

Diesel Combustion Characteristics of Biodiesel with 1-Butanol

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ABSTRACT

In order to improve the fuel properties and diesel combustion of biodiesel, waste vegetable oil methyl ester (from rapeseed and soybean oil mixture) with 5-20 mass% 1-butanol (BWME) are tested using a DI diesel engine. The viscosity and pour point of BWME decrease by blending 1-butanol. There is no problem in the startability and stability of the engine operation with BWME. Thermal efficiency of BWME is almost the same as that of the gas oil. The smoke emission decreases with increasing 1-butanol although the HC and CO emissions increase due to the longer ignition delay. It is concluded that BWME can be utilized as an alternative diesel fuel. Furthermore, to improve the ignitability and exhaust emissions of biodiesel with 1-butanol, palm oil methyl ester (PME) with high cetane number is tested as a base fuel of the 1-butanol blend. When the 1-butanol content in PME/1-butanol (BPME) is 15 mass%, BPME has almost the same ignition delay and HC and CO emissions compared with the gas oil. From the experimental results, it is concluded that PME is better than rapeseed oil methyl ester as a base fuel of the biodiesel with 1-butanol due to the better ignitability and lower exhaust emissions.

INTRODUCTION

Biofuel, such as biodiesel and bio-alcohol, is a renewable, biodegradable and nontoxic alternative fuel with the potential to reduce lifecycle CO₂ emissions [1, 2]. Biodiesel produced from vegetable oils and animal fats is utilized as an alternative diesel fuel. On the other hand, bio-ethanol produced by fermentation from various organic substances, such as agricultural crops and garbage, is utilized as an alternative fuel for SI engine. Bio-butanol also can be made from various organic substances by fermentation, but it is different fermentation, such as Acetone-Ethanol-Butanol (ABE) fermentation [3]. It is possible to use alcohol for diesel engines with higher thermal efficiency if alcohol is blended with high cetane number fuels, such as conventional diesel fuel and biodiesel. Butanol has higher net calorific value and cetane number compared with ethanol [4]. Therefore, butanol may be better alternative diesel fuel or diesel fuel additive than ethanol. Also, biodiesel has higher kinematic viscosity and distillation temperature compared with conventional diesel fuel. These fuel properties are improved by blending butanol with biodiesel, and the oxygen content in the fuel increase. As the result, it may be

expected that the smoke emission of biodiesel with butanol is lower than that of neat biodiesel.

In this study, to improve the fuel properties and diesel combustion of biodiesel, the blend fuels (BWME) of waste vegetable oil methyl ester (WME), which was made from rapeseed oil and soybean oil mixture, with 5-20 mass% 1-butanol were investigated using a DI diesel engine. The effects of 1-butanol content on the diesel combustion characteristics and exhaust emissions of BWME were investigated by the comparison with WME and JIS No.2 diesel fuel (gas oil). Furthermore, to improve the ignitability and exhaust emissions of biodiesel with 1-butanol, palm oil methyl ester (PME) with high cetane number was tested as a base fuel of the blended fuel. The comparison with the case with rapeseed oil methyl ester (RME) as a base fuel was carried out.

TEST FUELS

WME, PME and RME were made by alkali catalyst transesterification. KOH was used as the alkyl catalyst. In the transesterification reaction of WME the molar ratio of methanol to waste vegetable oil was 3.6:1 and 1% mass of KOH to waste vegetable oil was used. The reaction was taken for one hour at room temperature 20-25 °C. On the other hand, in the transesterification reaction of PME and RME the molar ratio of methanol to vegetable oil was 6:1 and 1% mass of KOH to vegetable oil was used for PME and RME. The reactions were taken for two hours at the reaction temperature 60 °C. After the end of the reaction, the mixtures were kept at the room temperature of 20-25 °C for eight hours and then the settled glycerin layer was drained off. Finally, the residual methanol in methyl ester mixtures was evaporated. The properties of WME, PME, RME, 1-butanol and JIS No.2 diesel fuel (gas oil) are shown in Table 1. The density, kinematic viscosity, pour point, the 50% distillation temperature and the residuals, such as water, alcohol, and glycerides, were observed by measurements. The net calorific values and the carbon, hydrogen and oxygen contents of ester fuels (WME, PME and RME) were calculated from the fatty acid methyl ester (FAME) compositions shown in Table 2. The net calorific values of ester fuels are about 15% lower than that of the gas oil due to about 11 mass% of oxygen in the fuel molecule. Also the kinematic viscosities of ester fuels are higher than that of the gas oil. WME contains triglyceride to 5 mass%. The glycerides of PME and RME meet the JIS biodiesel standards.

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Table 1 Properties of WME, PME, RME, 1-Butanol and gas oil

Test fuels	WME	PME	RME	1-Butanol	Gas Oil (JIS No.2)
Cetane number	-	64 ^a	54	-	56
Net calorific value, MJ/kg	36.42	37.20	37.04	33.00	43.12
Density @ 288K, kg/m ³	895	878	884	813	832
Kinematic viscosity@ 293K, mm ² /s	9.1	-	-	3.0	4.7
Kinematic viscosity@ 313K, mm ² /s	-	3.57	3.69	-	2.66
Pour point °C	-5.0	15.0	-10.0	(-89.6) ^b	-12.5
C mass %	76.5	76.2	77.1	64.8	87.3
H mass %	11.6	12.4	12.0	13.6	12.5
O mass %	10.9	11.4	10.9	21.6	0
Sulfur mass ppm	< 10	< 10	< 10	-	< 50
Water mg/kg	600	716	810	-	-
Monoglyceride mass %	-	0.35	0.28	-	-
Diglyceride mass %	-	0.16	0.12	-	-
Triglyceride mass %	5	0.01	0.01	-	-
(A/F) _{st}	12.4	12.5	12.5	11.1	14.2
50% distillation temperature °C	342	329	340	(117) ^c	278

a) Cetane number from Ref. 5 b) Melting point c) Boiling point

Table 2 FAME composition, mass %

FAME	C:N	WME	RME	SME	PME
Palmitic	16:0	8.3	4.5	11.2	48.6
Stearic	18:0	0.1	0.1	0.2	1.5
Oleic	18:1	51.8	64.2	28.6	38.1
Linoleic	18:2	30.7	19.6	52.3	9.2
Linolenic	18:3	8.5	10.8	7.3	0.6
Others	-	0.7	1.0	0.5	2.0

C: No. of carbon, N: No. of carbon-carbon double bond

The FAME compositions in the ester fuels were measured by gas chromatography. In Table 2, the FAME composition of soybean oil methyl ester (SME) also is shown. In Table 2, the letter C denotes the number of carbon molecules and the letter N denotes the number of carbon to carbon double bond. FAME without carbon to carbon double bond is saturated FAME, and with carbon to carbon double bond is unsaturated FAME. From Table 2, it can be seen that PME contains about 49 mass% palmitic acid methyl ester. On the other hand, RME contains about 64 mass% oleic acid methyl ester. Also, from Table 2, it is estimated that waste vegetable oil composes of rapeseed oil (65mass%) and soybean oil (35mass%).

WME, PME, RME, WME with 1-butanol (BWME), PME with 1-butanol (BPME), RME with 1-butanol (BRME) and the gas oil were used as test fuels. The properties of BWME, BPME and BRME are shown in Table 3. The 1-butanol content of BWME is 5-20 mass%. The 1-butanol content of BPME is 10-30 mass%. Also, the 1-butanol content of BRME is 10 mass%. The densities and kinematic viscosities of the 1-butanol blend fuels decrease with increasing 1-butanol content. When 1-butanol content increases, the net calorific values of the 1-butanol blend fuels decrease due to

the increase in the oxygen content. The pour points of WME, PME and RME decrease by blending 1-butanol. The pour point of BWME with 10mass% 1-butanol is -12.5 °C and the same as that of the gas oil. The pour point of BPME with 15mass% 1-butanol is 10.0 °C.

EXPERIMENTAL APPARATUS AND PROCEDURE

A single cylinder DI diesel engine was used for the experiments. It is a naturally aspirated, water-cooled, four stroke diesel engine with jerk-type fuel injection pump (single-barrel injection pump). The specifications of the test engine are shown in Table 4. The standard fuel injection system recommended by the engine manufacturer was used for all test fuels.

The type of experiment is steady state engine test and the experiments were started with the engine warmed up. When test engine achieved the stable condition, the loads were applied and the measurements were started. The engine speed was fixed at 2000 rpm and the loads were applied from 0% to 25, 50, 75, 100% using an electronic dynamometer. At 100% load condition the brake mean effective pressure (BMEP) of the test engine was 0.67 MPa. The exhaust gases were sampled from the exhaust system of the test engine and measured by following standard procedure. From the exhaust gases, the CO emission was measured by a non-dispersive infrared detector (NDIR), the HC emission was measured by a flame ionization detector (FID), the NO_x emission was measured by a chemiluminescent detector (CLD), and the smoke emission was measured by a Bosch type smoke meter and a light transmitting type smoke meter (Opacimeter). Also the cylinder pressure and the needle lift of the fuel injector were recorded with a digital scope recorder at all load conditions.

Table 3 Properties of BWME, BPME and BRME

Test Fuels	BWME5	BWME10	BWME15	BWME20	BRME10	BPME10	BPME15	BPME20	BPME25	BPME30
1-Butanol content, mass%	5	10	15	20	10	10	15	20	25	30
Net calorific value, MJ/kg	36.25	36.08	35.91	35.74	36.61	36.62	36.54	36.25	35.91	35.72
Density @ 288K, kg/m ³	891	886	882	878	875	868	863	861	857	854
Kinematic viscosity, @313K mm ² /s	10.5 @293K	9.4 @293K	8.5 @293K	7.7 @293K	3.26	3.19	3.06	2.76	2.67	2.57
Flash point, °C	-	-	-	-	-	44	42	41	38	38
Pour point, °C	-10.0	-12.5	-12.5	-12.5	-12.5	12.5	10.0	10.0	10.0	10.0
C mass%	76.0	75.4	74.8	74.3	75.9	75.1	74.6	74.0	73.4	72.8
H mass%	12.0	12.1	12.2	12.2	12.2	12.5	12.6	12.6	12.7	12.8
O mass%	12.0	12.5	13.0	13.5	12.0	12.4	12.9	13.4	13.9	14.4
(A/F) _{st}	12.31	12.26	12.20	12.12	12.35	12.37	12.30	12.24	12.17	12.10

Table 4 Specifications of test engine

Engine Type	1 Cylinder, 4 Stroke, D.I., Water Cooled
Bore × Stroke	110×106 mm
Stroke Volume	1007 cm ³
Compression Ratio	16.3
Rated Power	11.77 kW / 2200 rpm
Fuel Injection Pump	Jerk type
Nozzle Opening Pressure	19.6 MPa
Nozzle Holes	ϕ 0.33 mm×4

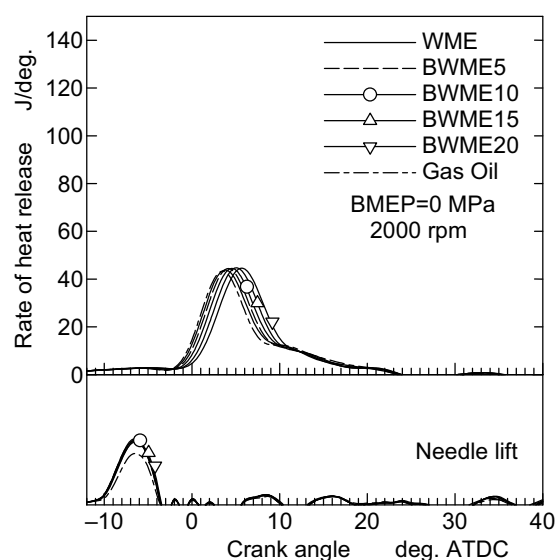


Figure 1 Heat release rate and needle lift of BWME at 0% load

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RESULTS AND DISCUSSION

First, an engine test was carried out using WME, BWME and the gas oil as test fuels (1st Test). Next, an engine test was carried out using PME, BPME, RME, BRME and the gas oil as test fuels (2nd Test). In both Test 1 and Test 2, there was no problem in the startability and the stability of the engine operation with BWME (1-butanol content: 5-10 mass%) and BPME (1-butanol content: 10-30 mass%). In the following experimental results, data of the gas oil in 1st Test is slightly different from that in 2nd Test because there is long time interval between 1st Test and 2nd Test.

IGNITABILITY AND COMBUSTION CHARACTERISTICS OF BWME IN 1ST TEST

The heat release rate and the needle lift of the fuel injector at BMEP=0 and 0.67MPa (0 and 100% load conditions, respectively) are shown in Figure 1 and 2. These values are average of 50 cycles. From Figure 1 and 2, it can be seen that the needle lift profile of BWME at BMEP=0MPa is almost the same as that of WME, and that the fuel injection duration of BWME at BMEP=0.67MPa become longer with increasing 1-butanol content. Fuel injection duration at same load condition is depended on the net calorific value of the fuel. As the net calorific value of the fuel decreases, the quantity of fuel that must be injected to supply the same amount of chemical energy to the combustion chamber increases. So, at BMEP=0.67MPa, BWME shows longer fuel injection interval with increasing 1-butanol content. On the other hand, at BMEP=0MPa, BWME shows same fuel injection interval compared with WME due to less amount of fuel injected. From Figure 1 and 2, it also can be seen that the ignition of BWME retards with increasing 1-butanol content in BWME. This is due to the lower ignitability with the increase in 1-butanol content with low cetane number.