

Characteristics of PM Exhausted from Pool Diffusion Flame with Gasoline and Surrogate Gasoline Fuels

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ABSTRACT

In order to clarify the trend of PM emission characteristic caused by fuel change, we propose a fundamental flame research method using a small pool flame system. Characteristics such as size distribution and formation rate of PM from laminar diffusion flames of gasoline fuels (JIS No.1 and No.2) were investigated by an electric microbalance and a SMPS (Scanning Mobility Particle Sizer). PM exhaust from flame of surrogate gasoline fuels and hydrocarbon fuels of various chemical structures were also measured. As the result, it was found that both of exhaust-PM concentration and PM number peak size increased with increasing of alkene and aromatic compositions in fuel.

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INTRODUCTION

Particulate matter (PM) emission from automotive engines is one of the major air pollutants. Reduction of PM emission from automotive engines is strongly required for future engine development. In order to reduce the PM emission, many studies have been carried out by engine researchers(1), (2), (3), (4), (5), (6), and PM emission decreased obviously. For further reduction of PM emission from automotive engines, detailed information about chemical and physical processes of PM formation and oxidation in combustion process is necessary.

It has been known that nanometer size PM (nano-PM) is formed in combustion field such as diesel and gasoline engines(7). In recent years, nano-PM emission from direct injection (DI) type gasoline engine is regarded as an emission problem. Though a weight ratio of nano-PM in engine emission is very low, it seems that considerable numbers of nano-PM are formed in DI gasoline engine(8), (9), (10). Since nano-PM is harmful to human health, new fuel technologies should be established to remove exhaust emission of the nano-PM from gasoline engine.

Polycyclic aromatic hydrocarbons (PAHs) are precursors of nano-PM. Therefore, an investigation of PAHs behavior in a flame is very important to understand the formation mechanism of nano-PM. A laser induced fluorescence (LIF) method was one of the powerful tools for direct measurement of PAH distribution in a flame(11), (12), (13), (14), (15). Number of carbon atoms in a PAH molecule was estimated by LIF spectrum. Moreover, quantitative measurement of PAHs concentration in a diffusion flame was carried out using a gas chromatography (GC) system(13). As for the measurement of soot particles, a laser induced incandescence (LII) method had been

developed(16). Soot growth behavior in a flame was discussed by using LII results(17). By these investigations, relationship between flame structure and transition region from PAHs to soot was clarified. However, more detailed discussions concerning PM characteristics are required.

Liquid fuel such as gasoline was composed of many hydrocarbons with different molecular structures and different boiling temperatures. These properties greatly affected PM characteristics through flame behavior related with combustion process. Then fuel technologies which include gasoline material production and mixing of various base materials were necessary to supply a suitable gasoline for PM reduction. However, influence of these base material properties on PM formation processes was not clarified. In this paper, fundamental characterization of PM released from laminar diffusion flames of gasoline fuel and hydrocarbon fuels with various chemical structures were investigated. Moreover, PM from various surrogate gasoline fuels were also investigated and reported.

EXPERIMENTAL SETUP

A pool combustion equipment was used to form a laminar diffusion flame of liquid fuel. Figure 1 shows the scheme of equipment, and an example of diffusion flame formed by this system. This equipment consisted of a fuel tank, a fuel supplying system, a fuel pool and an electric microbalance. The fuel was supplied from the fuel tank through a float chamber. Inner diameter of the pool was 16mm and 6mm in depth. The float chamber could keep the fuel surface at a constant level. The fuel consumption rate M_f (flame length L_f) was controlled by an adjustment of the fuel surface level. The weight of equipment was measured by the electric microbalance and the M_f was derived from the weight loss of it.

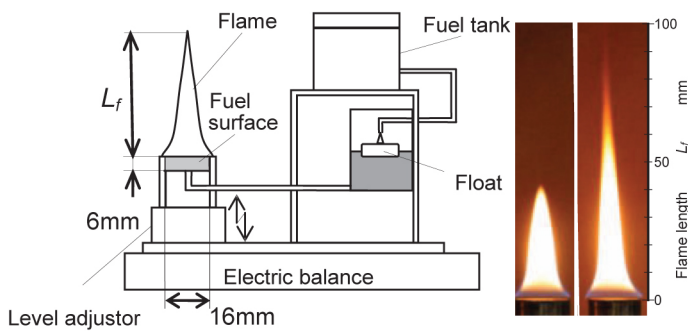


Figure 1. Pool combustion system

Figure 2 shows the PM sampling system used here. In order to measure PM emission rate, PM in a whole burned gas from diffusion flame was captured on a quartz-fiber filter with a suction pump system shown in Fig.2 (a). PM mass (M_{PM}) captured on the filter was measured by an electric microbalance. Size distribution and number concentration of PM were measured by a scanning mobility particle sizer (SMPS3034 and SMPS3936, TSI) in Fig.2 (b).

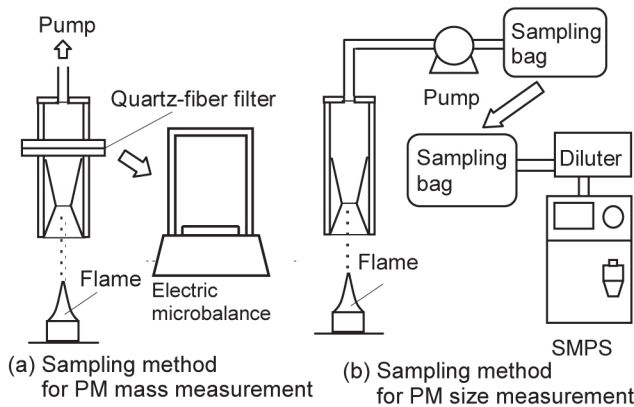


Figure 2. PM sampling method

RESULTS AND DISCUSSION

Gasoline Flame PM

In this study, exhaust rate of PM released from a tip of gasoline fuel flame was investigated. Sampling position was around 300mm above the flame tip. Winter season gasoline of JIS No.1 and No.2, those were sold in Tokyo area, were used but their fuel properties were unclear except RON (Research Octane Number). Relationships between flame length and fuel consumption rate of gasolines (JIS No.1 and No.2) were shown in Fig.3. PM exhaust rates (M_{PM}/M_f) were also shown in the figure. Moreover, direct photographs of test flames were summarized in the figure. Photographs of G1-1, G1-2 and G1-3 were indicated examples of JIS No.1 gasoline flame, those of G2-1, G2-2 and G2-3 were indicated examples of JIS No.2 gasoline flame. Flames indicating in G1-3 and G2-3 were examples of flames emitting visible smoke.

For both flames of JIS No.1 (RON = 102) and No.2 (RON = 92), flame length increased with an increase of fuel consumption rate. However, flame length of JIS No.1 gasoline was longer than that of JIS No.2 gasoline. As for the flame of JIS No.1 gasoline, smoke at downstream of flame tip was not observed under the fuel

consumption rate less than 1.5mg/s, though smoke emission from flame tip was observed when the fuel consumption rate was over 1.5mg/s. Flame structure forming no visible smoke, where fuel consumption rate was less than 1.5mg/s, was called “closed tip shape”, and flame structure forming visible smoke emission at over 1.5mg/s was called “open tip shape”. As for the JIS No.2 gasoline, the critical fuel consumption rate corresponding to the change from closed tip to open tip was 2.3mg/s.

As for a relationship between fuel consumption rate and PM exhaust rate shown in the lower part of Fig.3, PM exhaust rate of JIS No.1 gasoline flame was higher than that of JIS No.2 flame. Generally, aromatic and alkene compositions were highly contained in JIS No.1 gasoline as a high RON fuel composition. So, it was considered that higher PM exhaust rate of JIS No.1 compared with JIS No.2 was caused by these fuel compositions.

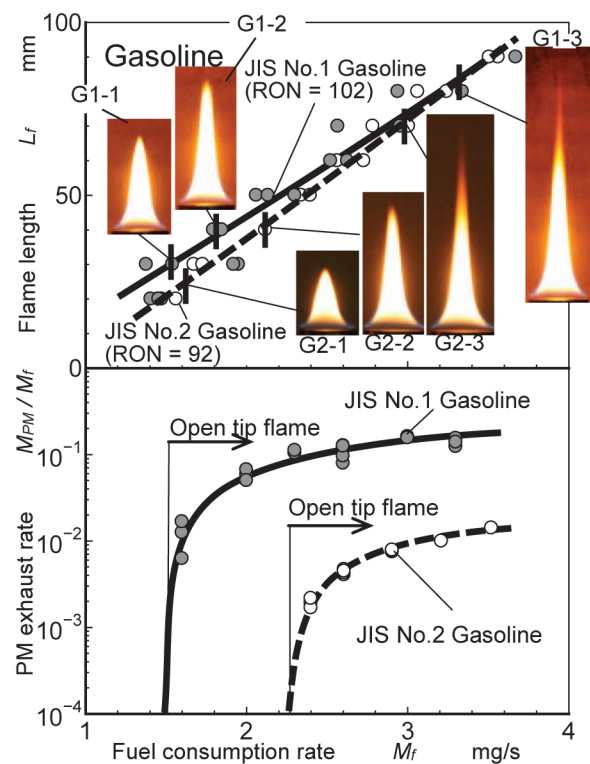


Figure 3. Flame length and PM exhaust rate of gasoline pool diffusion flames

Figure 4 shows size distributions of PM released from flames of JIS No.1 and JIS No.2 at the same fuel consumption rate ($M_f=3.0$ mg/s). Size distribution was analyzed by SMPS and normalized by a unit mass of consumed fuel. In the case of JIS No.1 gasoline flame with open tip, particle size corresponding to the peak number concentration appeared at around 300nm. The peak PM diameter of JIS No.2 gasoline flame (around 150nm) was smaller than that of JIS No.1 gasoline flame PM. In general, size of nuclei mode PM is several ten nanometers. Then, it suggested that the main PM from both gasoline flames was accumulation mode particles. In other words, typical feature of PM size distributions of both gasolines was accumulation mode PM widely distributing from 60nm to over 600nm. Further the JIS No.1 gasoline flame PM contained larger

particles of more accumulated than JIS No.2 gasoline flame PM. It suggested high RON gasoline such as JIS No.1 was not suitable as a stand point of PM emission.

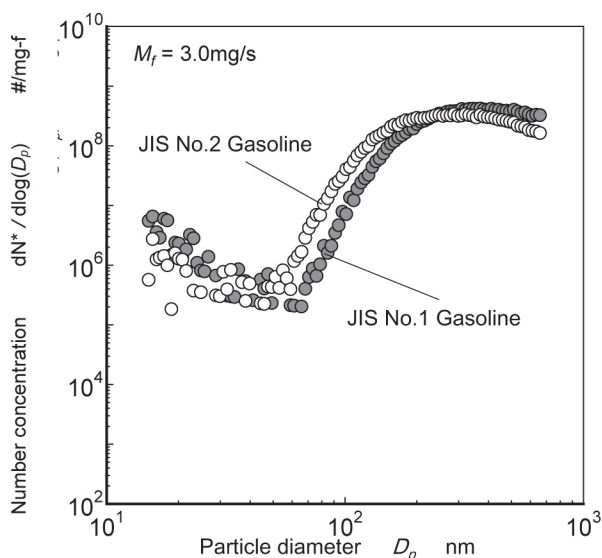


Figure 4. PM number distributions of gasoline diffusion flames

Hydrocarbon Fuels and PM

Hydrocarbon fuels of various chemical structures such as n-alkane (n-heptane), n-alkene (1-octene), iso-alkane (iso-octane), cyclo-alkane (methyl-cyclohexane) and aromatic (toluene) with $n_c = 7 - 8$ were used to investigate the influence of chemical structure on PM characteristics. Structural formula and RON of test fuels were shown in table 1. Figure 5 shows relationship between fuel consumption rate and flame length of various hydrocarbons shown in table 1. The exhaust rate (M_{PM} / M_f) of PM released from flame tip was also shown in the figure. Here, PM exhaust rate of n-heptane was not measured by filter sampling. So, n-heptane data could not be indicated in lower part of figure 5.

In the case of n-heptane flame, incandescence flame of soot oxidation was observed, although visible smoke at the downstream of flame tip was not observed in all M_f condition of this study. It was thought that soot formed inside the n-heptane flame was almost oxidized at the reaction zone or flame surface. Because of this oxidation effect, it was considered that the flame of n-heptane having low RON hardly exhausted PM. As for the methyl-cyclohexane having cyclo-structure, the critical fuel consumption rate corresponding to the transition from closed tip to open tip was 2.0mg/s. At $M_f = 3.0$ mg/s, PM exhaust rate from methyl-cyclohexane (cyclo-alkane) flame was around 4×10^{-3} (M_{PM} / M_f). It was shown that the flame of cyclo-alkane (such as methyl-cyclohexane) fuel had higher PM exhaust rate comparing with n-alkane (iso-octane) fuel at small flame less than 3.2mg/s.

Iso-octane having branched chain and 1-octene having double bond showed clear critical fuel consumption rates corresponding to the transition from closed tip to open tip. PM exhaust rate of iso-octane flame at $M_f = 3.0$ mg/s was lower than that of methyl-cyclohexane, although RON of iso-octane was higher than methyl-cyclohexane. Since iso-octane having high RON showed low PM exhaust rate,

iso-octane was thought to be more suitable gasoline composition than n-heptane (low RON and low PM) and methyl-cyclohexane (high RON and high PM). In the case of 1-octene, PM exhaust rate at $M_f = 3.0$ mg/s was higher than iso-octane and methyl-cyclohexane. Further, RON of 1-octene was lower than iso-octane and methyl-cyclohexane. Then, 1-octene was not suitable for gasoline composition as a view point of PM reduction.

Table 1. Test fuels

Species	Chemical formula	RON	Structural formula
n-Heptane (n-alkane)	C_7H_{16}	0	
1-Octene (n-alkene)	C_8H_{16}	28.7	
Iso-octane (iso-alkane)	C_8H_{18}	100	
Methyl-cyclohexane (cyclo-alkane)	C_7H_{14}	75	
Toluene (aromatic)	C_7H_8	120	

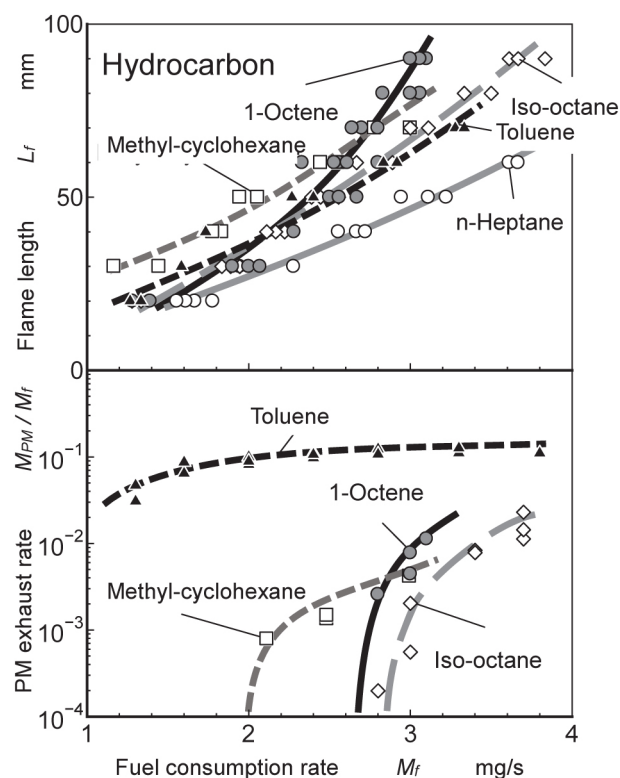


Figure 3. Flame length and PM exhaust rate of various hydrocarbon diffusion flames

Toluene was an aromatic fuel and formed incomplete combustion flame with open flame shape. PM exhaust rate from toluene flame at $M_f = 3.0$ mg/s was the highest in the test flames, and its PM exhaust rate was around order of 10^{-1} (M_{PM} / M_f). On the other words, 10% of toluene fuel was exhausted as PM. RON of toluene was the highest in the test fuels. It seemed that toluene as an aromatic had characteristics of high RON and high PM exhaust rate. PM exhaust rate from toluene flame was almost same level to that of JIS No.1 gasoline.