Instantaneous Two Dimensional Visualization of Soot Concentration Profiles in the Diesel Spray Flame

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ABSTRACT
An experimental study has been made of the instantaneous two dimensional visualization of soot concentration profiles in the diesel spray flame. A spray flame was formed by a single shot of fuel injection in high pressure and high temperature gaseous environments. A cross section of the spray flame was illuminated by a sheet of incident laser light. The images of visible flame and scattering light intensity were recorded simultaneously at an arbitrary instant of time after injection by using a CCD camera with a gated image intensifier. The fuels employed in the experiment were emulsified fuels and some binary mixtures of hydrocarbons. The results showed that the high concentration region of soot existed along the central axis of the spray, and the soot concentration profile was highly heterogeneous. The effects of ambient oxygen concentration, injection pressure and fuel properties on the soot concentration profiles were revealed.

INTRODUCTION
The superior fuel economy of the diesel engine over the gasoline engine has resulted in increasing its penetration in the automotive applications and expanding its use from trucks to light duty passenger cars. However, the use of the diesel engine in such vehicles might be ruled out if it cannot meet the expected future standards for exhaust soot particulates. Therefore, experimental and theoretical studies are needed to understand the soot particulate formation mechanisms and develop techniques for their control.

Kadota et. al\textsuperscript{(2)} reported the time resolved measurement results of the mean diameter, C/H ratio, number and concentration of soot for the autoignited intermittent spray flame formed in a steadily flowing high temperature air stream by using the direct sampling method. Kamimoto et. al\textsuperscript{(3),(5)} investigated the instantaneous two-dimensional soot concentration, size of soot particles and number density of soot by using the laser light scattering (LLS) or laser induced incandescent (LII) method in the unsteady free spray flame formed in a rapid compression machine. Mtsui et. al\textsuperscript{(6)} measured the time and space resolved soot concentration profiles of the spray flame formed in the actual engine by using the two-color pyrometry measurements. Shioji et. al\textsuperscript{(9)} applied LLS to study the effects of the fuel quantities, injection timings, chamber geometry and rate of heat release on the soot concentration in the spray flame formed in the actual diesel engines. Some other results of soot concentration profiles of the spray flame formed in the actual engines by using LLS or LII were also reported\textsuperscript{(10,11)}. A review of literature indicates that there is a lack of the knowledge of time and space resolved soot concentration profiles affected by operating parameters.

The primary objective of the present work is to study the time histories of instantaneous two dimensional soot concentration profile in a diesel spray flame. The diesel spray flame was formed by injecting an intermittent fuel spray into high pressure and high temperature gaseous environments which were produced by combustion of homogeneous mixture of methane, air and oxygen inside the constant volume combustion chamber. The advantage of the newly developed combustion system is that wide view of the process is possible and measurement can be easily made in a wide range of parameters. Among a variety of nonintrusive soot diagnostics, the planer laser light scattering was selected because of its comparatively simple optical system. The effects of ambient oxygen concentration, injection pressure and fuel properties on the soot concentration profiles are revealed.

EXPERIMENTAL PROCEDURE
Figure 1 shows a schematic diagram of the experimental apparatus. The combustion chamber for observation of a spray was a cylindrical chamber with the
inner diameter of 120 mm and the width of 80 mm. Two glass windows were installed in the sidewall for observation of the spray. A pair of the windows was installed for the access of laser light sheet on the opposite side of the wall of the combustion chamber. The diesel injector with a single hole nozzle with a diameter of 0.3 mm was installed in the upper wall of the chamber. A fuel spray was discharged inside the test chamber from the diesel injector by using the single shot injection unit consisted of servo valve controller, the oil cylinder and the oil pump. The oil pressure generated by the motor and oil pump was controlled by the servo valve controller. When the oil pressure was transferred to the oil cylinder, the oil cylinder pushed the plunger of the Bosch type of fuel injection pump and the fuel was discharged from the nozzle. In order to assure the stability of fuel injection, the liquid fuel was pressurized by the automotive fuel pump. The variations of pressure in the injection pipe and the needle lift with time were measured by using the pressure transducer and the gap sensor, respectively. The results showed that the reproducibility of the injection was fairly well. The injection pressure was defined as the nozzle opening pressure, which was set to be 10-30 MPa. The output of the gap sensor was also used to trigger the laser.

Experiments were carried out by using premixed fuel combustion method. The high pressure and temperature environment was produced by combustion of stochiometric mixture of methane, air and oxygen in the chamber. The fuel spray was injected in the high temperature and high pressure environments. This results in the autoignition of the fuel spray injected. The remained oxygen concentration could be changed by the initial oxygen concentration, which was returned by the equilibrium of methane-air-oxygen balance. The ambient oxygen concentration was varied from 4.3 % to 34.3 %. The time histories of the pressure and temperature in the chamber after ignition were measured by the pressure transducer and the thermocouple with the diameter of 0.1 mm, respectively. After the end of combustion, the spray was discharged at the moment when the pressure and temperature in the chamber reached to the predetermined ones. The ambient pressure and temperature in this work were determined to be 1.8 MPa and 1300 K, respectively.

Two dimensional soot concentration profiles in the spray flame were visualized by planar Mie scattering technique. The light source was the second harmonic (532 nm) of the pulsed Nd: YAG laser, which provided 210 mJ of energy in a 6-7 nsec pulse. The beam was formed into a thin sheet by use of a cylindrical lens. The thickness of the resulting laser light sheet was approximately 0.5 mm. The laser light sheet passes through the central axis of spray. An interference filter was provided to remove a chemical luminescence of the flame. The image of the light scattering intensity and the visible flame were recorded by a CCD camera with image intensifier synchronized with a laser pulse.

The fuels used in this work were n-dodecane, binary mixtures of n-dodecane and methanol, ethanol or benzene. Fuel in water emulsified fuel which consisted of n-dodecane and water doped with small amount of surfactant was also tested.

RESULTS AND DISCUSSIONS

Figure 2(b) shows the image of instantaneous two dimensional scattered light intensity in a vertical cross section passing through the center of the spray flame at 5.5 ms after the start of fuel injection. Also shown is the direct photograph of the diesel spray flame in Fig. 2(a). It is evident that the highly sooting region exists along the central axis of the spray flame. Also evident is that the soot concentration profile is highly heterogeneous. The profiles resemble the branch structure observed in a diesel spray evaporating in high pressure and high temperature gaseous environment\(^{(12)}\). In the early stage of the combustion, it is difficult to divide the scattering intensity from the soot and fuel droplet prior to the evaporation in the image analysis. Thereupon, the measurements of soot concentration profiles were carried out at the period of time after fuel droplet vaporized completely.

Figure 3 shows the spacing between neighboring stripes for a diesel spray and diesel spray flame. It has been reported that the spacing is almost independent of ambient
pressure and temperature for evaporating spray\(^{12}\). There is no appreciable difference between results. This implies that the heterogeneity in soot concentration profiles would be caused by the heterogeneous profiles of the liquid fuel in the spray flame.

The intensity of the scattered light would result in the determination of the soot concentration with appreciate assumptions\(^{13}\). Instantaneous amount of soot in the flame can be obtained by integrating the intensity of the scattered light over the whole volume of the sooting region in the spray flame. Figure 4 shows the time histories of the normalized intensity integrated with axial symmetric assumption for n-dodecane. Also shown is the intensity integrated over the cross sectional area interested. There is no great difference between them. There are some ambiguities of axial symmetry for high heterogeneous soot concentration profile. So the intensity integrated over the cross sectional area will be selected for the qualitative representation of the amount of soot in the whole flame. It is evident that soot increases with the lapse of time after fuel ignition and

Fig. 2 Image of instantaneous two dimensional scattered light intensity and direct photograph of the diesel spray flame at 5.5 ms after fuel injection.

Fig. 4 Time histories of the normalized intensity integrated with axial symmetric assumption

Fig. 3 Spacing between neighboring stripes for a diesel spray and diesel spray.

Fig. 5 Effect of the oxygen concentration on time histories of the normalized amount of soot.
reaches a peak after which it decreases to very low values approaching to zero.

Figure 5 shows the effect of the oxygen concentration in the ambient gas on time histories of the normalized amount of soot for n-dodecane. The abscissas represent the time elapsed after fuel injection. It is evident that the increase in oxygen concentration results in the decrease in the peak amount of soot and the decrease in the period of time between the start of fuel injection in the time at peak amount of soot. It is likely that the high concentration oxygen causes the high rate of gasification of the soot formed and the decrease in ignition delay.

Figure 6 shows the amount of soot as a function of time elapsed after autoignition of the fuel spray. The time at peak amount of soot advances slightly with an increase in an oxygen concentration. It is probable that high concentration of oxygen results in the high flame temperature which leads to the high rate of soot formation and its gasification.

Figure 7 shows the effect of oxygen concentration on the peak amount of soot. It is apparent that the peak amount of soot decreases with an increase in oxygen concentration. Previous study implies that the peak amount of soot would show the maximum at the oxygen concentration lower than 5%.

Figure 8 shows the effect of the injection pressure on time histories of the normalized amount of soot for n-

Fig. 6 Amount of soot as a function of time elapsed after autoignition of the fuel spray.

Fig. 7 Effect of oxygen concentration on the peak amount of soot.

Fig. 8 Effect of the injection pressure on time histories of the normalized amount of soot.

Fig. 9 Amount of soot as a function of time elapsed after autoignition of the fuel spray.
dodecane. The abscissas represent the time elapsed after fuel injection. It is evident that the increase in injection pressure results in the decrease in the peak amount of soot and the decrease in the period of time between the start of fuel injection in the time at peak amount of soot. It is probable that the high injection pressure causes the enhanced atomization and mixing of fuel and ambient gas which result in the decrease in ignition delay.

Figure 9 shows the amount of soot as a function of time elapsed after autoignition of the fuel spray. The time at peak amount of soot advances slightly with an increase in an injection pressure. It is likely that high injection pressure causes the enhancement of atomization and mixing, which result in the high rate of chemical reaction and combustion. So the decrease of degree of heterogeneity causes the decreases of the peak amount of soot in the spray flame.

Figure 10 shows the effect of the water content on time histories of the normalized amount of soot for n-dodecane in water emulsified fuel. The abscissas represent the time elapsed after fuel injection. It is observed that the remarkable decrease in the peak amount of soot was caused by the addition of water of 5%. However, the peak amount of soot decreases slightly in an increase in water content from 5% to 10%. It is also obvious that the increase in water content of emulsified fuel results in the increase in the period of time between the start of fuel injection and the time at peak amount of soot. It is conceivable from the results of previous researches, the reduction of the amount of soot was caused by the promotion of mixing of fuel and air by a secondary atomization and the decrease of flame temperature. However, those phenomena could not be observed clearly from the result of this experiment.

Figure 11 shows the effect of methanol or ethanol added to n-dodecane on the time histories of the normalized amount of soot in the spray flame. It is clear that the peak amount of soot was decreased by the addition of the substances compared with n-dodecane. Methanol as the addition to n-dodecane was more effective than ethanol for the reduction of the amount of soot in the diesel flame. It is also evident that the period of time after the start of fuel injection to the peak of the amount of soot was almost constant for the additional substance of methanol or ethanol.

Figure 12 shows the effects of ethanol content exert to the normalized amount of soot in the spray flame. The results showed that amount of soot decrease with an increase in ethanol content. The effect of ethanol contents is less dominant to the soot reduction than water contents of the

![Graph showing the effect of water content on normalized amount of soot](image.png)

**Fig. 10** Effect of water content of emulsified fuel on the time histories of the normalized amount of soot.

![Graph showing the effect of ethanol added to n-dodecane](image.png)

**Fig. 11** Effect of methanol and ethanol added to n-dodecane on the time histories of the normalized amount of soot.

![Graph showing the effect of ethanol added to n-dodecane](image.png)

**Fig. 12** Effect of ethanol added to n-dodecane on the time histories of the normalized amount of soot.
CONCLUSIONS

The instantaneous two dimensional visualizations of soot concentration in the diesel spray flame were conducted by using the planer laser light scattering method. A spray flame was formed by a single shot of fuel injection in high pressure and high temperature gaseous environments. The images of visible flame and scattering light intensity were recorded simultaneously at an arbitrary instant of time after the start of fuel injection by using a CCD camera with a gated image intensifier. The effects of ambient oxygen concentration, injection pressure and fuel properties on the soot concentration profiles were revealed.

The primary conclusions are as follows:

(1) High sooting region exists near the central axis of spray flame.

(2) The branch structure in the soot concentration profile is observed in the spray, which resembles liquid droplet density distribution in the cold spray.

(3) The peak amount of soot decreases monotonically with an increase in ambient oxygen concentration or injection pressure.

(4) The period of time after the start of fuel injection to a peak amount of soot decreases with an increase in ambient oxygen concentration or injection pressure. The period of time after autoignition to a peak amount of soot decreases slightly with an increase in ambient oxygen concentration or injection pressure.

(5) An increase of water content of the emulsified fuel causes a decrease of the peak amount of soot and an increase of the period of time after the start of fuel injection to peak amount of soot.

(6) The peak amount of soot decreases by addition of methanol or ethanol.

(7) An increase of benzene content results in an increase of the peak amount of soot and a decrease of the period of time after the start of fuel injection to peak amount of soot.

REFERENCES


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