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REVIEW

The Effect of Unreacted Residue in Biodiesel Fuel on Diesel Engine Performance

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Abstract

This paper reviews the impact of using biodiesel fuel containing large amounts of raw material components on engine performance in an agricultural tractor. If a fuel containing abundant methanol, a raw material component, is used, the engine output decreases; presumably due to the drop in fuel injection. Accordingly, it emerged that the engine's original fuel consumption could not be maintained as methanol vapor was generated from the fuel and accumulated in the fuel pipe. Moreover, the engine was operated for 700 hours using a fuel containing abundant triglyceride, which, in itself, is a raw material fat residue for a new tractor, regularly inspecting and servicing as specified by the tractor manufacturer and using the electrical dynamometer. Consequently, the power output from the power take-off shaft (hereinafter referred to as "PTO") decreased by 0.4 to 1.2kW from the value before the start of the operation, the specific fuel consumption (hereinafter referred to as "SFC") increased by 7 to 23g/kWh and the carbon monoxide (CO) and black smoke concentrations increased significantly. Based on the disassembly and adjustment of engine parts after the operation, this phenomenon is considered attributable to the reduction in exhaust valve clearance accompanying the wear of the valve seat, which may occur, even in the middle of the operation with diesel fuel.

Discipline: Biofuel
Additional key words: fuel injection, long-term operating, methanol vapor, torque, triglyceride

Introduction

Attention is currently focused on biofuels made from recyclable resources such as plants, animals, etc., from the perspective of global warming countermeasures, reduced fossil fuel consumption and reduced waste materials. Under such circumstances, biodiesel is expected to be used for agricultural machines equipped with diesel engines, such as tractors.

The general type of domestically manufactured biodiesel fuels is based on the fatty acid methyl ester (hereinafter referred to as "FAME"), which can be produced by chemical reaction between fat contained in waste edible oil mainly discharged from households or food processing and methanol. The reaction triggered through the alkali catalyst method, which is representative of manufacturing, is as shown in Fig. 1.

To spread the use of FAME products in Japan, the required qualities of FAME products to be mixed with diesel fuel with 5 mass% or less were defined under Japanese Industrial Standards (JIS) K2390 in 2008. Also, during the same year, 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 to allow FAME-mixed diesel fuel conforming to the relevant quality standards (i.e. Standard Conformable Diesel Fuel, hereinafter referred to as "SCDF") to be sold or self-consumed as a fuel for vehicles running public roads. In response, domestic agricultural machinery manufacturers, etc. started to guarantee the use of SCDF.

Meanwhile, according to the report on biofuels issued by the Japan Agricultural Machinery Manufacturers Association, a survey on the properties of FAME products manufactured domestically exposed variation in qualities depending on manufacturers. For example, some products did not meet "JIS K2390", its equivalent European Standard "EN14214" and the US standard "ASTM D6751". Furthermore, some cases of FAME products being used at high concentrations (100%) were also reported, requiring

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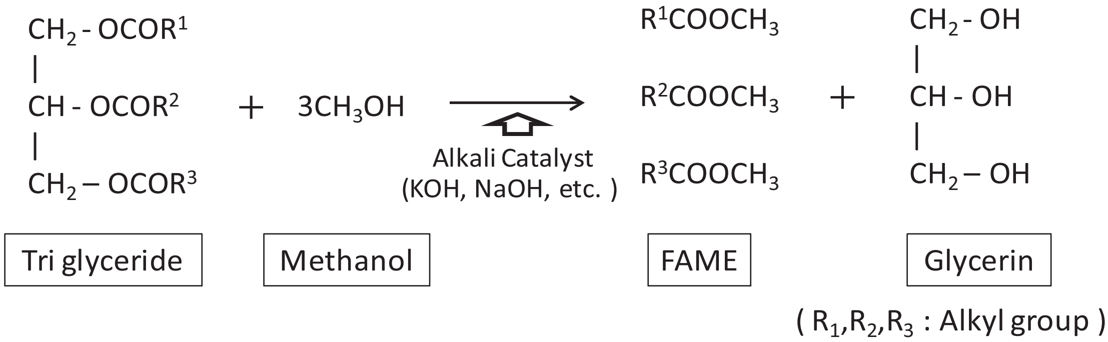

Fig. 1. Chemical reaction of oils and fats using the alkali catalyst method

users' self-responsibility[1].

However, to date, there have been no cases where the impacts of the FAME product failing to meet quality standards on engine output, etc. were comparatively surveyed. In guidelines for those using FAME products at high concentrations, issued by the Ministry of Land, Infrastructure, Transport and Tourism, the 5 items which need to be taken into consideration in terms of product qualities are highlighted, namely, 1. Triglyceride, which in itself is a raw material fat residue, 2. residual methanol used with fat as a raw material of FAME, 3. glycerine, as a by-product of FAME, 4. residual water used for fuel cleaning and 5. kinetic viscosity, which increases depending on the mixture of impurities and glyceride substances, etc[3]. By taking this into consideration, the impact on engine output of using FAME products containing residual triglyceride and methanol, etc. for a diesel engine, was studied and the results reported as follows:

Table 1. Properties of test fuels and qualities required under JIS K2390

Items		Test Fuels		Quality required by
	FAME1	FAME2	FAME3	JIS K2390[2]
Lower calorific value (kJ/kg)	38010	38550	38800	-
Density (15°C)(g/cm^3)	0.8880	0.8868	0.8834	0.860 - 0.900
Cetane index	54.8	55	56.4	-
Kinematic viscosity (40°C)(mm^2/s)	5.123	4.449	4.314	3.50 - 5.00
Water content (ppm)	907	613	561	< 500
Sulfur content (ppm)	6	4	3	≤ 10
Carbon residue at 10% (mass%)	0.61	0.72	0.48	≤ 0.3
Pour point (°C)	-7.5	-5.0	-7.5	-
CFPP (°C)	-8	-6	-7	-
Oxygen content (mass%)	10.4	10.5	11.0	-
Carbon conten (mass%)	77.1	77.1	76.8	-
Free glycerin (mass%)	0.00	0.01	0.02	≤ 0.02
Mono glyceride (mass%)	0.95	1.58	0.43	≤ 0.80
Di glyceride (mass%)	0.88	0.46	0.16	≤ 0.20
Tri glyceride (mass%)	5.52	0.70	0.75	≤ 0.20
Methanol content (mass%)	0.04	0.16	1.30	≤ 0.20
Flash point (°C)	168	163	41.0	120 ≤
FAME (mass%)	89.50	95.04	97.00	96.5 ≤
Distillation character-istics: First distillation (°C)	280.0	299.0	274.0	-
Distillation character-istics: Distillation temperature 10% (°C)	350.0	349.0	350.0	-
Distillation character-istics: Distillation temperature 50% (°C)	352.5	351.5	352.0	-
Distillation character-istics: Distillation temperature 90% (°C)	363.5	357.5	356.0	-

Engine performance test

1. Test fuel and engine

Table 1 shows the properties of 3 FAME products used for the test and the quality requirements defined by JIS K2390, which is an SCDF FAME standard. These FAME products were manufactured by independent organizations located in Japan using waste edible oil as a main raw material and the alkali catalyst method.

As for triglycerides, FAME1 significantly exceeded the quality standard requested by JIS K 2390, but for methanol, only FAME3 exceeded it and its flash point was particularly low. This was presumably due to the fact that abundant methanol with a flash point of 11°C was contained. As for water, all the FAME products exceeded the quality standard, particularly FAME1 almost twofold. Meanwhile, as for free glycerine, all the FAME products remained within the quality standard.

For the test, a naturally-aspirated 3-cylinder auxiliary-chamber diesel engine (rated power: 22.1kW/2500 rpm, displacement: 1.498L) was selected.

2. Test Methods

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 affair rules defining the matters concerning the methods for examining vehicles and vehicle equipment to be used by the National Traffic Safety and Environment Laboratory and identify the basic performance of diesel engines. The engine speed was changed at intervals of 200 rpm within the range 1100 to 2500 rpm with the governor control lever set to the full speed position, outside the active range of the speed governor and under full-load operation. The engine speed and torque were measured using the dynamometer indicator, and the 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.). Furthermore, an original fuel hose was changed to a transparent oil-resistant hose to remove the air from the fuel pipe in the middle of preparation for the test by readily checking the conditions in the pipe[4].

3. Results

Fig. 2 shows the relationship between engine speed and engine torque while Fig. 3 shows the relationship between engine speed and fuel injection.

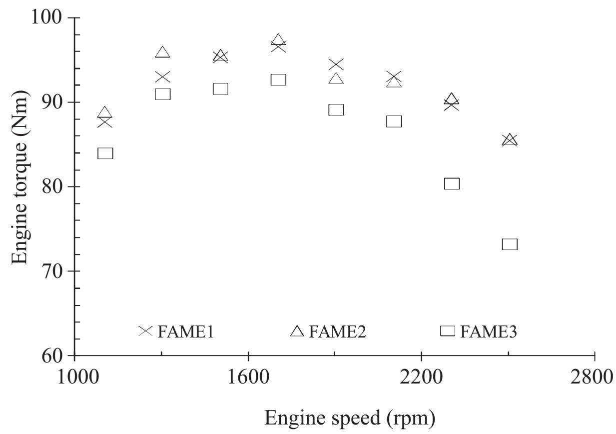

Fig. 2. Relation of engine speed and torque (FAME)

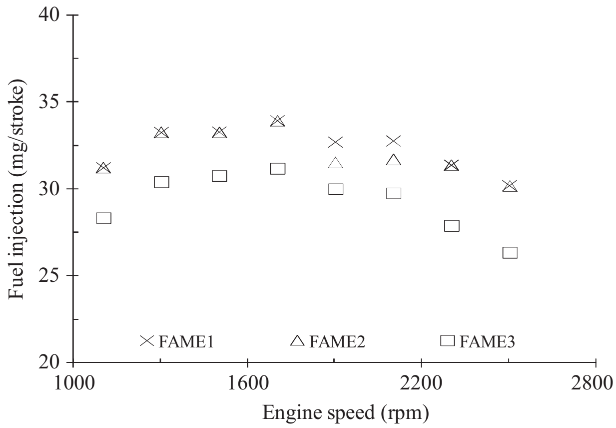

Fig. 3. Relation of engine speed and fuel injection (FAME)

With regard to the relationship between torque and fuel consumption, the torque and fuel consumption at the rated engine speed (2500 rpm) were 85.5Nm and 30.4mg/stroke with FAME1, 85.7Nm and 30.1mg/stroke with FAME2, and 72.5Nm and 25.9mg/stroke with FAME3. Meanwhile, at the engine speed of 1700 RPM, at which the generated engine torque peaked, the figures were 96.6Nm and 34.1mg/stroke for FAME1, 97.8Nm and 33.8mg/stroke for FAME2, and 92.5Nm and 31.1mg/stroke for FAME3 respectively.

The lower calorific value and density of each fuel were similar. However, a significant drop in torque was shown along with the reduction in fuel injection at every engine speed with FAME3 rather than FAME1 and FAME2. Meanwhile, there was no significant difference in fuel consumption and torque between FAME1 and FAME2. In the middle of the test with FAME3, bubbles and retained gas were identified in the fuel hose from the fuel injection pump to the fuel injection nozzle and the return fuel hose after fuel injection. At the time, the temperature around the fuel injection nozzle was 80 to 90°C, the engine oil temperature was 79 to 95°C and the coolant temperature was 61 to 82°C.

After the test with FAME3 was complete and the air bubbles had been eliminated from the fuel hose, the presence of bubbles and residues in the fuel hose was reconfirmed by resuming engine operation at a speed of 2500 rpm and 100% load factor, which caused a significant drop in fuel consumption. In particular, FAME3 contained abundant methanol, the boiling point of which is 64.7. Therefore, it is surmised that the torque dropped because the engine's original fuel injection could not be maintained as the methanol was evaporated in the fuel.

4. Influence of methanol on diesel engine performance

(1) Test fuel and tractor

For the test, the JIS No. 2 diesel fuel and products with methanol were used. The proportions of methanol added to the diesel fuel were 1. 0, 2. 0.48, 3. 0.96 and 4. 1.44 mass% (hereinafter referred to as "M0", "M0.5", "M1.0" and "M1.5"). Also, for the test, a (riding-type) tractor manufactured in Japan in 1992 and equipped with a naturally-aspirated 3-cylinder auxiliary-chamber diesel engine (rated power: 18.4kW/2600 rpm, displacement: 1.463L) is used.

(2) Test Methods

Similarly to the output test, the tractor was connected to the electrical dynamometer (FC-R manufactured by Meidensha Corporation, absorption power: 55kW) and the PTO speed and load were adjusted.

The test was conducted in accordance with the "PTO performance test" method, which aims to identify the PTO shaft performance of the relevant engine; based on the main methods and standards used to test (riding-type) agricultural tractors, as specified under Article 7-3, Act on Promotion of Agricultural Mechanization (Act No. 252 of 1953). The engine speed was changed at intervals of 200 rpm within the range 1100 to 2500 rpm with the governor control lever set to full speed, which is outside the range of the effect of the speed governor and full-load operation condition. The PTO speed and torque were measured by the dynamometer indicator while the fuel consumption was measured 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.). Also, the engine speed is calculated with the PTO speed and the speed reduction ratio. Furthermore, the original fuel hose was exchanged for a transparent oil-resistant hose to eliminate the air from the fuel pipe during preparation for the test by readily checking the conditions in the pipe.

(3) Results

Fig. 4 shows the relationship between engine speed and fuel injection, while Fig. 5 shows the relationship between engine speed and PTO torque.

With regard to the relationship between fuel injection and PTO torque, the fuel injection and PTO torque at the rated engine speed: 2600 rpm resulted in 21.9 mg/stroke and

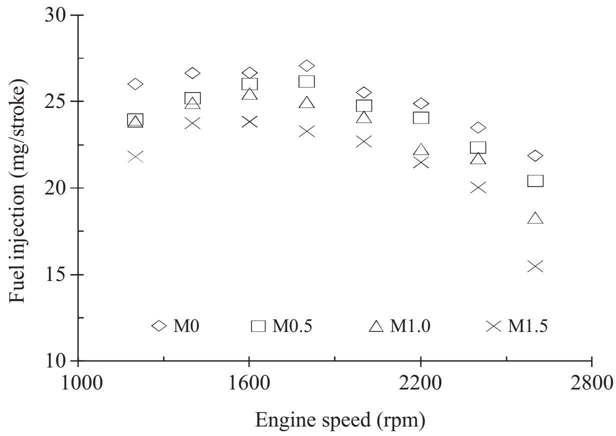

Fig. 4. Relation of engine speed and fuel injection (diesel fuel with methanol)

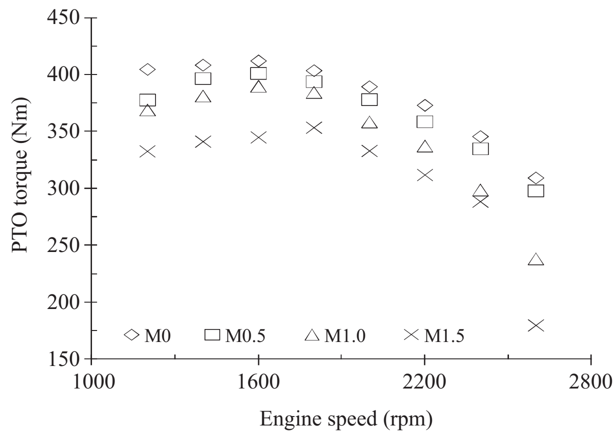

Fig. 5. Relation of engine speed and PTO torque (diesel fuel with methanol)

309.5Nm with M0, 20.5mg/stroke and 298.1Nm with M0.5, 18.3mg/stroke and 238.3Nm with M1.0, and 15.5 mg/stroke and 179.9Nm with M1.5. The fuel injection and PTO torque at engine speed with maximum PTO torque: 1600 rpm were 26.7mg/stroke and 412.3Nm with M0, 26.1mg/stroke and 401.2Nm with M0.5, 25.5mg/stroke and 390.0Nm with M1.0, and 23.8 mg/stroke and 345.0Nm with M1.5. The larger the proportion of added methanol was, the smaller the fuel injection was. At the same time, the torque emerged to have reduced. Also, in the middle of the test, bubbles and gas residues were identified in the fuel hose from the fuel injection pump to the fuel injection nozzle and the return fuel hose after fuel injection in all of fuels M0.5, M1.0 and M1.5 with methanol. It emerged that the temperature around the fuel injection nozzle was 95°C for the M0 test, 94°C for the M0.5 test, 92°C for the M1.0 test and 90°C for the M1.5 test, exceeding the boiling point of methanol: 64.5°C.

Consequently, it emerged that if a fuel containing methanol was used, the output dropped due to the fact that the engine's original fuel injection could not be maintained

Table 2. Properties of fuels used for long-term operation test

Items	Elapsed time(h)				
	0 - 175	176 - 316	317 - 461	462 - 650	651 - 700
Lower calorific value (kJ/kg)	37580	36950	36750	36960	37670
Density (15°C)(g/cm^3)	0.8864	0.8893	0.8904	0.8886	0.8879
Kinematic viscosity (40°C)(mm^2/s)	4.80	5.45	5.84	5.26	5.20
Flash point (°C)	180.5	178.5	180.5	184.5	175
Water content (ppm)	1100	933	1100	954	1200
Acid number (mgKOH/g)	0.14	0.15	0.15	0.18	0.15
Cetane index	53.7	52.7	53.1	51.6	60.0
Iodine value	114	116	114	114	115
Methanol content (mass%)	<0.01	<0.01	0.01	<0.01	<0.01
Triglyceride (mass%)	1.18	6.01	8.56	4.70	3.05
FAME (mass%)	94.0	83.5	81.0	85.7	88.7

as methanol vapor was generated from the fuel and it was accumulated in the fuel pipe while the temperature of each engine part increased.

Long-term operation test

1. Test tractor and fuels

For the test, a new tractor equipped with an in-line 3-cylinder auxiliary-chamber diesel engine (rated power: 22.1kW/2800 rpm, displacement: 1.498L) was selected and a FAME product containing abundant triglyceride was applied and manufactured by the same manufacturer (Table 2).

2. Test Methods

Similarly to the test case mentioned above, the tractor was connected to the electrical dynamometer (FC-R manufactured by Meidensha Corporation, absorption power: 55kW) and the PTO speed and torque were measured while applying a load.

The engine was repeatedly driven with 700 cycles (700 hours) in accordance with the operation pattern (1 cycle = 1 hour) (Table 3) designated based on the engine speed and load factor shown in TRIAS24-8-2003 "Diesel special vehicle 8-mode emission gas test method" included in the new vehicle test methods while inspected and serviced as specified by the tractor manufacturer.

Before the operation started and every time 50 cycles were complete, the CO concentration, etc. were measured using the emission gas component meter (MEXA-9400D manufactured by Horiba, Ltd.) and the black smoke concentration was measured using the filter paper type smoke meter (GSM-3 manufactured by Tsukasa Sokken, Co., Ltd.).

The inspection and service items included replacing the engine oil, engine oil filter, fuel filter, mission oil, and mission oil filter. As for the engine oil, the viscosity, acid value, base value, etc. were analyzed every 200 cycles to survey the impact on oil deterioration.

Table 3. Operation patterns for long-term operation test

Test mode	Duration (s)	Engine Speed (rpm)	Load (%)	Operating state
	4	Low Idle	0	Transition
	8	High Idle	0	
Mode 1	30	2800	100	Transition
	418			Steady
Mode 2	30	2800	75	Transition
	418			Steady
Mode 3	30	2800	50	Transition
	418			Steady
Mode 4	30	2800	10	Transition
	418			Steady
Mode 5	30	1700	100	Transition
	418			Steady
Mode 6	30	1700	75	Transition
	418			Steady
Mode 7	30	1700	50	Transition
	418			Steady
Mode 8	30	Low Idle	0	Transition
	418			Steady
	4	Low Idle	0	Transition
Total	3600			

Also, after the 700-cycle test operation was complete, the engine was disassembled to examine the influence on each component.

3. Results

No change in performance was observed before the 400-cycle operation was complete. However, when the operation period exceeded 400 cycles, black smoke and CO

Table 4. Test progress and variation in engine performance

Items	Engine Speed (rpm)	Elapsed time(h) 0	100	200	300	400	500	600	700
PTO Power (kW)	2800	19.1	19.1	19.4	19.3	19.5	19.3	18.7	18.7
	2400	18.6	18.8	18.9	18.9	19.0	18.8	18.2	17.9
	2000	16.7	17.0	16.9	16.8	17.0	16.5	16.0	15.8
	1600	13.9	14.0	14.1	14.0	13.9	13.5	13.0	12.9
Specific fuel consumption (g/kWh)	2800	396	399	393	390	389	394	398	403
	2400	368	369	365	362	364	366	372	378
	2000	355	354	355	351	350	357	363	368
	1600	349	351	348	342	346	356	363	370
CO (ppm)	2800	75	77	69	72	83	147	229	703
	2400	80	72	83	71	91	216	593	1488
	2000	102	107	113	102	179	575	1557	3437
	1600	239	280	250	211	321	1644	3998	4000 <
Black Smoke (%)	2800	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.0
	2400	0.0	0.0	0.0	0.0	0.0	1.2	6.5	17.7
	2000	0.0	0.0	0.0	0.5	3.8	14.4	22.6	34.0
	1600	7.2	12.1	15.8	11.2	12.0	32.3	44.3	48.5

Table 5. Post-test engine oil properties

	New oil	After 200 h	After 400 h	After 600 h
Test period (h)	-	100 - 200	300 - 400	500 - 600
Kinematic viscosity (40°C)(mm^2/s)	78.43	66.71	68.32	73.09
Acid number (mgKOH/g)	1.93	2.51	2.54	2.54
Base number (mgKOH/g)	5.18	3.08	3.05	2.97
Flash point (°C)	226	224	218	218
Carbon residue at 10% (mass%)	1.23	2.12	2.28	2.86
Pentane insolubles (mass%)	0.01	0.05	0.05	0.05
Water content (ppm)	174	157	164	196

concentrations soared while PTO power output declined and a gradual increase in SFC became apparent. After the 700-cycle operation was complete, the PTO power output was shown to have dropped by 0.4 to 1.2kW and the SFC was shown to have increased by 7 to 23g/kWh in comparison with the pre-test figures (Table 4).

Also, a mixture of approx. 1% FAME was observed in the used engine oil. However, it was surmised that there had been no deterioration in engine oil due to FAME products (Table 5).

After disassembling the engine, a drop in sliding properties of the injection pump plunger emerged due to FAME products although almost no carbon had accumulated in the combustion chamber or injection nozzle, etc. Also, 2 valve clearances (hereinafter referred to as “VC”) (correct value: 0.35mm) had reduced to 0mm and one to 0.11mm, which was presumably due to the wear in the valve seat. However, every component remained available for continuous use.

4. Valve clearance test

To study the variation in engine output and emission gas characteristics caused by the change in VC, arrangements were made to source a new tractor of the same model used for the long-term operating test and ensure it was installed it in the laboratory in the same manner. The JIS No. 2 diesel fuel was adopted for the test and the engine VC was reduced gradually from the correct values: 0.35 to 0.15mm to measure the PTO power output, fuel consumption, CO concentration and black smoke concentration, etc. Consequently, the concentrations of CO and black smoke increased while VC declined as shown in Table 6. Moreover, a drop in PTO power output and increased SFC were also observed. Thus, it is surmised that the change in engine performance occurring midway through the long-term operating test was due to the reduction in VC, which might occur during operation with diesel fuel.

Table 6. Valve clearance and engine performance

Items	Engine Speed (rpm)	Valve Clearance (mm) 0.350	0.300	0.025	0.200	0.187	0.175	0.150
PTO Power (kW)	2800	20.4	20.8	21.2	20.9	19.9	19.2	16.3
	2400	19.8	20.0	20.2	20.0	19.0	18.1	15.4
	2000	17.6	17.9	18.0	17.6	16.8	15.9	13.2
	1600	14.4	14.6	14.6	14.6	13.6	12.7	10.2
Specific fuel consumption (g/kWh)	2800	336	343	340	343	363	374	442
	2400	313	322	317	321	336	354	418
	2000	311	315	316	325	340	357	432
	1600	302	310	310	310	331	358	446
CO (ppm)	2800	142	134	150	142	777	2853	4000 <
	2400	170	252	167	157	1129	4000 <	4000 <
	2000	725	949	1358	1242	4000 <	4000 <	4000 <
	1600	1188	1194	1419	1481	4000 <	4000 <	4000 <
Black Smoke (%)	2800	4.8	3.5	5.1	4.8	17.9	34.7	63.4
	2400	7.9	8.2	6.7	5.8	22.6	45.5	69.3
	2000	24.0	26.8	35.0	27.0	48.0	61.9	79.5
	1600	32.1	31.2	33.7	33.8	58.9	70.3	83.2

Conclusion

An impact on engine performance was seen by adopting FAME products with abundant residual methanol and glyceride substances for a tractor diesel engine. The major test results obtained are as shown below.

1) After operating a tractor engine by adopting FAME products with abundant residual methanol, it emerged that methanol components might have evaporated and accumulated in the fuel pipe to prevent the engine's original fuel injection from being maintained, resulting in a drop in engine output.

2) By adopting FAME products with abundant unreacted triglyceride for a new tractor, 700-hour operation was conducted. Consequently, the PTO power output dropped by 0.4 to 1.2kW, the SFC increased by 7 to 23g/kWh and the black smoke concentration increased. By disassembling and checking engine components after the operation, it emerged that a reduction in VC may occur, even with diesel fuel.

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