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REVIEW

Diesel Engine Performance and Emissions When Using Biodiesel Fuel

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Abstract

This paper reviews the impact of biodiesel called "fatty acid methyl ester" (hereinafter referred to as "FAME"), which was manufactured domestically using waste edible oil, on the performance and gas emissions of agricultural diesel engines. In terms of engine performance, one indicator showed output equivalent to diesel fuel. However, the resulting specific fuel consumption (hereinafter referred to as "SFC") was high because the density of FAME, which exceeded that of diesel fuel, increased the mass flow rate of the fuel. Moreover, the nitrogen oxide (NO_X) emissions of FAME were comparable to those of diesel oil. However, emissions of particulate matter (hereinafter referred to as "PM") discharged by FAME were smaller than from diesel fuel. Under a driving condition tending to generate a large amount of black smoke due to high engine load, PM emissions were halved compared to those of diesel fuel. This phenomenon is presumed attributable to the reduction in soot production achieved using FAME, which contains a relatively high amount of oxygen.

Discipline: Biofuel

Additional key words: black smoke, NO_X, PM, specific fuel consumption, torque

Introduction

Since plants absorb atmospheric carbon dioxide (CO_2) as they grow, biofuels made from recyclable resources such as plants, animals, etc. are considered carbon neutral. Reducing CO_2 emissions is thus expected to be an effective countermeasure to global warming. Biodiesel, a biofuel, can be used in agricultural tractors equipped with diesel engines, trucks for transportation and a wide range of automotive use, which has meant the consumption of biodiesel and bioethanol, one of the biofuels used in gasoline engines, have both continued to increase. According to a report of U.S. Energy Information, biodiesel consumption in 2012 was three times larger than that of 2007. Meanwhile, in Japan, the "Act on the Quality Control of Gasoline and Other Fuels," which ensures the appropriateness and stability of fuels, was revised and enforced in 2009. Based on this act, the sale of diesel fuel mixed with FAME with 5 mass % or less commenced and FAME product consumption is expected to increase. However, biodiesel is generally made from oil crops such as soybean and corn, etc. The spread of biodiesel is leading to a lack of farm goods for edible use and farmland for growing food.

Conversely, FAME products, which are widely manufactured in Japan, are highly valuable with the effective use of resources and reduction of waste materials in mind, by recycling waste edible oils. However, to date, although cases on impacts of FAME products on automobiles have been recorded, there have been few such cases involving agricultural equipment. We therefore examined the impact on basic engine performance and gas emissions from FAME products comprising waste edible oils when used in agricultural diesel engines.

Test fuel and engine

The FAME products used for the test mainly comprised waste edible oils and were manufactured using the alkali catalyst method. The manufacturers were separately and independently located in Japan. The test was conducted using said FAME products as well as JIS type 2 diesel fuel (hereinafter referred to as "diesel fuel"), which is generally available in Japan. The characteristics of the tested fuel are

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shown in Table 1.

Compared to diesel fuel, FAME products are characterized by high densities, kinetic viscosities and flow points, inclusion of oxygen and lower calorific values, etc. Also, their characteristics include residues of methanol and triglyceride. They function as raw materials.

For the test, a naturally-aspirated in-line 3-cylinder swirl-chamber diesel engine (rated power: 22.1kW/2500rpm, displacement: 1.498L) (Manufactured in 2006, conforming to the standard values defined by the diesel special automobile exhaust gas regulations from 2006 to 2008)was selected.

Methods

1. Engine performance test

In the engine bench test chamber of the Bio-oriented Technology Research Advancement Institution, the engine was installed and its output shaft connected to the electrical dynamometer (FC95-355L manufactured by Meidensha Corporation, absorption power: 200kW) to measure the relationship between engine speed, engine output and fuel consumption.

The test was conducted by observing TRIAS99-015-01 "Test for Vehicle Mounted Engine Power (Diesel Engines)" under examination affairs rules defining matters concerning methods for examining vehicles and vehicle equipment to be used by the National Traffic Safety and Environment Laboratory to identify basic diesel engine performance. The engine speed was changed at intervals of 200rpm within the range 1100 to 2500rpm with the governor control lever set to the full speed position, which is outside the range of the effect of the speed governor and full load operation condition. The engine speed and torque were measured using the indicator of the dynamometer, and fuel consumption using the flow detector (FP-2140H, measurement range: 0.3 to 120L/h, manufactured by Ono Sokki Co., Ltd.) and flow indicator (DF-210A manufactured by Ono Sokki Co., Ltd.)[4].

2. Exhaust emissions test

Similarly to the output test, the engine was connected to the electrical dynamometer and its load level was changed progressively to measure the emission gas component concentration, PM emission and black smoke concentration.

The test was conducted by adjusting the operation con-

Table 1. Characteristics of the fuels

Items		Test Fuels			
		Diesel fuel	FAME1	FAME2	FAME3
Lower calorific values (kJ/kg)		43030	38010	38550	37970
Density (15°C)(g/cm^3)		0.8271	0.8880	0.8868	0.8864
Cetane index		64.9	54.8	55.0	55.3
Kinematic viscosity (40°C)(mm^2/s)		3.304	5.123	4.449	4.601
Water content (ppm)		28	907	613	283
Sulfur content (ppm)		5	6	4	8
Carbon residue at 10% (mass%)		0.01	0.61	0.72	0.80
Pour point (°C)		-15	-7.5	-5.0	-2.5
CFPP (°C)		-13	-8	-6	-4
Oxygen content (mass%)		< 0.5	10.4	10.5	9.8
Carbon conten (mass%)		86.1	77.1	77.1	77.0
Monoglyceride (mass%)		—	0.95	1.58	1.04
Diglyceride (mass%)		—	0.88	0.46	0.45
Triglyceride (mass%)		—	5.52	0.70	1.90
Methanol content (mass%)		—	0.04	0.16	0.79
Flash point (°C)		72	168	163	67
FAME (mass%)		—	89.50	95.04	92.17
Distillation character -istics	First distillation (°C)	176.0	280.0	299.0	268.5
	Distillation temperature 10% (°C)	223.5	350.0	349.0	348.5
	Distillation temperature 50% (°C)	292.0	352.5	351.5	352.0
	Distillation temperature 90% (°C)	343.0	363.5	357.5	358.5

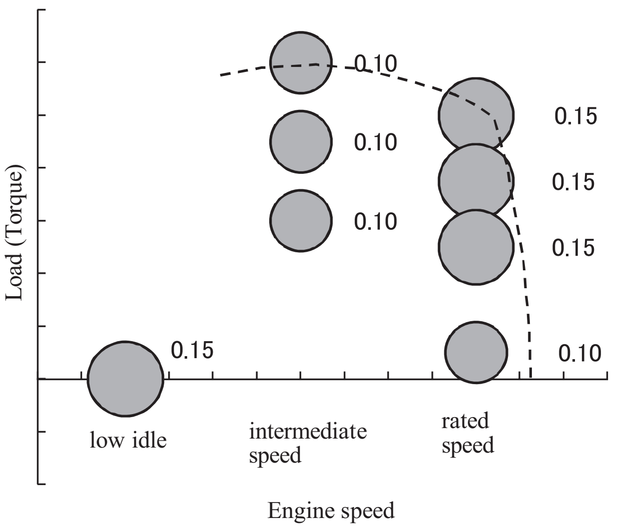

Fig. 1. Measuring point and weighting factor of the 8mode test[1]

Table 2. Weighting factor of the 8-mode test for diesel[1]

Mode number	Operating state		Minimum test time (min)	Weighting factor
	Engine speed	Engine torque (%)		
1	Rated speed	100	10	0.15
2		75	10	0.15
3		50	10	0.15
4		10	10	0.1
5	Intermediate speed	100	10	0.1
6		75	10	0.1
7		50	10	0.1
8	Low idle	-	10	0.15

Notes:
1) Engine torque is expressed in percent of the maximum available torque at a given engine speed
2) Rated speed is the speed at which the manufacturer specifies the rated engine power
3) Intermediate speed is the speed corresponding to the peak engine torque

dition of the engine in each mode (Fig. 1 and Table 2) by using the governor control lever and electrical dynamometer in accordance with Annex 43 “Diesel special vehicle 8-mode emission gas measurement method”[3] of the announcement which defines the detailed rules of the road transport vehicle safety standards, used to identify the general emission characteristics of diesel special vehicles. The rated and intermediate speeds were 2500 and 1500rpm, as designated by the manufacturer. The operation period in each operation mode was 10 minutes, and the period for measuring CO, etc. was 1 minute. PM was sampled using the multiple filter method.

With regard to emission gas components, nitrogen oxide (NOx), carbon monoxide (CO), CO_2 and hydrocarbon (HC) were measured using a gas component measurement device (MEXA-9400D manufactured by Horiba, Ltd.). The mass of the PM collecting filter was measured within the weighing chamber after collecting the emission gas through the micro tunnel (MDLT-1300T manufactured by Horiba, Ltd.). Furthermore, the black smoke concentration was measured using a filter papertype smoke meter (GSM-3 manufactured by Tsukasa Sokken Co., Ltd.).

Results

1. Engine performance test

Fig. 2 shows the relationship between engine speed and torque, and Fig. 3 shows the relationship between engine speed and SFC. With regard to the relationship between torque and SFC, the torque and SFC at a rated engine speed of 2500rpm were 85.5Nm and 305.5g/kWh with FAME1 (diesel fuel proportion: -0.9%, +22.2%; the same hereinafter), 85.7Nm and 301.4g/kWh (-0.6%, +20.5%) with FAME2, and 87.5Nm and 300.7g/kWh (+1.5%, +20.2%) with FAME3 respectively. Meanwhile, at an engine speed of 1700rpm, which is the output at maximum engine torque, they resulted to be 96.6Nm and 305.1g/kWh (-1.7%, +24.4%) with FAME1, 97.5Nm and 297.5g/kWh (-0.8%, +21.3%) with FAME2, and 97.9Nm and 295.3g/kWh (-0.4%, +20.4%) with FAME3. For the FAME products used in the test, torque from -4.8 to +2.0% was output at each engine speed compared to diesel fuel and the resulting engine output was almost equal to that output with diesel fuel, while the SFC increased from 18.9 to 29.6%. This phenomenon is presumed attributable to the low calorific values of the FAME products compared to diesel fuel.

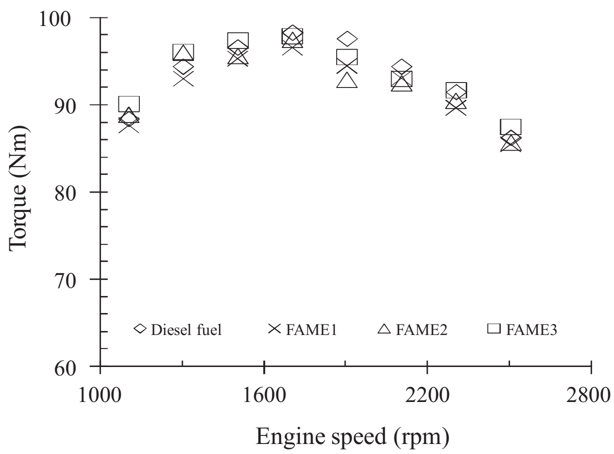

Fig. 2. Relation of engine speed and torque

2. Exhaust emissions test

The specific NO_X, CO and HC emissions in 8 modes

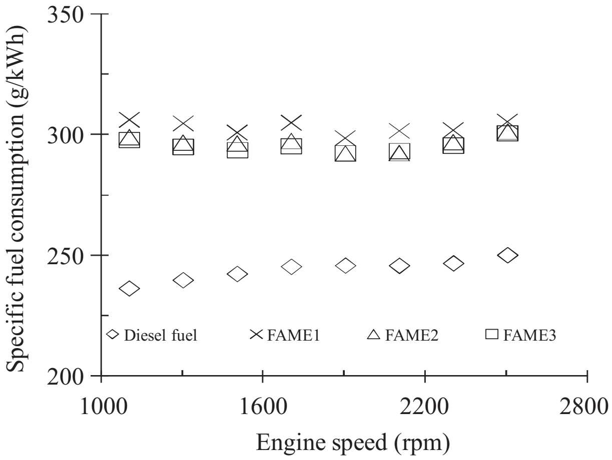

Fig. 3. Relation of engine speed and specific fuel consumption

are shown in Figs. 4, 5 and 6, while PM emissions in each operation mode are shown in Table 3, and the black smoke concentration in the 5th mode is shown in Fig. 7, respectively.

With regard to measurements of NOx and PM, considerable amounts of which are contained in diesel engine emissions, the specific NO_X emissions were 6.3g/kWh for diesel fuel, 6.3g/kWh for FAME1 (diesel fuel proportion: -0.4%, the same hereinafter), 6.1g/kWh for FAME2 (-2.9%) and 6.5g/kWh for FAME3 (+2.6%). In the first mode, with a 100% engine load rate at the rated speed, the resulting PM emissions were 2.3g/h with diesel fuel, 2.1g/h (-10.2%) with FAME1, 2.3g/h (-2.6%) with FAME2 and 1.9g/h (-20.2%) with FAME3 respectively. In particular, in the fifth mode, in which PM emissions increased, resulting PM emissions were as low as 8.0g/h (-56.3%) with FAME1, 9.4g/h (-48.8%) with FAME2 and 8.6g/h (-53.0%) with FAME3 respectively. With regard to NOx, there are reports that emissions with FAME products will increase compared to those with diesel fuel[5]. However, the resulting emissions were at almost the same level. With regard to PM, the amounts decreased in most operation modes and halved in

Table 3. PM emissions according to test mode

Mode number	PM emission(g/h)			
	Diesel fuel	FAME1	FAME2	FAME3
1	2.348	2.109	2.287	1.873
2	1.336	1.031	1.330	1.148
3	1.134	1.173	1.493	0.789
4	1.079	0.861	0.576	0.669
5	18.384	8.028	9.421	8.640
6	1.341	0.551	0.712	0.787
7	0.729	0.312	0.430	0.483
8	0.284	0.157	0.232	0.359

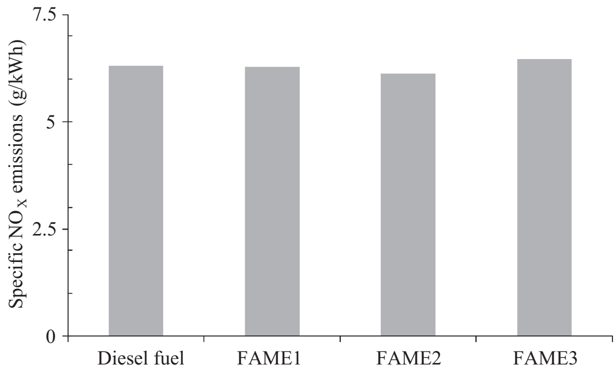

Fig. 4. Specific NO_X emissions

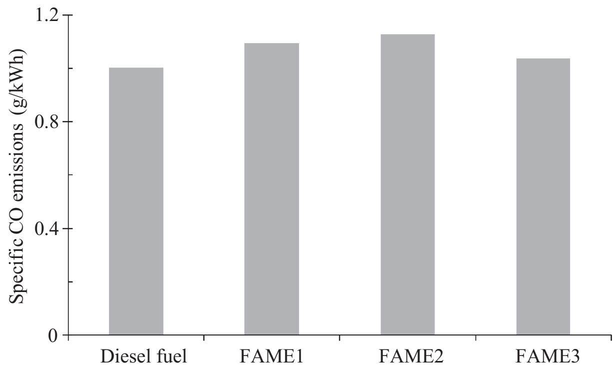

Fig. 5. Specific CO emissions

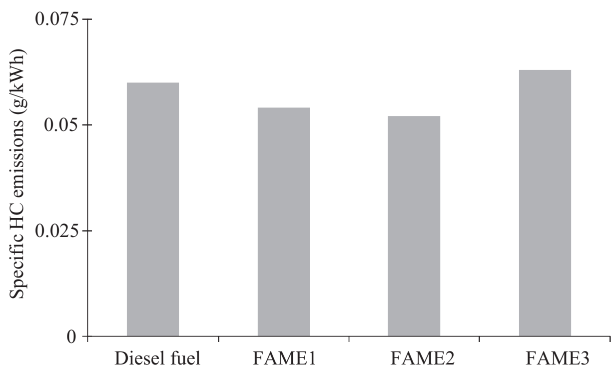

Fig. 6. Specific HC emissions

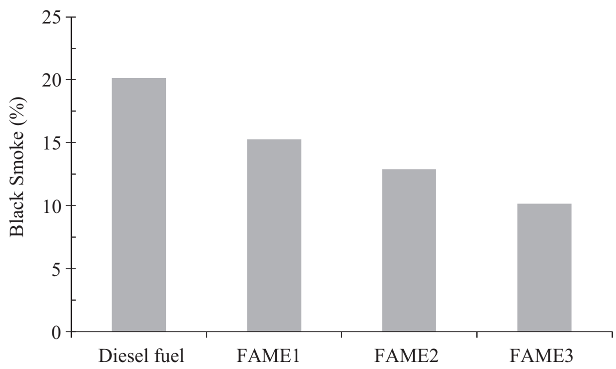

Fig. 7. Black Smoke concentration in the 5 th mode

Table 4. Emission standards for diesel nonroad vehicles 2006-2008

Rated Power (kw)	CO g/kWh	HC g/kWh	NOx g/kWh	PM g/kWh	Black Smoke %
$19 \leq P < 37$ (Applied to 2007)	5.0	1.00	6.0	0.400	40
$37 \leq P < 56$ (Applied to 2008)	5.0	0.70	4.0	0.300	35
$56 \leq P < 75$ (Applied to 2008)	5.0	0.70	4.0	0.250	30
$75 \leq P < 130$ (Applied to 2007)	5.0	0.40	3.6	0.200	25
$130 \leq P < 560$ (Applied to 2006)	3.5	0.40	3.6	0.170	25

the fifth mode, where a significant amount of PM was discharged. In the fifth mode, the black smoke concentrations with FAME1, 2 and 3 significantly decreased compared to diesel fuel. Consequently, the amount of PM is presumed to have declined based on the fact the FAME products contained a high proportion of oxygen and the generation of soot was limited, etc.

Also, the specific CO emissions resulted to be 1.00g/kWh with diesel fuel, 1.10g/kWh (+9.3%) with FAME1, 1.13g/kWh (+12.6%) with FAME2 and 1.04g/kWh (+3.5%) with FAME3. Meanwhile, the specific HC emissions resulted as 0.060g/kWh with diesel fuel, 0.054g/kWh (-10.0%) with FAME1, 0.052g/kWh (-13.3%) with FAME2 and 0.063g/kWh (+5.0%) with FAME3. Those results satisfy the emission gas standard values to which this engine conforms, as shown in Table 4[2].

Conclusion

In power test and emission gas tests using diesel fuel and multiple FAME products for the tractor diesel engine, the following results were obtained:

1) If the engine is operated using a FAME product, an engine output equivalent to when diesel fuel was used may be achieved. However, the resulting SFC was high because the calorific values of FAME products were low compared to diesel fuel, etc.

2) Of the diesel engine emission gas components, NOx, which is discharged in bulk, reportedly increases if the engine is driven with FAME products. However, the actual emission rate is -2.9 to +2.6% compared to diesel fuel, namely, almost equivalent. As for PM, if a FAME product is used, emissions decreased compared to diesel fuel in most operation modes when the test was conducted using the diesel special vehicle 8-mode method. Inparticular, in the fifth mode where emissions were considerable, overall emissions halved.

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