

Combustion Improvement of Diesel Engine by Alcohol Addition - Investigation of Port Injection Method and Blended Fuel Method

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ABSTRACT

Alcohol fuels that can be produced from cellulose continue to become more widely used in gasoline engines. This research investigated the application of alcohol to diesel engines with the aims of improving the combustion of diesel engines and of utilizing alternative fuels. Two methods were compared, a method in which alcohol is injected into the air intake system and a method in which alcohol is blended in advance into the diesel fuel. Alcohol is an oxygenated fuel and so the amount of soot that is emitted is small. Furthermore, blended fuels have characteristics that help promote mixture formation, which can be expected to reduce the amount of soot even more, such as a low cetane number, low viscosity, low surface tension, and a low boiling point. Ethanol has a strong moisture-absorption attribute and separates easily when mixed with diesel fuel. Therefore, 1-butanol was used since it possesses a strong hydrophobic attribute and does not separate easily. In this research, the low soot characteristics of alcohol were utilized and a method of improving combustion was tested that raised the premixed compression ignition combustion ratio while suppressing combustion noise. In addition, the possibility of improving thermal efficiency and reducing NO_x was also investigated. The results showed that at middle and high loads the tradeoff between NO_x and thermal efficiency was improved and that NO_x could be significantly reduced at a constant thermal efficiency. A 73% reduction in NO_x was achieved with the port injection method, while a 61% reduction was achieved with the blended fuel method at middle load when using a butanol volume ratio of 50%. On the other hand, thermal efficiency became worse at low load, even at constant NO_x, due to increases in the unburned fuel loss and cooling loss. However, in the blended fuel method, it was possible to

reduce NO_x by 48% at low load by adding a cetane number improver and thereby improving the ignition attribute. The results of simulated testing using the New European Driving Cycle (NEDC) showed that NO_x could be reduced by 38% without diminishing thermal efficiency using the port injection method, while NO_x was only reduced by 24% and thermal efficiency diminished by 0.1 point using the blended fuel method. If a cetane number improver was added to the blended fuel to improve the ignition attribute and thermal efficiency, the results showed 37% reduction in NO_x with constant thermal efficiency, which approximately equal to port injection method. However, even further improvement is necessary in order to reach the levels specified in the Euro 6 emissions regulations. Furthermore, this research also analyzed the differences in soot generation by visualizing the combustion. The results showed that even under conditions that simulated the same ignition delay, both methods generated less soot from initial combustion in comparison to diesel fuel. Post injection of blended fuel was also effective in reducing soot.

INTRODUCTION

The use of biofuels is expanding in order to increase energy security and to reduce CO₂ emissions. The increased adoption of bio-diesel fuels, such as fatty acid methyl ester and hydrotreated vegetable oil, is also being promoted. On the other hand, alcohol is increasingly being blended with gasoline since it can also be produced from cellulose, and there is less concern about cellulose competing against food resources.

The separation of ethanol from gasoline after blending due to the strong moisture-absorption attribute of ethanol is becoming an issue. On the other hand, butanol has begun to

gain more attention in recent years since it can also be produced from biological sources in the same way as ethanol and it has a weak moisture-absorption attribute. Furthermore, research is being conducted into methods of producing butanol that is far more efficient than the conventional acetone butanol ethanol method and research is also being conducted into the application of butanol for use in gasoline engines [1].

If the use of alcohol in gasoline engines is promoted, then it is predicted that the consumption of gasoline will be reduced and the volume of crude oil that is refined will become lower, thereby reducing the supply of diesel fuel. Furthermore, it is predicted that the demand for diesel fuel for construction machinery in rising nations and particularly for automobiles in Europe, as shown in [Figure 1](#), will increase and lead to a crunch in global diesel fuel supply and demand. On the other hand, emissions regulations for diesel automobiles are becoming increasingly stringent and a significant reduction in NOx emissions is being demanded to comply with the Euro 6 emissions regulations that are scheduled to go into effect in Europe in 2014.

Based on the background described above, this research aims to address the predicted global diesel fuel crunch as well as the requirement to reduce CO₂ emissions by making it possible to use alcohol in diesel engines as well as gasoline engines, thereby increasing the number of choices in biofuels to compensate for the insufficient diesel supply. Furthermore, it also aims to address the strengthening of emissions regulations by utilizing the low soot characteristics of alcohol to reduce the amount of smoke and NOx exhaust emissions.

The research proceeded as follows. First, an analysis was made of the low soot characteristics of alcohol. Next, a technique of improving combustion that utilizes these characteristics was proposed, and finally, reductions in NOx to meet the level specified in the Euro 6 emissions regulations were investigated.

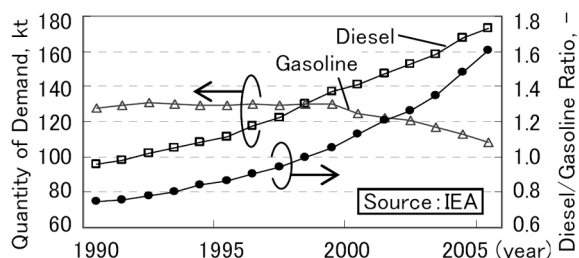


Figure 1. Transition of Diesel Fuel Demand in Europe
[2]

TESTING APPARATUS AND METHOD

The blending attributes of ethanol and 1-butanol with diesel fuel (DF) were investigated. It is possible to mix highly pure ethanol with a concentration of 99.5% into diesel fuel until it reaches approximately 20% of the volume. However, ethanol has a strong moisture-absorption attribute and if the blended fuel is left standing for a few hours, the ethanol will absorb moisture out of the atmosphere and separate from the diesel fuel. In addition, ethanol will also separate in cold conditions, which makes it difficult to blend ethanol into diesel fuel without additional processes. On the other hand, it was found that butanol, which has a stronger hydrophobic attribute than ethanol, can be mixed in any desired ratio, and does not separate as easily. Therefore, as shown in [Figure 2](#), it was decided that the method of supplying alcohol to a diesel engine would be different for ethanol and butanol. The ethanol was not blended with the diesel fuel and instead was supplied via another means, the port injection (PI) method. The butanol was supplied by two methods: the port injection method and the blended fuel (BF) method.

The merits and demerits of both of these methods are summarized in [Table 1](#). In the port injection method it is necessary to add additional parts, such as an alcohol tank and injectors, which increases the cost. However, the optimum amount of alcohol is supplied via the injectors in accordance with the driving conditions and this allows the process to be controlled so that the effect of the alcohol injection is maximized. On the other hand, it may be possible to use the blended fuel method with conventional fuel system parts without modification, but the effectiveness of the alcohol is limited since it is not possible to change the ratio of alcohol in the fuel. In addition, there are concerns about the poor cold start capability of blended fuel due to the reduction in the ignition attribute.

For previous researches, port injection of lower reactivity fuel such as ethanol and gasoline [3, 4, 5, 6], and blended fuel of ethanol and biodiesel fuel [7] were researched respectively in effort to reduce smoke and NOx while maintaining or improving thermal efficiency. Therefore, this research focused mainly on 1-butanol since it allowed for the comparison of both methods. The combustion characteristics, and smoke and NOx reduction effects were compared based on the differences in the methods of supplying alcohol. As shown in [Table 2](#), the engine that was used for the testing was based on a 2.2-liter, 4-cylinder, mass-produced diesel engine that complies with the Euro 5 emissions regulations. An alcohol injection system was added to inject the alcohol into the air intake system and gasoline engine injectors were used for the alcohol injectors.

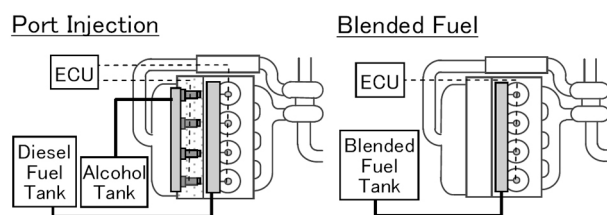


Figure 2. Experiment Apparatus

Table 1. Comparisons of Merits and Demerits

	Port Injection	Blended Fuel
Fuel system	2 tanks 2 injector sets	1 tank 1 injector set
Controllability of alcohol ratio	Variable	Fixed
Cost	×	○

Table 2. Engine Specifications

Engine Type	In-line 4-cylinder
Bore and Stroke	φ86.0×96.0 mm
Displacement	2,231 cm ³
Compression Ratio	15.7
Fuel Injection System	Common Rail and Piezo Injector (Nozzle: φ0.098mm×9 holes)
Intake System	Variable Nozzle Turbo Charger with Intercooler
EGR System	High Pressure Loop with Cooler
Swirl Ratio	2.2

TEST RESULTS AND CONSIDERATIONS

CHARACTERISTICS OF BUTANOL-BLENDED DIESEL FUEL

The results from measuring the physical properties of the butanol-blended diesel fuel are shown in Table 3. The cetane number declines in accordance with the ratio of the butanol mixture and with 30% butanol the cetane number declines to 38. The kinematic viscosity and the surface tension also decline. The lubricity with the high frequency reciprocating rig (HFRR) decreases in accordance with the ratio of the butanol mixture. However, the following engine testing was conducted without adding a lubrication improver because even blended fuel with 30% butanol meets the EN590 (460 μm). In addition, as shown in Figure 3, it was found that the distillation characteristics move toward the low temperature side over a wide distilling ratio. The distillation characteristics were measured by atmospheric distillation method based on JIS K 2254.

The estimated effects of the alcohol characteristics are summarized below and there are many characteristics that are able to reduce soot.

- (1). Oxygenation
- (2). Promotion of mixture formation (blended fuel)
 - Low cetane number → Increase in premixed compression ignition combustion ratio
 - Low kinematic viscosity, low surface tension → Atomization of fuel spray
 - Low boiling point → Improvement in fuel spray vaporization

Table 3. Measurement Fuel Properties

	DF	Bu10※	Bu30	1-Butanol
Density@15°C, kg/ L	0.834	0.831	0.825	0.810
Heating Value, MJ/kg	43.0	42.0	40.1	33.3
Cetane Number, -	53	49	38	25 (Reference)
Kinematic Viscosity @30°C, mm ² /s	3.5	3.1	2.9	2.46
Surface tension @25°C, mN/m	26.8	25.4	24.9	24.9
HFRR@60°C, μm	297	360	425	-
H/C	1.88	1.93	2.03	2.5
O/C	0.00	0.02	0.06	0.25

※ 1-Butanol 10vol.% + DF 90vol.%

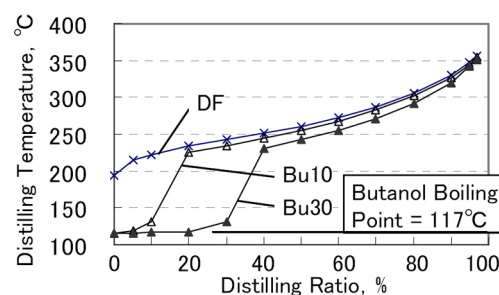


Figure 3. Distillation Characteristics

FUEL SPRAY CHARACTERISTICS OF BUTANOL-BLENDED DIESEL FUEL

The kinematic viscosity and surface tension are both reduced in butanol-blended diesel fuel, so better atomization of the fuel spray can be expected. In order to confirm this, visualization of the fuel spray and measurement of the fuel spray particle size using a laser diffraction particle size distribution measuring apparatus (LDSA-1500A) were conducted. In order to simulate the density within the cylinder at the time of combustion, the fuel was injected within an enclosed container that had been pressurized at 0.7