The 2D Measurement of Soot Diameter and Number Density in a Diesel Engine Using Laser Induced Methods

Myung-Jun Lee*
Department of Automotive Engineering, Yangsan College, Kyungnam 626-740, Korea
Jung-Kuk Yeom
School of Mechanical & Aerospace Engineering, Seoul National University, Seoul 151-742, Korea
Jong-Yul Ha, Sung-Sik Chung
Department of Mechanical Engineering, Donga University, Pusan 604-714, Korea

It is necessary to diagnose accurately the characteristics of soot formation and oxidation in a diesel engine. Whereas past measurement techniques for soot concentration give limited information for soot, laser-based two-dimensional imaging diagnostics have a potential to provide temporally and spatially superior resolved measurements of the soot distribution. The technique using laser sheet beam has been applied to an optically accessible diesel engine for the quantitative measurement of soot. The results provided the information for reduction of soot from the diesel engine. Both LIS (Laser Induced Scattering) and LII (Laser Induced Incandescence) techniques were used simultaneously in this study. The images of LIS and LII showed the quantitative distribution of the soot concentration in the diesel engine. In this study, several results were obtained by the simultaneous measurements of LIS and LII technique. The diameter and number density of soot in combustion chamber of the test engine were obtained from ATDC 20 degree to 110 degree. The soot diameter increased about 37 % between ATDC 20 degree and 110 degree. The number density of soot, however, decreased significantly between ATDC 40 degree and 70 degree.

Key Words: Soot, Laser Sheet, LIS, LII, Optically Accessible Diesel Engine, Number Density

1. Introduction

Two-dimensional techniques using a laser sheet have been used recently for combustion diagnostics in internal combustion engines (Dec, 1997; Ni et al., 1995). Especially, many studies on the quantitative measurement of harmful emissions and radicals, which have influence on the emissions have been performed. Although techniques for emissions diagnostics using a laser sheet are advanced, the information on the measured objects have not been cleared.

As for soot in diesel engine, several methods of its measurement have been established, however, it is necessary to provide clear information for characteristics of soot formation and oxidation. Therefore, the techniques for soot measurement have to have temporally and spatially excellent resolution in a diesel engine where combustion is very rapid and complex.

Won et al. (1992) investigated the structure of flame using laser induced scattering technique in unsteady free spray flame. The study showed that soot was mainly formed at flame tip and transferred to the circumference of flame by relatively large vortex of flame head. Two-dimensional distribution of soot clouds velocity in cross section of unsteady free spray flame was measured to investigate the relation between

* Corresponding Author,
E-mail : leemj@mail.yangsan.ac.kr
TEL : +82-55-370-8218; **FAX** : +82-55-387-0325
Department of Mechanical Engineering, Donga University, Pusan 604-714, Korea. (Manuscript **Received** September 8, 2000; **Revised** June 15, 2001)

sooting mechanism and the large vortex movement of soot using LIS and correlation PIV.

Dec et al. (1991) introduced laser induced incandescence to obtain distribution of soot concentration in a D. I. diesel engine and soot distribution between 25 mm and 30 mm from injector. According to the results, the nuclei of soot were formed at irregular place and grown through cross section of the flame in rich premixed combustion of the early stage. However, large soot particles were formed at circumference of spray from the early diffusion combustion.

Although laser is used as a light source, the past optical soot measurements have limitations in that they obtain only integrated values of soot concentration in the light path such as one point light extinction method. It is not possible to clarify soot distribution in diesel flame yet. It is necessary to use techniques with high temporal and spatial resolution for measurement of soot distribution.

Therefore, the purpose of this study is to obtain two-dimensional images and the information for the distribution of soot concentration using laser induced scattering and incandescence techniques in an optically accessible diesel engine. Concretely, measuring the generated scattering and incandescence signals from soot, the information for the relative diameter and number density of soot could be obtained through the correlation based on theoretical background.

2. Theoretical Background

Laser Induced Scattering is a method that measures scattering signals from soot particle, when laser is irradiated and collided with soot particle. This means that the wavelength of scattering signal is equal to the wavelength of incident beam. This method has merits that it requires simple apparatus for experiment. It has demerit that it is difficult to distinguish soot in measurement field. In order to investigate distribution of soot concentration in this study, Eq. (1) was used for signal intensity of LIS using Rayleigh scattering assumption (Kosaka et al., 1995).

$$I_{LIS} \propto f(D^6 \times N) \quad (1)$$

When laser is irradiated into soot clouds in measurement field, laser induced incandescence is the method that it measures radiation signal from soot particle heated to 4000K over, while soot is heated and cooled. LII signal shows intensity of blackbody from soot particle of high temperature, thus LII is the method to measure concentration of soot using the phenomenon that LII signal is proportional to the concentration of soot (Melton, 1984). However, laser power over 10^7 W/cm^2 is required to measure LII signal (Loye et al., 1990), and the signal intensity of LII is weaker than that of LIS by 1/100. In this study, it is assumed that I_{LII} is proportional to volume concentration of soot (Melton, 1984).

$$I_{LII} \propto f(D^3 \times N) \quad (2)$$

where D and N are the diameter and number density of soot particle, respectively. Using Eq. (1) and Eq. (2), Eq. (3) and Eq. (4) is derived as follows;

$$D \propto (I_{LIS}/I_{LII})^{1/3} \quad (3)$$

$$N \propto (I_{LII})^2/I_{LIS} \quad (4)$$

Thus, relative diameter and relative number density is obtained by measuring LIS and LII signal.

3. Experimental Apparatus and Methods

Table 1 shows the specification of a test engine. In this study, a direct injection diesel engine was used as a test engine. For this study, the engine was modified to access optically, especially cylinder head for taking images and cylinder liner for irradiation of laser sheet were changed. Figure 1 shows the diagram of a cylinder head with window for visualization and a cylinder liner that has two windows for laser sheet. As shown in this figure, the cylindrical window for visualization was installed to upper point of an injector place to measure one of four diesel sprays. In order to irradiate and dump laser sheet into the combustion chamber, two windows were installed at both sides of a cylinder liner, and cylinder liner was

Table 1 Specification of a test diesel engine

Items	Specification
Engine Type	D.I. Diesel Engine with Single Cylinder
Bore×Stroke(mm)	95×95
Compression Ratio	17.2
Piston Length(mm)	126
Piston Cavity	Toroidal
Fuel Injector	Conventional Injector, 4-Holes(φ=0.3)
Injection Timing	BTDC 17 Deg.
Injector Opening Pressure	22 MPa

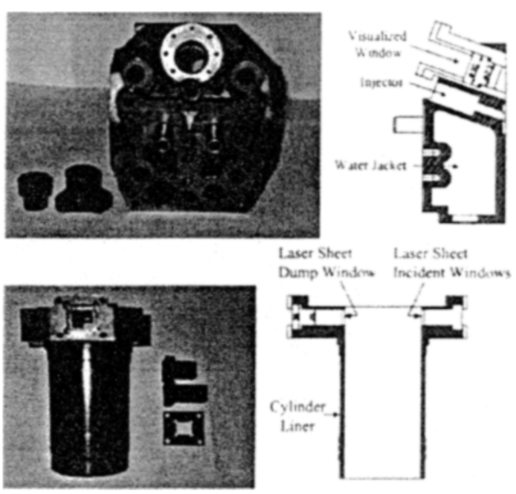

Fig. 1 Cylinder head and liner of an optically accessible diesel engine

elongated by 36 mm. The piston was elongated correspondingly also.

The optical measurement system consisted of the optical components including Nd:YAG pulse laser that irradiated laser sheet into diesel engine, the measurement parts for measuring LIS and LII signals simultaneously, and the PC controller that controlled light source and ICCD camera (SFC V-Tek, 8 Bit, Gain: 10^4) using crank angle signal of the test engine, and then saved images. The optical component included cylindrical lens assembly that transforms laser beam into sheet, mirrors, and so forth. The second harmonic generation (wavelength 532 nm) of Nd:YAG laser was used

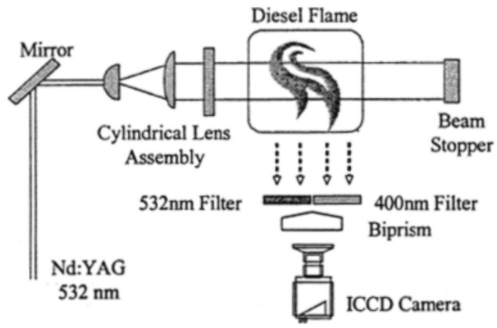

Fig. 2 Diagram for simultaneous measurement of LIS and LII signal

as light source and its power was 254 mJ/pulse. The laser beam was transformed into the sheet of height 40 mm, thickness 0.25 mm. The ICCD camera was used for measuring LIS and LII signals, and the gate time of ICCD camera was set at 300 ns in order to minimize influence of flame luminosity on laser induced signals.

Figure 2 shows the diagram of optical apparatus for LIS and LII simultaneous photography. Laser induced signals from in-cylinder were branched off so that two images of LIS and LII were taken simultaneously by a bi-prism and two band pass filter that has different center wavelength from each other. The one (center wavelength: 532 nm, FWHM 3 nm) was used to take LIS image and the other (center wavelength: 400 nm, FWHM 40 nm) was used for LII image.

Figure 3 shows the diagram of the experimental apparatus for this study. An encoder was set up at crankshaft of test engine, and a pulse per one degree of crank angle from the encoder was input into the synchronization circuit. And the synchronization circuit input the pulse and TDC pulse into crank angle count PC. The crank angle count PC counts the pulses and generate one trigger at the operating time of laser and ICCD camera that was given by crank angle count program. The trigger was input to control PC that operates laser and ICCD camera through synchronization circuit. The control PC gives signals to laser and ICCD camera through program of time setting.

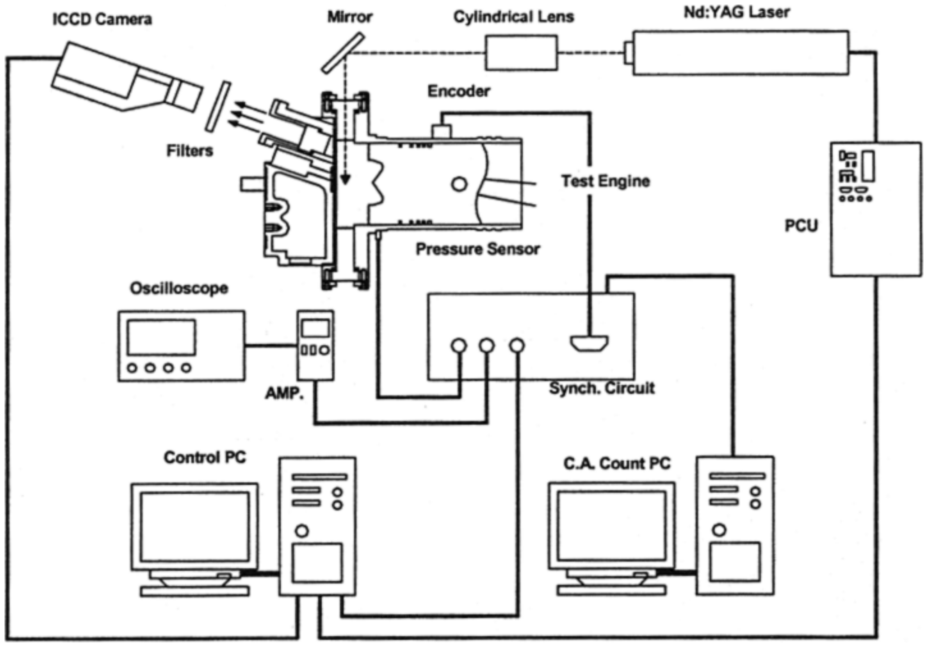

Fig. 3 Diagram of the experimental apparatus

4. Results and Discussion

Before the measurement of LIS and LII, flame luminosity from the cylinder was taken by the ICCD camera. The operation conditions of the test engine for capturing the luminosity were 1000 rpm and nonload. The time of fuel injection was BTDC 17 degree. Figure 4 shows images where flame luminosity was taken with crank angle from TDC to the end of combustion through visualization windows. The lower side of each image is located in diesel injector and starting point of injected spray, and the wall of cylinder liner is located in the opposite side. The spray proceed from down to up in each image.

As shown in Fig. 4, flame can be observed from TDC and its size grows up from cavity to squish area with crank angle. In measurement range of this study, flame shows maximum size and luminosity at ATDC 10 degree, combustion was going to finish from ATDC 40 degree gradually. And, in this study, LIS and LII signals that soot particle in a cylinder scatter and radiate by laser sheet were obtained simultaneously. And soot

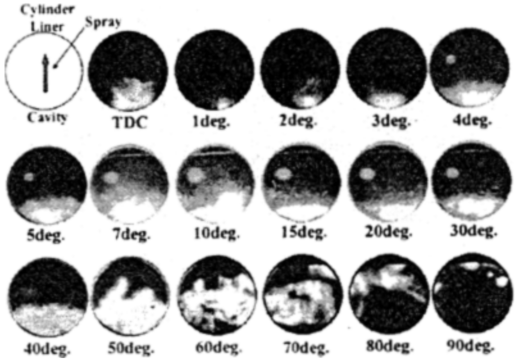

Fig. 4 Flame images in diesel engine with crank angle

concentration was measured by ICCD camera from ATDC 20 degree to ATDC 110 degree by 10 degree. It was impossible to take the images between TDC and ATDC 20 degrees owing to the limitations in optical accesses. Thus, in this study, measured images between ATDC 20 degree and 110 degree were considered.

Figure 5 shows the region that the LIS and LII images were measured by ICCD camera. The area of the place is about 6 % of that of cross section of a cylinder. In the place, cavity is located in

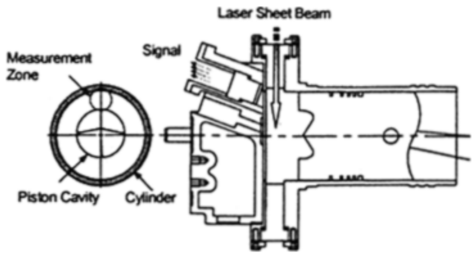

Fig. 5 Diagram of measurement zone

lower side and cylinder liner is in the opposite.

Figure 6 shows the simultaneously measured 2D raw images of LIS and LII signals that soot clouds of in-cylinder scatter and radiate, when laser sheet was irradiated into the cylinder. The left side of images is showing those captured by LIS method for soot concentration and the right side of images is by LII method. The Flame luminosity that has influence on raw images was removed in each image by the adjustment of ICCD camera.

The LIS and LII raw images were taken fifteen times a set crank angle from ATDC 20 degree to ATDC 110 degree by 10 degree, while the test engine was operated. Before starting the experiment, the measurement was not performed until constant engine speed after dumping about 30 cycles. Although the raw images were measured at different cycles, they showed almost same. In this study, the early captured images when visualization window was not soil so much were chosen and analyzed.

As shown in these raw images, LIS intensity is stronger than LII intensity and the distribution area is large also. It is considered that intensity of LIS is stronger than that of LII, whereas LII image was not taken clearly by ICCD in the later, because of weak intensity of the signal. Thus it is considered that image of LIS is more advantageous than that of LII for image analysis and combustion diagnostics. In LIS signal, the intensity decreased from ATDC 20 degree to ATDC 60 degree, and increase on ATDC 70 degree. It is considered that concentration of soot should be moved by a kind of turbulence flows in cylinder.

Figures 7 and 8 show contour diagrams for

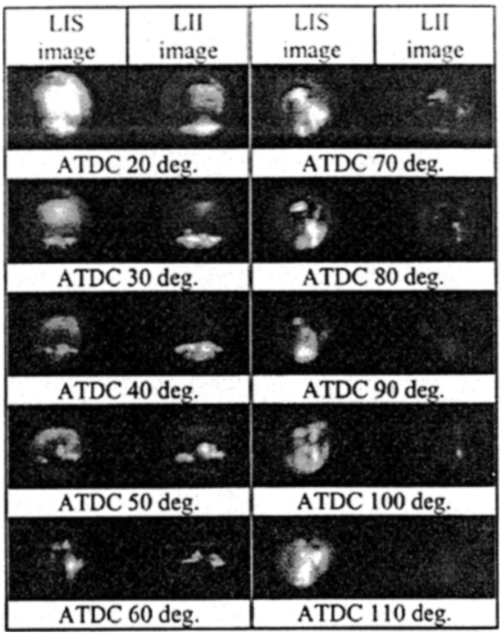

Fig. 6 Images of soot concentration by LIS and LII measurement

relative diameter and number density of soot clouds calculated from intensity of above raw images through Eq. (3) and Eq. (4). The diameter distribution of soot is similar to that of LIS intensity and the distribution for number density of soot is similar to that of LII intensity.

In Fig. 7, the relative diameter of soot with crank angle had not significant variation in measurement range, but the area of soot distribution decreased gradually. The diameters of mid-sized soot were mainly located at the center of image in the distribution of soot diameter with crank angle, small soot were located out of them. These trends almost proceed to the end of combustion process, and the small soot would remain to the last. In the period from ATDC 20 degree to ATDC 50 degree, the diameter of soot located in cavity that had the diesel flame has smaller values than side of cylinder wall relatively, the soot diameter in the side of cylinder wall showed larger values. As for the distribution in the side of cylinder wall, large soot in diameter was located in outer place relatively. It is considered that soot was formed in the inside of flame and their diameters were increased by mutual combination

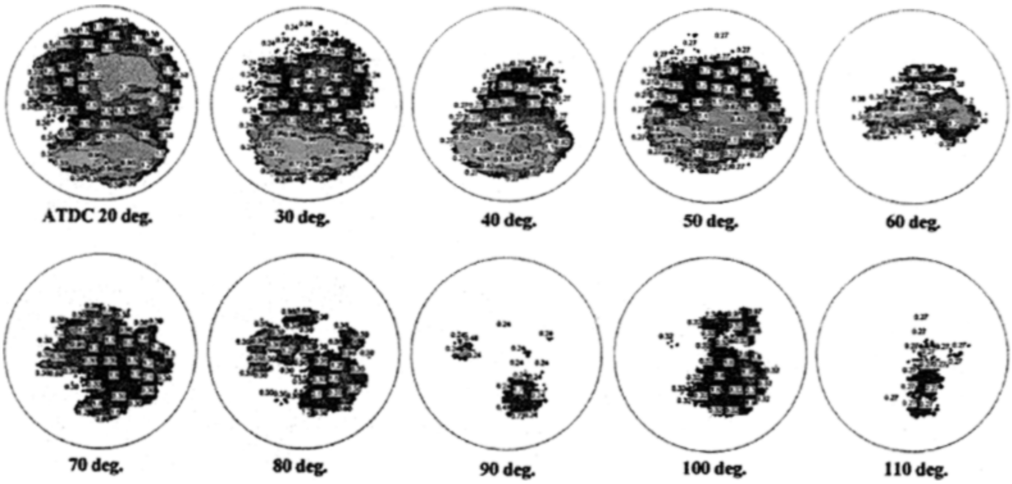

Fig. 7 Distribution of relative diameter of soot

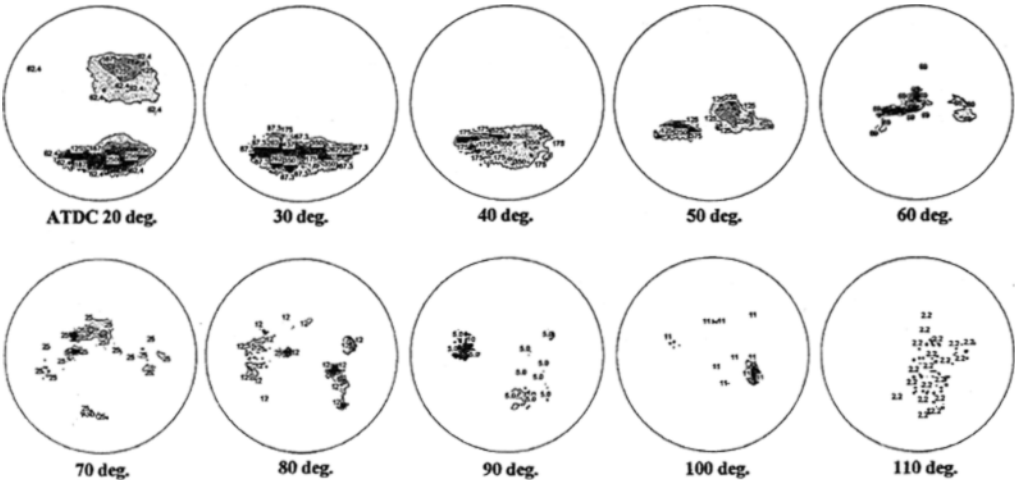

Fig. 8 Distribution of relative number density of soot

in low temperature place. Many distribution of large soot in diameter may explain these facts as combustion proceed to the end.

In Fig. 8, the distribution area of soot number density and values with crank angle decreased significantly. The distribution areas of number density were decreased from ATDC 20 degree to ATDC 110 degree, and the values of number density were decreased rapidly from ATDC 40 degree to ATDC 70 degree. The number density shows large values significantly from ATDC 20 degree to ATDC 40 degree, when the flame in cavity run over by inverse squish flow. It may be owing to transferring of soot clouds by the inverse squish flow. The value of number density showed rapid reduction from ATDC 40 degree to the end of combustion. Soot formed in the inside of flame was oxidized with increasing combustion volume; therefore it is considered that the number density may be reduced. Because Fig. 8 has similar intensity to Fig. 6 of LII intensity, hence it reflects the result of Eq. (4) well.

Figure 9 shows the information of relative mean diameter and number density after image processing of the signal intensity of measured soot with crank angle. The number density of soot has

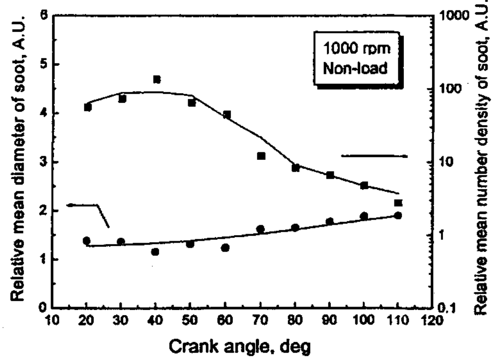

Fig. 9 Relative mean number density and diameter of soot with Crank Angle

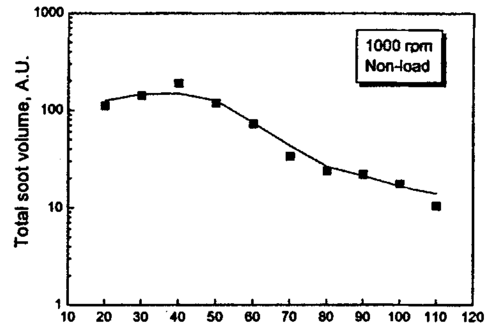

Fig. 10 Relative quantification by diameter and number density of soot

large values between ATDC 20 degree and ATDC 40 degree and are decreased until ATDC 70 degree rapidly and ATDC 110 degree gently. It has the rate of reduction about 91 % from ATDC 40 degree to ATDC 70 degree. In the variation of soot diameter, it shows trend of gentle increasing wholly, and has the increase rate about 37 % from ATDC 20 degree to ATDC 110 degree. Therefore, soot from diesel engine increases slightly in the diameter and decreases rapidly in the number density, proceeding to the late period of combustion. During expansion stroke, the diameter of soot particles near the cylinder wall of low temperature increases through coagulation and aggregation processes and then the number density decreases. When the air is introduced into a inner flame, oxidation of soot progress there.

Assuming soot is a sphere, soot volume was obtained through the above value of soot diameter. Therefore, it can be considered that the quantity of soot is determined multiplying the volume by number density of soot. Figure 10 shows the result. As shown in Fig. 9, because the value of number density is larger than that of soot diameter, the number density has influence on final quantity of soot.

5. Conclusions

The distribution of soot concentration was measured using laser diagnostics in an optically accessible diesel engine, and the relative diameter and the relative number density of soot were obtained by image processing from the simultaneously measured raw images of LIS and LII. Generally, the intensity of LIS signal was stronger than that of LII signal, and the simultaneously measured images generally have shown similar intensity of soot distribution in measured area. The followings summarize the results that were obtained.

(1) The distribution of soot diameter is similar to that of LIS intensity and the images for number density of soot is similar to that of LII intensity.

(2) The diameter ranges of soot particles obtained, that is, the maximum and the minimum values of soot diameter were generally similar with the crank angle. However, relative mean diameter of them increases about 37 % from ATDC 20 degree to ATDC 110 degree slightly.

(3) The number density of soot with crank angle has large values between ATDC 20 degree and ATDC 40 degree, and the rate of decrease was about 91 % by ATDC 70 degree. And, diameters of soot increased slightly and number density decreased significantly into late combustion period. Therefore, the number density has influence on final quantity of soot rather than its diameter.

Acknowledgments

This paper was supported by Research Fund of Dong-A University in 1999. The authors would like to thank their support during this study.

References

Dec, J. E., Loye, A. O. zur and Siebers, D. L., 1991, "Soot Distribution in a D. I. Diesel Engine Using 2-D Laser-Induced Incandescence Imaging," *SAE Paper*, No. 910224, pp. 277~288.

Dec, J. E., 1992, "Soot Distribution in a DI Diesel Engine Using 2-D Imaging of Laser-Induced Incandescence, Elastic Scattering, and Flame Luminosity," *SAE Paper*, No. 920115, pp. 101~112.

Dec, J. E., 1997, "A Conceptual Model of DI Diesel Combustion Based on Laser-Sheet Imaging," *SAE Paper*, No. 970873.

Kosaka, H., Nishigaki, T., Kamimoto, T. and Harada, S., 1995, "A Study on Soot Formation and Oxidation in an Unsteady Spray Flame via Laser Induced Incandescence and Scattering Techniques," *SAE Paper*, No. 952451, pp. 11~20.

Loye, A. O. zur, Siebers, D. L. and Dec, J. E., 1990, "2-D Soot Imaging in a Direct Injection Diesel Engine Using Laser-Induced Incandescence," *International Symposium COMODIA 90*, pp. 523~528.

Melton, L. A., 1984, "Soot Diagnostics Based on Laser Heating", *Applied Optics*, Vol. 23, No. 13, pp. 2201~2208.

Ni, T., Pinson, J. A., Gupta, S., and Santoro, R. J., 1995, "Two-Dimensional Imaging of Soot Volume Fraction by the Use of Laser-Induced Incandescence," *Applied Optics*, Vol. 34, No. 30, pp. 7083~7091.

Pinson, J. A., Mitchell, D. L., Santoro, R. J. and Litzinger, T. A., 1993, "Quantitative Planar Soot Measurements in a D. I. Diesel Engine Using Laser-Induced Incandescence and Light Scattering," *SAE Paper*, No. 932650.

Shioji, M., Ito, S., Yamane, K. and Ikegami, M., 1995, "A Study of Diesel Combustion and Soot Formation as Observed by High-Speed Photography," *JSME(B)*, Vol. 61, No. 581, pp. 344~350.

Won, Y. H., Kamimoto T. and Kosaka, H., 1992, "A Study on Soot Formation in Unsteady Spray Flames via 2-D Soot Imaging," *SAE Paper*, No. 920114, pp. 89~100.