INVESTIGATION OF ODOROUS COMPONENTS IN THE EXHAUST OF DI DIESEL ENGINES

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Abstract This study investigated the odorous components in the exhaust of DI diesel engines. The complete products of combustion are H2O and CO2 and they have no odor. Therefore, other products of incomplete combustion like unburned fuel components, partially burned components, cracked products from thermal cracking and others are thought to be responsible for exhaust odor. As the THC in the exhaust is the result of incomplete combustion, it is a logical guess that THC in the exhaust would correlate with exhaust odor. This study measured THC in the exhaust, and a good correlation was found between THC and exhaust odor at different engine conditions. In the next step, GC-analysis was used to detect individual HC component, and its effect on odor formation was investigated. It is found that the low boiling point hydrocarbon components, especially CH4 in diesel exhaust has a good correlation with exhaust odor.Aldehyde is one partially burned component which has very strong odor. This study used high performance liquid chromatography to measure aldehydes, and four aldehydes : formaldehyde, acetaldehyde, acrolein and propionaldehyde are found significant in exhaust gases. Each aldehyde correlates with exhaust odor very well and formaldehyde among all aldehydes is found the most important component for irritating odor.

Keywords: Exhaust odor, DI diesel engine, Aldehyde, HC component.

INTRODUCTION

Direct injection (DI) diesel engine vehicles are increasing worldwide because of the superior fuel economy and low carbon dioxide (CO_2) emissions. But such engines emit more unpleasant exhaust odor than gasoline engines, especially during warm-up and at idling of the engine. With increasing numbers of DI diesel engines, reductions in exhaust odor to acceptable levels are an urgent need. It is easier to reduce exhaust odor if the main odorous components in the exhaust gas are known. Much research has been conducted to learn about the main odorous components in diesel exhaust [1-3], but there is no clear indication about specific odorous components. This study investigated in detail about specific odorous components.

The diesel combustion reaction primarily consists of hydrocarbon chains (C_xH_y) being oxidized in an explosive reaction to form CO_2 and steam (H_2O). However, the reaction is not 100% efficient. Therefore other products of incomplete combustion are produced in diesel combustion, and these incomplete combustion products like unburned fuel components, partially burned components, cracked products and others are responsible for exhaust odor.

Total hydrocarbon (THC) in the exhaust is the result of incomplete combustion. So, it would be logical to expect a relationship between THC and exhaust odor. It has been reported that odor reductions correlate with THC reductions in case of catalyst operation [4]. This study measured THC in the exhaust, and a good correlation was found between THC and exhaust odor not only incase of catalyst operation but also at different engine conditions.

The effect of individual hydrocarbon (HC) component on odor formation was investigated. It has been shown in a previous paper of the author that the low boiling point hydrocarbon components in diesel exhaust have a good correlation with exhaust odor [5]. This study further extended this idea and showed that CH_4, the simplest low boiling point HC component in diesel exhaust has a good correlation with exhaust odor, although CH_4 itself has no odor.

Barnes [6] concluded that certain odor species were generated by partial oxidation of fuel. Aldehyde is one partially burned component, which has strong odor. This study measured four aldehydes and found that each aldehyde correlates with exhaust odor very well and formaldehyde (HCHO) among all aldehydes is found the most important component for irritating odor.

EXPERIMENTAL APPARATUS AND INVESTIGATION METHODS

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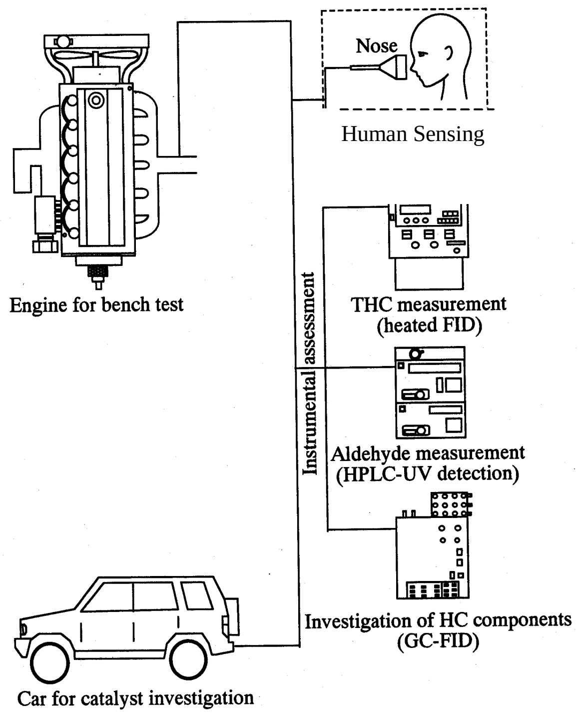

Fig.1 Schematic diagram of the experimental system

Fig.1 shows the schematic diagram of the experimental system. Two types of tests with DI diesel engines were performed. One is the bench test where a DI diesel engine was used to investigate the effects of engine parameters. The other is the test of actual car engine fitted with oxidation catalyst for the catalyst investigation. Specifications of the engine for the bench test are shown in Table-1. Table-2 shows the specifications of the catalyst fitted car engine. Two types of assessments are performed. One is human-sensing where the nose is used as the detector of smell of exhaust gases. The other is instrumental assessment methods where many instruments such as THC-meter for THC, high performance liquid chromatograph (HPLC) for aldehydes and gas chromatograph (GC) for HC components are used to identify the odorous components and to standardize them with human-sensing results.

Sensual Assessment

In assessing odors, a group of test persons is exposed to diluted exhaust gases to determine the odor threshold, which is identified as the dilution ratio where odor is detected by 50% of the test persons. This odor threshold method does not include any evaluation of discomfort from exhaust gas and is time consuming. This study used an odor intensity scale to evaluate the discomfort level of the exhaust gases. The intensity scale and corresponding explanation of odor ratings are given in Table-3.

Deviations in sensual assessments vary from person to person when the test personnel is inexperienced, while reliable results can be obtained with experienced personnel [3]. Thus the results obtained with a few experienced assessors are adequate for the assessment, and this study used three experienced assessors.

Exhaust Components

To investigate the odorous gas components, the THC was measured first with a heated flame ionization

Table-1: Bench test engine specifications

Engine type	4-Stroke, DI diesel engine
Number of cylinders	6, in-line
Bore × Stroke	115 × 125 mm
Swept volume	7799 cc
Compression ratio	16.8
Combustion chamber type	Re-entrant
Injection system type	Common rail, electronic control
Nozzle hole × Dia.	6 × 0.19 mm, L/D=4
Nozzle opening pressure	15 MPa
Maximum injection pressure	135 MPa

Table-2: Catalyst fitted car engine specifications

Engine type	4-Stroke, DI diesel engine
Number of cylinders	4, in-line
Bore × Stroke	95.4 × 104.9 mm
Swept volume	2999 cc
Compression ratio	19
Rated power	118 kW @ 3900 rpm
Maximum torque	333 N-m @ 2000 rpm
Combustion chamber type	Re-entrant
Injection system type	Common rail, hydraulically actuated electronically controlled injector
Nozzle hole × Dia.	6 × 0.18 mm

Table-3: Odor rating scale

Intensity rating	Verbal	Description
1	Not detectable	No odor
2	Slight	Odor but not uncomfortable
3	Moderate	Uncomfortable odor
4	Strong	Irritating odor; long time exposure not possible
5	Very strong	Very irritating odor; exposure for even 1 or 2 seconds impossible

detector (FID). The HC components in the exhaust were analyzed by GC-analysis. A packed glass column (squalane, uniport B) separated the low boiling point hydrocarbons carbon numbers from 1 up to 5. GC-capillary separation was used to separate hydrocarbons with carbon numbers from 6 to 32.

Aldehyde components were separated by HPLC where Dinitrophenylhydrazine (DNPH) was used as the standard derivatising agent to form the corresponding dinitrophenylhydrazones, and four components : formaldehyde, acetaldehyde, acrolein, and propionaldehyde were separated. The concentration of other higher aldehydes in the exhaust gas is very small and they cannot be separated.

EXPERIMENTAL RESULTS AND DISCUSSION

Correlation between THC and Exhaust Odor

As the THC measurement includes unburned fuel components and partially burned components, it is thought that THC may be correlated with exhaust odor. The correlation between odor and THC was investigated for two cases. One is at different catalyst temperatures with different catalyst activities and the other is at different engine conditions.

Fig.2 shows the relationship between odor and THC at different catalyst conditions. It was found that the catalyst is not active when the catalyst temperature is around 120°C, and the odor level is high and similar to that without catalyst. When the catalyst is moderately active at around 180 to 200°C odor is reduced about 0.5 to 0.75 point, a moderate odor reduction. In case of a fully active catalyst (catalyst temperature 300 to 450°C), there is almost no odor. This indicates a good correlation between odor and THC with catalyst operation at different temperatures.

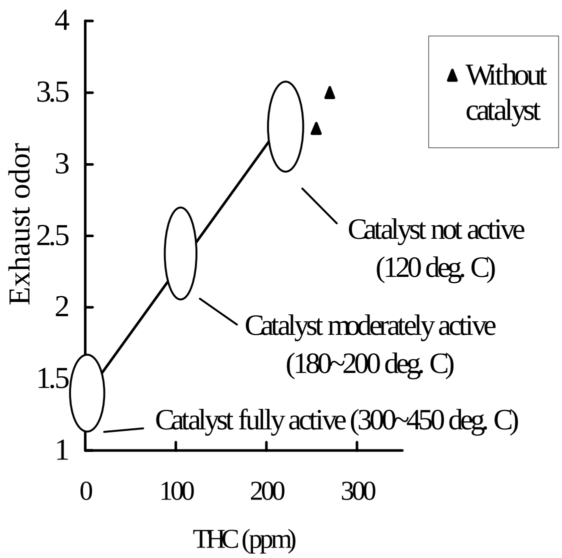

Fig.2 Correlation between exhaust odor and THC at different catalyst conditions

The correlation between odor and THC was then investigated with changing engine parameters and with changing ambient condition. Three conditions: different

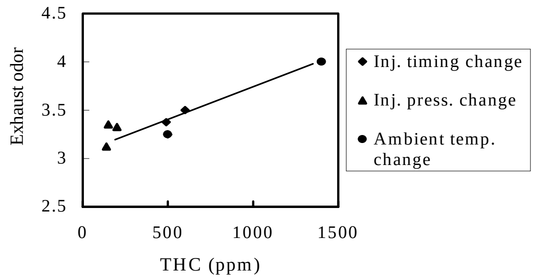

Fig.3 Correlation between exhaust odor and THC at different engine parameters

injection timings, different injection pressures and different ambient temperatures were selected. Fig.3 shows that there is a fairly good correlation between odor and THC with different engine conditions. Therefore, it may be concluded that at different engine conditions with or without catalyst operation, THC has a good correlation with exhaust odor. And THC-meter is an important instrument for odor checking.

Correlation between HC Component and Exhaust Odor

To investigate the correlation between HC components and exhaust odor, HC components are separated by GC-analysis. Two engine conditions were selected for the correlation. One was just after engine start where the exhaust gas was more odorous, and the other after engine warm-up where the gas was less odorous.

Fig.4(a) shows exhaust odor at engine start and after engine warm-up. The odor at engine start is more than 0.5 point higher than after warm-up. Fig.4(b) and 4(c) show the HC components at engine start and after warm-up. Here HC components carbon number 1 to 10 is termed as low boiling point hydrocarbons (LBHC), carbon number from 11 to 14 as medium boiling point hydrocarbons (MBHC), and carbon number above 14 as high boiling point hydrocarbons (HBHC). It is found that the concentrations of HBHC after warm-up are higher than at engine start, but exhaust odor is lower in this condition. This means that HBHC have no direct effect on exhaust odor. The MBHC are very similar in both engine conditions, indicating that MBHC are not responsible for odor control. The concentrations of LBHC, carbon number 1 to 5 in Fig.4(b) and carbon number from 6 to 10 in Fig.4(c) are higher at engine start than after warm-up, and exhaust odor is also higher. This indicates that LBHC may have some direct influence on exhaust odor.

The other possibility is that intermediate odorous components like aldehydes, organic acids, or other oxygenated components increase in the combustion condition where the LBHC increase, and the oxygenated components are responsible for exhaust odor.

It has just been shown that LBHC may have some direct influence on exhaust odor. The methane (CH_4) is one LBHC and its relationship with odor is investigated at different engine conditions. Fig.5 shows that the exhaust odor increases with the increase in CH_4 in the exhaust. This correlation between odor and CH_4 may be explained in the following way.

At the beginning of the combustion in the cylinder, two types of reactions take place. One is oxidation of fuel-air mixture, which is desirable. The other is thermal cracking of fuel when there is a shortage of oxygen. Methane is a cracked product from thermal cracking and a stable component. HCHO, an odor indicator [5] is produced both from oxidation of fuel-air mixture at low temperature combustion and from thermal cracking of fuel. When the combustion progresses under higher temperature condition, both the CH_4 and HCHO tend to complete combustion producing less concentration of them. When the combustion progresses under lower temperature condition, further oxidation of CH_4 and HCHO is stopped resulting higher concentration of both CH_4 and HCHO. Thus, CH_4 shows a correlation with HCHO as well as with odor, though CH_4 has no odor.

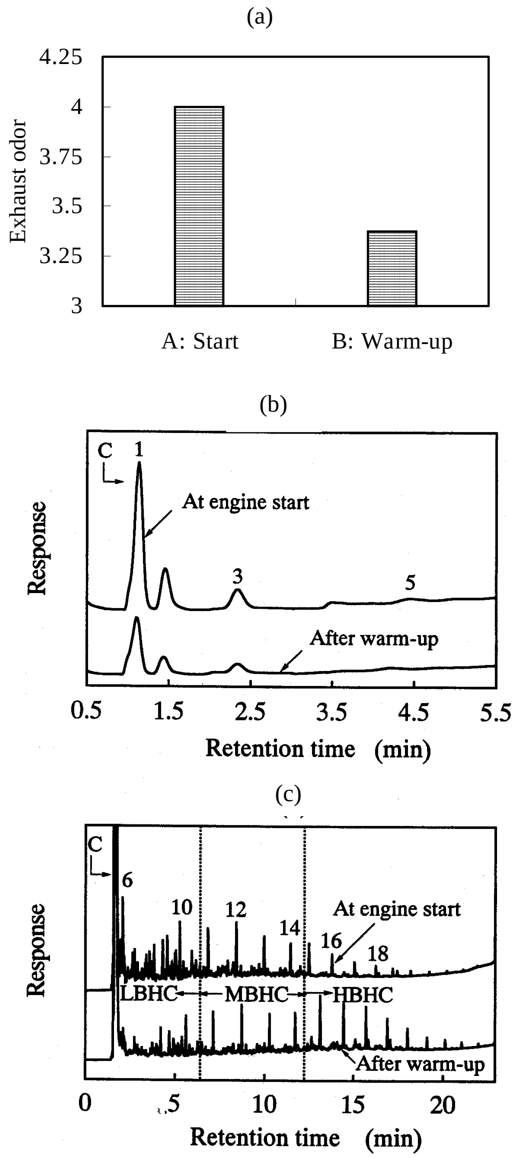

Fig.4 Exhaust Odor at engine start and warm-up with HC components

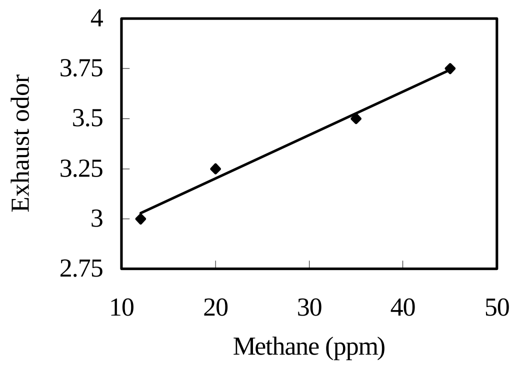

Fig.5 Relationship between exhaust odor and methane in exhaust gases

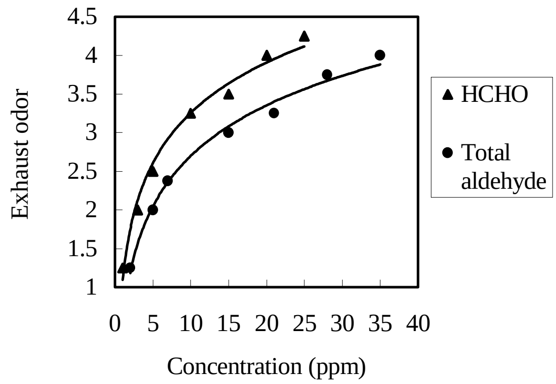

Fig.6 Correlation of odor with HCHO and total aldehyde

Correlation between Aldehyde and Exhaust Odor

It has already been mentioned that oxygenated components may be responsible for exhaust odor. Aldehydes are one of the oxygenated components in exhaust gases and they have a very strong odor. The relationship between aldehyde and odor is investigated. The concentration of four aldehydes: HCHO, acetaldehyde, acrolein and propionaldehyde are found significant in exhaust gases. It is also found that at bad engine condition where the odor is higher, all the aldehydes increase simultaneously, and at good engine condition where the odor is lower, all the aldehydes decrease at the same time. Therefore, it may be said that any aldehyde corresponds odor and total of all aldehydes also corresponds odor. Fig.6 shows the relationship of odor with HCHO, the biggest part of aldehyde in exhaust gases and with total aldehyde. There is a very good correlation for both.

Share of HCHO on Exhaust Odor

This study has also measured the relative weight of aldehydes, especially for HCHO, the biggest part of aldehydes in exhaust gases at any engine condition. Fig.7 shows aldehyde concentrations in exhaust gases at three sets of engine conditions. The conditions are: a) start-warm up, b) worst-best injection pressure and c) worst-best injection timings. In each set there is a good and a bad engine condition. It is found that at every engine condition, the concentration of HCHO is the highest about double to that of the sum of the other aldehydes.

Fig.8 shows the influence of HCHO and other higher aldehydes on exhaust odor. Here two conditions were selected. In one condition (condition A) the gas contained mostly HCHO, and there was very small amount of other aldehydes. In this condition the gas has an irritating odor rating of 3.5. In the other condition (condition B) the gas contained higher amount of other aldehydes, while HCHO concentration was low. Here the gas has a milder odor rating of 2.5 with no irritation. This suggests that HCHO must be considered as an important odor parameter.

(a)

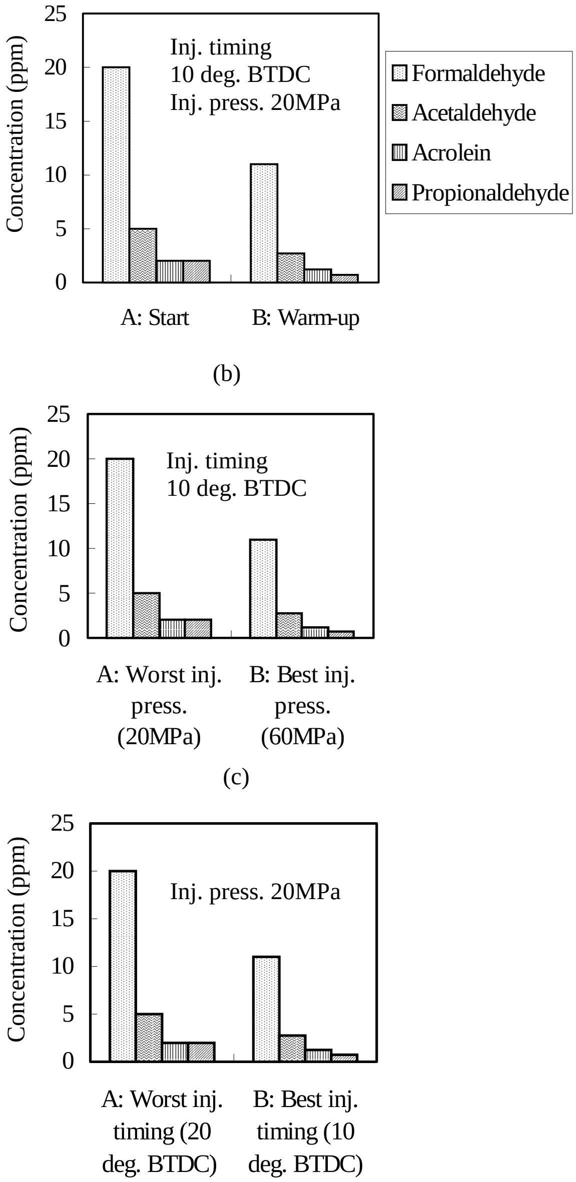

Fig.7 Aldehyde concentration in exhaust gases at different engine conditions

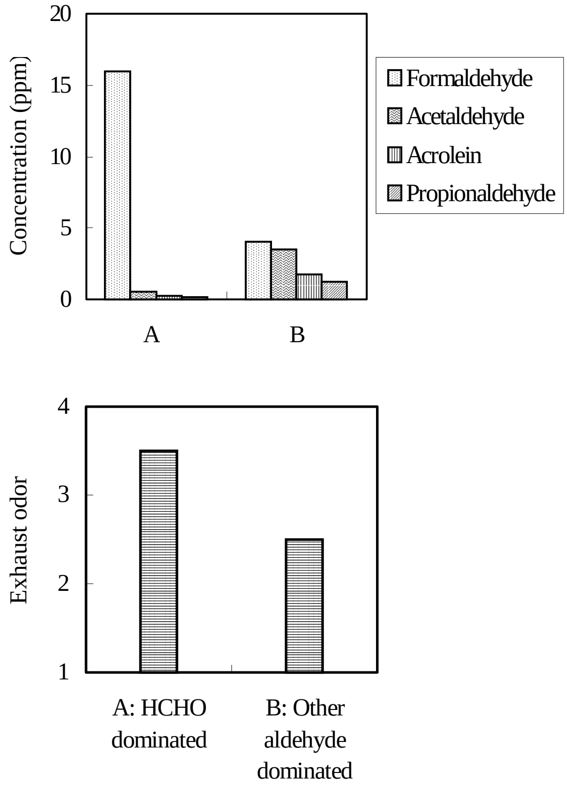

Fig. 8 Influence of HCHO and other aldehydes on exhaust odor

CONCLUSIONS

This study investigated the odorous gas components in the exhaust of DI diesel engines. The THC, some HC components and aldehydes are found to correlate with exhaust odor. The following conclusions can be made from the results.

(1) The THC in the exhaust of DI diesel engine includes unburned fuel components and partially burned components, and the THC may be considered as an odor checking parameter.

(2) The concentration of the low boiling point HC components correlates closely with exhaust odor, and exhaust odor increases with the increase of these components and vice versa. Especially CH_4, the simplest low boiling point HC component has a good correlation with exhaust odor, although CH_4 itself has no odor.

(3) Any aldehyde or sum of all aldehydes in exhaust

gases is a very good indicator for the exhaust odor. And the best way of reducing exhaust odor in DI diesel engines is to reduce the aldehyde concentrations in exhaust gases.

(4) The amount of HCHO among all aldehydes in the exhaust is maximum at any engine condition, and its share for the irritating odor is remarkable. Exhaust odor in DI diesel engines can be kept low if the concentration of HCHO in exhaust gases is reduced.

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