47 Characteristics of Exhaust Gas Emission of Bio Fuel Oil
--- On Board Measurement ---

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This paper describes the experimental results of the on board measurement of the exhaust gas emission through a CI engine which was installed in a commercial van type truck, supplying to the bio fuel oil. The fuel was produced by the reformation of the waste of cooking oil. The measuring items were carbon dioxide, carbon monoxide, total hydrocarbons, nitrogen oxide, particulate matters and running fuel cost under the different seasons at the town area and at the expressway. Also they were obtained at not only cold starting but also hot starting at the town area in the winter. The data were compared with those of JIS second class gas oil.

***Keywords*: DI Diesel Engine, Bio Fuel Oil, On Board Measurement, Exhaust Emission**

1. INTRODUCTION

The save of energy is very much significant and urgent issue for the earth environment and the human healthy. However, the energy itself is the source of the comfortable and convenient life style. The other issue is to find the countermeasures against very much severe recent regulation of the exhaust gas through a reciprocating, especially, a CI engine. One of solutions is the usage of bio fuel oil and the supply of this kind of fuel oil to a CI engine which shows the highest thermal efficiency comparing with an SI engine and a gas turbine.

The guideline of the use of bio fuel oil has already published [1]. One of researches relating to the bio fuel oil shows that carbon dioxide, total hydrocarbon and particulate maters through a CI engine decreases more than those of the conventional gas oil [2]. The authors published the experimental results related to the bio fuel; (1) spray characteristics in a constant volume chamber [3], (2) fundamental combustion characteristics in a rapid compression and expansion machine [4] and the on board measurement of NOx and particulate matters against the engine output [5].

Kyoto city has supplied the bio fuel oil of 1.5 million litters per year to city buses and garbage carts. Also Wakayama city has supplied this kind of fuel of 120 thousand litters per year to 5 generators. However, the bio fuel oil has much different properties comparing to those of gas oil. Thus, it is expected to examine the detailed information of the exhaust gas to understand the phenomena itself and to gather the on board data.

From the standpoint mentioned above this paper describes the experimental results of the characteristics of exhaust gas through a DI diesel engine installed in a commercial truck of van type with medium size. Two kinds of bio fuel oil produced in Kyoto City and Wakayama City were used in the experiments. The experiments were carried out on the city street of the town area and the expressway at the different season. The data seem to be useful to understand the actual phenomena much more than those obtained by the mode driving on the chassis dynamometer. The other experiments were the cold starting and the hot starting in the winter at the town area.

2. BIO FUEL OIL USED

Kyoto city has withdrawn the wasted fuel of the cooking fat from personal houses and restaurants in the model area. They have reformed this kind of fuel by the following way:

1. Elimination of water and impurities containing in the oil withdrawn as the pre-processing
2. Two times processing of adding methanol and potassium hydroxide as the catalyst in the oil after pre-processing
   It is capable of separating the crude methyl ester and the glycerol through this process.
3. Washing the crude methyl ester to get purer one after the process 2 by hot water
4. Elimination of water and impurities from the oil after process 3.

Hereinafter, this methyl ester is called KBDF-100. Kyoto city has supplied KBDF-100 to garbage trucks and the oil mixed with 20 [vol. %] of KBDF-100 and 80 [vol. %] of gas oil (hereinafter called KBDF-20) to city busses.

Wakayama city has gathered the wasted plant oil from the food industries and the restaurants in Wakayama prefecture. They eliminate water and impurities from the oil gathered. They blend this oil of 30 [vol. %] and kerosene of 70 [vol. %] to control the viscosity. Hereinafter, this blended oil is called WBF. They have supplied WBF to 5 generators.

Table 1 summarizes properties of JIS second class gas oil, KBDF-100 and WBF. Both fuel oil are the oxygenated fuel. The cetane index of three kinds of fuel is almost the same and the sulfur containing in both bio fuel is very small although their kinetic viscosity is about as twice as much as that of JIS second class gas oil. KBDF-100 is the fuel with high boiling point and low volatility. The properties of WBF are affected by those of kerosene.

Table 1 Fuel properties

	JIS second class gas oil	KBDF-100	WBF
Density [kg/m^3]	832 – 838	886	825 – 830
Kinetic viscosity [mm^2/s]	2.8	4.8	3.2 – 4.5
Cetane index	55 – 56	51	52 – 54
Flash point [K]	332 – 341	461	322 – 323
Distillation T10 [K]	488 – 498	606 – 616	451 – 463
Distillation T50 [K]	548 – 558	609 – 619	480 – 518
Distillation T90 [K]	605 – 618	628 – 641	581 – 598
Clog point [K]	264 – 271	269	231 – 232
Carbon [mass%]	86.7	77.1 – 77.9	79.1
Hydrogen [mass%]	12.8	11.7 – 11.8	12.2
Oxygen [mass%]	–	11.1 – 11.2	8.6
Sulfur [mass%]	0.02 – 0.05	0.0003	0.002 – 0.020
Calorific value [MJ/kg]	44.5 – 45.5	37.7	44.0 – 45.0

3. EXPERIMENTAL PROCEDURE AND CONDITION

Truck and Engine Used The commercial truck of van type used was 2.5 [ton] and it had 5 steps of manual shift. The many kinds of measurement instruments were installed in the carrier. One person was a driver and the other person measured all the information in the carrier. Total weight of the truck was about 2.9 [ton]. Its running history is about 110,000 [km]. The water cooled DI diesel engine of four stroke with 4 cylinders produced in 1993 was installed in the engine room. Its maximum output was 88.2 [kW] / 3500 [rpm] and its maximum torque was 264.6 [Nm] / 1900 [rpm], respectively. The bore and stroke of engine were 105 [mm] and 105 [mm], its displacement volume was 3.63 [*l*], its compression ratio was 17.5, respectively. The engine had no EGR system. The shape of combustion chamber was the rectangular type and the number of nozzle holes was 4. The injection pump was Bosch type and the nozzle opening pressure was 2.07 [MPa]. The start of the injection was 15 [deg. CA BTDC].

Measurement System Figure 1 illustrates the measurement system. The sensors installed are the THC analyzer of heating type **1**, the CO and CO_2 analyzer of heating type **2**, the opacity smoke meter **3**, the direct planting NOx analyzer **4** and the direct planting λ sensor **5** of which were installed in the carrier. The information related to the engine performance is taken by the Karman flow meter **6** for the flow rate of suction air, the temperature sensors for the fuel **7**, for the cooling water of engine **8**, for the lubricating oil **9**, for the crank case **10**, for the exhaust gas **11** and for the atmospheric temperature **12**. The pressure sensor **13** is set to detect the atmospheric pressure and the sensor of engine revolution **14** is installed. The humidity sensor **15** sensed the atmospheric humidity. The sensor **16** caught the run speed of the truck. The information of the location during the run is taken by GPS **17**. The other information is the accelerator stroke **18**, the light on/off **19**, the break on/off **20** and the air conditioner on/off **21**. All the data mentioned above are recorded on the data recorder **22** set in the carrier. And the generator **23** is set in the carrier to give the instruments the electric power.

Experimental Procedure and Condition The experiments were carried out at the sunny day in the summer, the autumn and the winter to obtain the data variation against the season. Before the run the engine was warmed up over 20 [min.] to increase the temperature of cooling water and that of lubricating oil so far as the given data, thereafter, the run was start. The truck was driven on the ordinal city road of the town area and the expressway near the Doshisha University. The ordinal

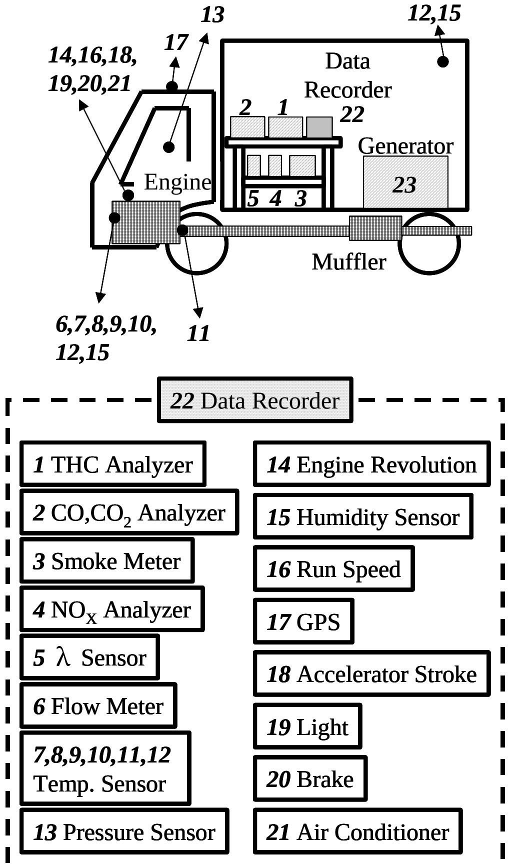

Fig. 1 Measurement system

road locates the suburb. The maximum difference in height was about 110 [m] as shown in Figure 2. The driver drove the truck with almost the same smooth speed as possible as he/she could. However, the wind velocity was different in each season, as a result, running resistance was different. The cold starting without idling and the hot starting with idling under the condition mentioned above were examined in the winter season. Table 2 lists the atmospheric condition. Table 3 summarizes the average condition relating to the engine performance.

4. EXPERIMENTAL RESULTS AND DISCUSSION

The on board data shown below are the average of 5 runs.

Pressure and Apparent Rate of Heat Release

Figure 3 is one of examples of the history of the pressure and that of the apparent rate of heat release at the stationary run of the engine not on board data as the reference. The mean effective pressure is 0.12 [MPa]. The ignition delay of WBF is the longest since the worse ignitability of kerosene included. The delay of KBDF-20 is almost the same as that of KBDF-100 and they are slightly shorter than that of gas oil because the bulk modulus of bio fuel oil is larger than that of gas oil, as a result, the injection delay becomes shorter than that of gas oil [6].

Effect of Kind of Fuel on Exhaust Emission

Figure 4 shows the characteristics of the exhaust gas emission at the expressway and the town area in the different season. The unit of PM is [1/m] because the measurement instrument is the opacity smoke meter.

NOx increases in order of summer, autumn and winter not only on the expressway but also on the town area. The reason of the trend is why the fuel viscosity increases accompanying with the decrease in the temperature of the suction air, namely, the atomization of fuel promotes less. NOx of WBF is the largest in the winter as the ignition delay judging on the history of apparent rate of heat release is the longest due to the properties of kerosene. Comparing with the data on the expressway and those on the town area, the former is lower than the latter regardless of the season. The trend is drawn from the repetition of start and stop and the increase in the consumption of fuel due to the uphill road shown in Figure 2.

PM shows almost the reverse trend of NOx. It is the largest in the summer on the expressway as well as on the town area. The difference in the atmospheric temperature between the summer and the winter is about

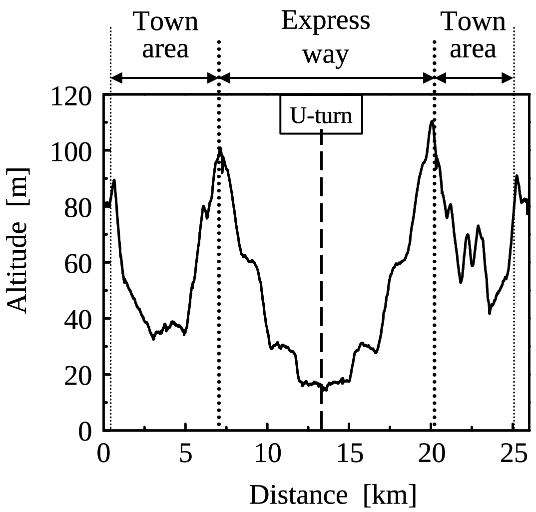

Fig. 2 Difference of altitude

Table 2 Atmospheric condition

	Fuel	Weather	Air temperature [deg.]	Absolute humidity [g/m³]	Distance [km]	Average speed [km/h]
Summer	Gas oil	sunny	32.0	20.4	26. 8	34.7
	KBDF-20	sunny	29.9	23.7	26.8	36.1
	KBDF-B100	sunny	31.7	21.2	26.8	35.5
	WBF	sunny	32.6	20.3	26.8	34.1
Autumn	Gas oil	sunny	16.7	9.5	26.5	34.9
	KBDF-20	sunny	16.5	10.1	26.7	34.4
	KBDF-100	sunny	16.4	9.7	26.7	34.0
	WBF	sunny	14.3	9.2	26.7	33.7
Winter	Gas oil	sunny	3.4	6.2	26.8	34.5
	KBDF-20	sunny	5.8	7.2	26.8	28.6
	KBDF-100	sunny	7.2	6.6	26.7	33.4
	WBF	sunny	7.7	7.2	26.7	31.3

Table 3 Average condition relating to engine performance

	Fuel temp. [deg.]	Excess air ratio	Charging efficiency [%]
Summer	48.3	4.03	68.0
Autumn	38.3	4.93	72.0
Winter	28.3	7.64	73.8

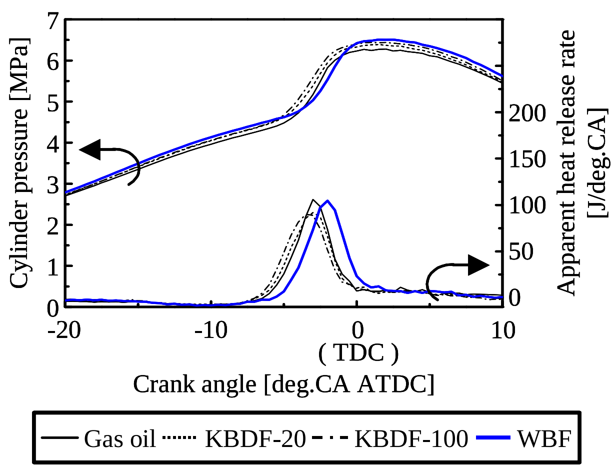

Fig. 3 One of examples of history of pressure and that of apparent rate of heat release at stationary run of engine not on board data (p_e = 0.12 [MPa])

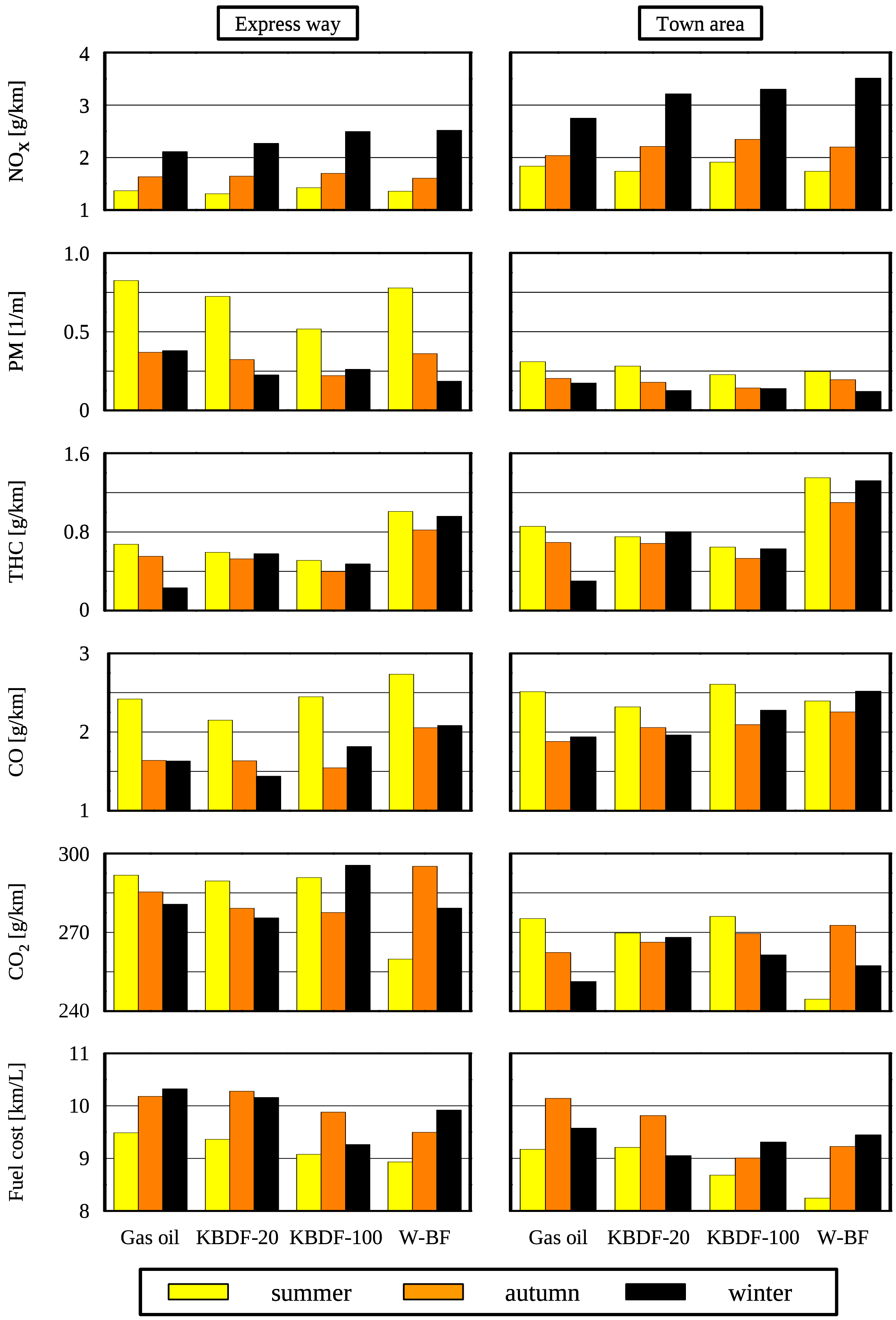

Fig. 4 Characteristics of exhaust gas emission on express way and at town area in different season

30 [K], thus, the difference in the compression temperature is about 100[K] and the viscosity of suction air in the summer increases as around 1.7 times as much as that in the winter. Then, the atomization of fuel in the summer proceeds less than that in the winter. Moreover, the viscosity of atmosphere around the spray in the summer is more than that in the winter, as a consequence, the mixing of droplets, their vapor and the surroundings in the summer does not go farther than that in the winter and the laminarization of flame becomes more distinguished. These are the reasons of the results mentioned above. The oxygen including in KBDF-100 and KBDF-20 affects the decrease in PM. The reasons of difference in the tendency of the expressway and that of the town area are almost the same as those of the case of NOx.

THC of gas oil decreases as the decrease in the atmospheric temperature not only on the expressway but also on the town area. The trend is the same as that of PM. The other fuel shows the different tendency comparing with gas oil, namely, it shows the smallest in the autumn. It seems that the trend is drawn in view of the wind velocity, in other words, the running resistance of truck, and the atmospheric temperature in the autumn. It is marked that THC of WBF shows the larger than those of the other fuel despite of the season. It seems that the trend is caused by the properties of kerosene. THC of KBDF-100 and that of KBDF-20 are relatively smaller than that of the other fuel since these includes the oxygen. THC on the town area is larger than that on the expressway. The reason is mentioned above.

The tendency of CO of gas oil and that of KBDF-20 show the gradual decrease as the decrease in the atmospheric temperature, on the expressway as well as on the town area. The trend is almost the same as that of PM. Namely, the gas oil including in KBDF-20 affects the generation of CO. In the case of KBDF-100 and WBF the tendency of CO is different from the other case. CO is the smallest in the autumn. The reason of this tendency is seemed to be the same as that of THC generation of bio fuel oil. The increase in CO in the summer is drawn from the decrease in the fuel viscosity due to the increase in the atmospheric temperature. The phenomenon appears in bio fuel which has higher viscosity by nature than gas oil.

On the expressway CO_2 of gas oil and KBDF-100 is almost the same trend as that of PM. The reason of the tendency is the same as that of NOx. However, the other fuel shows much different trends from the two kinds of fuel. The reason is not clear. On the town area the trend of gas oil and KBDF-100 increases as the atmospheric temperature decreases. CO_2 of KBDF-20 shows the minimum and WBF does the highest in the autumn. The explanation of the trend is not found. Generally speaking, CO_2 appears more on the expressway than on the town area. The reason is the same as that of NOx.

The running fuel cost of gas oil and WBF on the expressway decreases in order of winter, autumn and summer due to the decrease in the atmospheric temperature. In the case of KBDF-100 and KBDF-20 the best cost is the autumn. On the town area the trend of KBDF-100 and WBF is the same as that of gas oil on the expressway, on the other hand, gas oil and KBDF-20 show the same trend as that of KBDF-100 on the express way. It is able to explain the by the decrease in the atmospheric temperature that the running fuel cost of gas oil and WBF on the expressway and that of KBDF-100 and WBF on the town area decreases. However, it is unable to find the reason of the other trend.

Effect of hot starting and cold starting

Figure 5 is PM and THC at the cold starting and at the hot starting on the town area in the winter. The running distance is from the start point to 8 [km]. Generally speaking, PM and THC at the cold starting is larger than those at the hot starting due to the decrease in the atmospheric temperature, namely, due to the increase in the fuel viscosity. It is marked that the effect of bio fuel on PM is less at the cold starting although the effect is remarkable at the hot starting. And the other marked matter is that PM and THC generates at the run of uphill road.

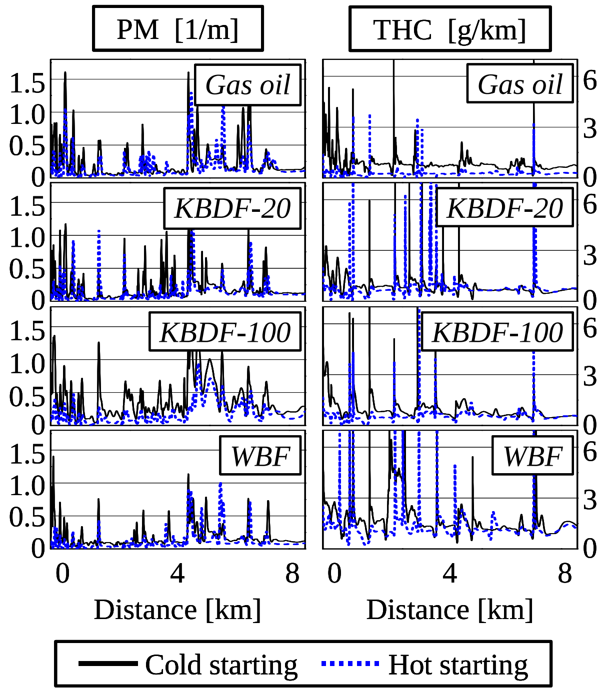

Fig. 5 PM and THC at cold starting and at hot starting on town area in winter

Figure 6 shows the characteristics of exhaust emission obtained on board measurement at the cold starting and at the hot starting in the winter. Generally speaking, the emissions at the cold starting are larger than that at the hot starting because of the lower atmospheric temperature and all the data show the same trend against the kind of fuel.

NOx at the cold staring is slightly larger than that at the hot stating regardless the kind of fuel. The order of the generation of NOx is gas oil, KBDF-100, KBDF-20 and WBF. The ignition delay of WBF is the longest; as a

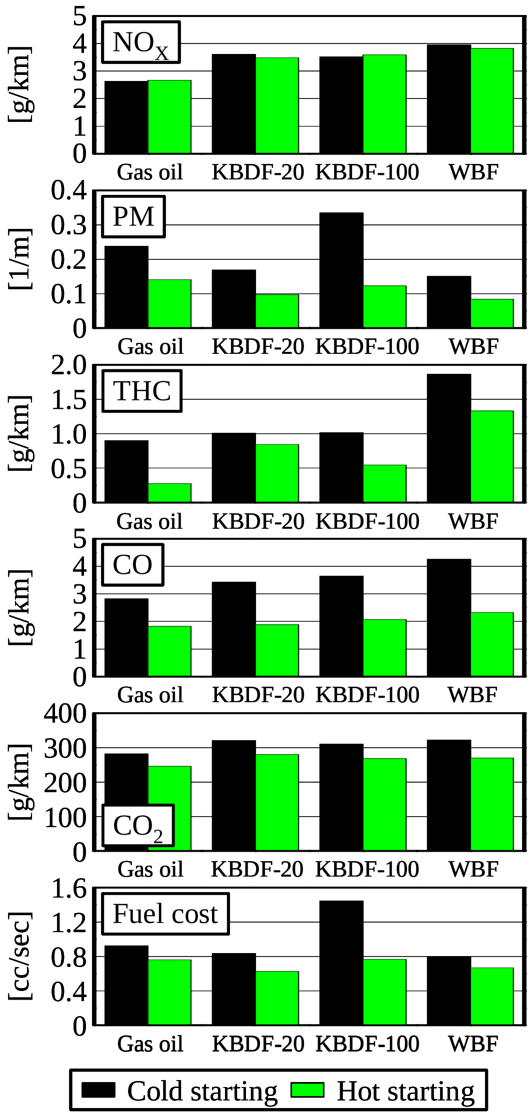

Fig. 6 Characteristics of exhaust emission at cold starting and at hot starting in winter

consequence, the pre-mixed burning is more remarkable than the other fuel. PM generates in order of WBF, KBDF-20, gas oil and KBDF-100 at the cold starting. Especially, it is remarkable in the case of KBDF-100 because its kinetic viscosity is the largest, thus, the state of atomization is worst. In other words, the effect of the oxygenated fuel on PM is very small at the cold starting. At the hot starting PM of WBF is the smallest and the effect of oxygen included in the fuel appears in the case of KBDF-20 and KBDF-100. The trend of THC and those of CO and CO_2 are that WBF has the largest since the ignition delay is the longest comparing with the other fuel. As for the running fuel cost the case of KBDF-100 is the highest at the cold starting. The reason is its highest kinetic viscosity.

5. CONCLUSION

The on board measurement of exhaust emission were carried out through the drive on the commercial truck of van type at the town area and on the expressway. The main conclusions are as follows:

(1) The atmospheric temperature, in other words, the fuel viscosity, affects the characteristics of the exhaust emission.
(2) The load of engine is the key factor affecting the characteristics of exhaust emission on the expressway.
(3) The repetition of start and stop of engine affects the characteristics of exhaust emission at the town area.
(4) The characteristics of exhaust emission are affected by the uphill/downhill road.
(5) The effect of oxygen included in the fuel on the characteristics of exhaust emission is little at the cold starting in the winter.
(6) It seems that the wind velocity, in other words, the running resistance, has to be consider when the on board experiments are carried out.
(7) It is not always to find the perfect reasons of the data obtained from the on-board experiments because it is unable to set just the same experimental condition in the different season, for example, the wind velocity.

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