbles are mixed in a high concentration, the fuel consumption is reduced by 3.2% at the load average and 6.2% at the max.
2) Nano bubble gas oil improved charging efficiency, temperature of exhaust gas, smoke and engine noise approximately by 1% at the max. compared to the control.

The bubble mixing effect, or its cost-effectiveness, remains to be clarified for practical use.

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Nomenclature

ATDC: after top dead center (degree)
BSFC: brake specific fuel consumption (g kWh^{-1})
DO_R: relative dissolved oxygen
HHR: heat release rate (J $degree^{-1}$)
N: rotation speed of engine (rpm)
Noise: engine noise (dB)
NOx: oxides per nitrogen
PM: particulate matter
P_{mec}: brake mean effective pressure (kPa)
Smoke: smoke in exhaust gases (BSN)
T_{eg}: temperature of exhaust gases (°C)
WDE: water-in-diesel emulsion
η_c: charging efficiency (%)