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LIF Applications for Practical Combustors

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***Abstract*:** This study demonstrates the applicability of LIF in several practical combustors. Temperature and species concentration were measured inside industrial model burners, gas turbine combustors, diesel engines, and large scale industrial burners. This visualization technique introduces a new tool for use with practical combustors for the analysis of NO formation characteristics, turbulent flame front structure, and differences between normal and improved combustors.

***Keywords*:** laser, laser induced fluorescence, combustion, nitrogen oxide, reaction mechanism.

1. Introduction

It has become increasingly important to understand the reaction mechanism of combustion to cope with environmental disruption and to improve the efficiency of combustors. In particular, detailed measurement techniques for temperature and species concentration are necessary to elucidate the overall nature of industrial combustion systems. Laser induced fluorescence (LIF) is suitable for species measurements in practical applications such as burners (Rothe and Andresen, 1997), gas turbines (Deguchi et al., 1995), and engines (Nakagawa et al., 1997; Knapp et al., 1997). Because of its strong signal intensity, LIF has been applied to 2D detection of temperature and species concentration (Hanson, 1986; Allen et al., 1995). Recently 3D detection (Kychakoff et al., 1987; Deguchi and Iwasaki, 1997) has also been shown to be capable of detecting several 2D sections simultaneously (Deguchi and Iwasaki, 1997). The present study demonstrates the applicability of temperature and species visualization inside industrial combustors using a combustion and plasma analysis system made by Mitsubishi Heavy Industries, Ltd. These results have been used to clarify the reaction mechanisms of combustion with the goal of reducing NO formation.

2. Industrial Model Burner

The burner used in this study is a reduced model of an industrial pulverized coal burner. A schematic of the experimental setup of the model burner measurement is shown in Fig. 1. Two CCD cameras were used to correct for the nonuniformity in the laser intensity distribution in the measured 2D measurement region. NH_3 gas was added to the fuel to simulate pulverized coal fuel NO_x formation. Time averaged OH, CN, NH, NO, as well as temperature distributions were analyzed to clarify the characteristics of NO formation in both normal and improved

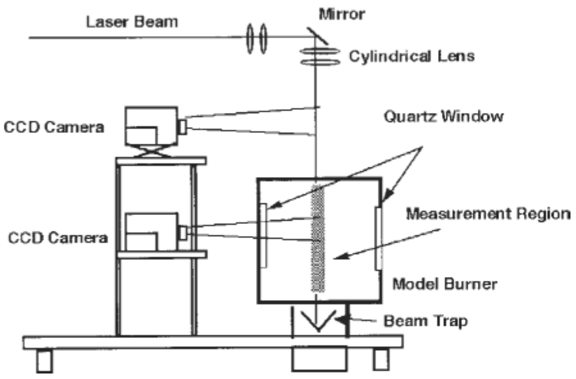


Fig. 1. For model burner measurement experimental setup.

burners. The improved burner was specially developed to reduce NO_x emission of the exhaust gas. The results are shown in Fig. 2.

The intensities of the fluorescence signals in the two burners were almost the same, although the OH, CN, and NH distribution pattern of the improved burner is shorter than that of the normal burner. These radicals tend to diminish much more quickly in the case of the improved one. Figure 3 shows the flame photograph with OH, CN, NH, NO, and temperature using different color bars. This visualization is quite useful in understanding the reaction mechanisms and in the improvement of these burners with the help of reaction theory.

3. Gas Turbine Combustor

A schematic of the gas turbine measurement section is illustrated in Fig. 4 (Deguchi et al., 1995). The gas turbine combustor used here has 8 main burners (premixed burners) and a pilot burner (diffusion burner) at the center, and 20 combustors of this type can produce 160 MW at a pressure of 1.6 MPa. In this study, a quartz cylinder ($f = 300$ mm, $t = 5$ mm) was placed behind the nozzle of the combustor and the air intake was divided by 4 ducts to observe its flame. Air was introduced to the combustor after heat exchange with the burned gas. The burned gas after heat exchange was sampled to measure temperature and CO_2, CO, O_2, and NO_x concentrations. The burners were operated at a pressure of 0.1 MPa to clarify the characteristics of NO formation and turbulent combustion characteristics inside the combustor. A photograph of a flame at 0.1 MPa is shown in Fig. 5.

The laser beam was focused by cylindrical lenses to a thickness of 1 mm and a width of 50 mm. The fluorescence signal was detected by a CCD camera system using UV transparent filters. The CCD signals were transferred to a computer and stored for later analysis.

Time averaged and single shot OH and NO distributions were observed in both the normal burner and the one with improved flame stabilization and low NO_x emission. The CCD camera, mirrors, and 2D optical sets were placed on X-Z traverse equipment which made it possible to change the measurement area without adjustment of the laser pass.

Time averaged OH and NO distributions inside the normal burner are shown in Fig. 6. OH exists in the mixing area of the pilot gas and the premixed gas of the main burners, and appears at the outer part of the combustion cylinder as the distance X from the end of the burner increases. On the other hand, NO exists at a high density in the outlet area of the pilot burner, and as X increases, the NO fluorescence intensity gradually drops.

It was found that NO is present mainly at the center of the burner cylinder. It can be inferred that NO is mainly produced from the reaction of the pilot burner flame. The sampling result also suggests that the emission of NO_x is from the reaction of the pilot burner flame.

Single shot OH distributions inside the normal burner are shown in Fig. 7. The turbulent flame front was clearly seen from this single shot OH measurement. The turbulent flame front was detected even at $X = 300$ mm. The single shot image is highly useful in order to understand the turbulent burning pattern in the combustor.

The time averaged NO distribution inside the improved burner is shown in Fig. 8. The improved burner has a different type of pilot burner to reduce NO_x emission and to stabilize its flame. NO fluorescence intensity is also strong near the burner nozzle and exists at the center of the burner cylinder. This is almost the same as in the normal burner. However, NO fluorescence intensity extends to the outer part of the burner cylinder near the nozzle as compared with the normal burner, and strong NO formation just behind the pilot burner is not seen in the case of the improved burner. The improvement of the pilot burner is intended to provide uniform flame reaction and to reduce partial NO formation.

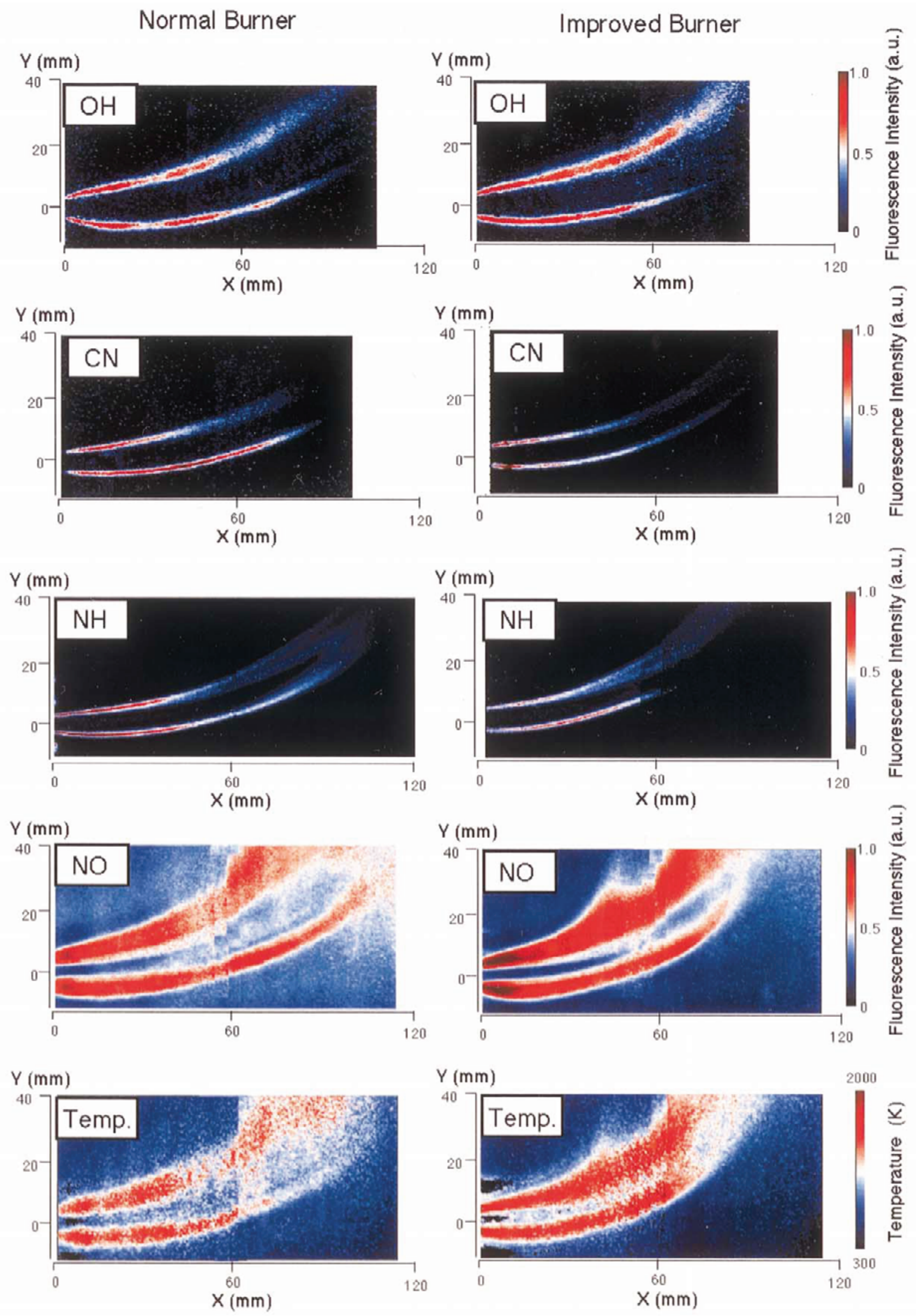


Fig. 2. OH, CN, NH, NO and temperature distributions in normal and improved burners.

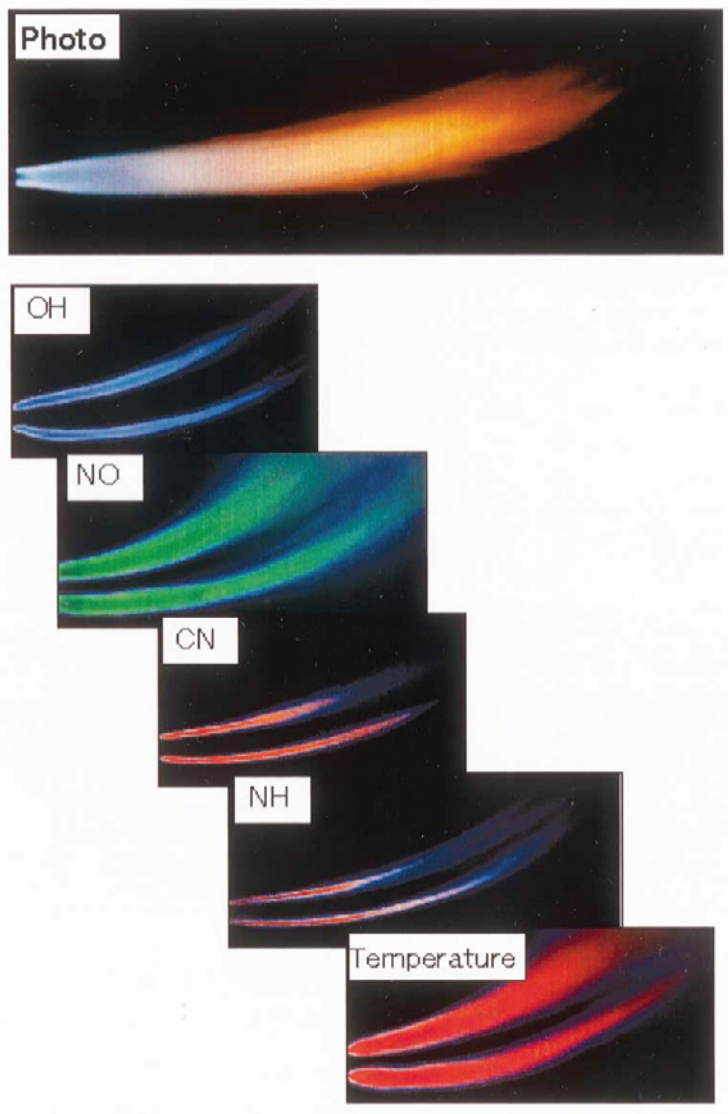
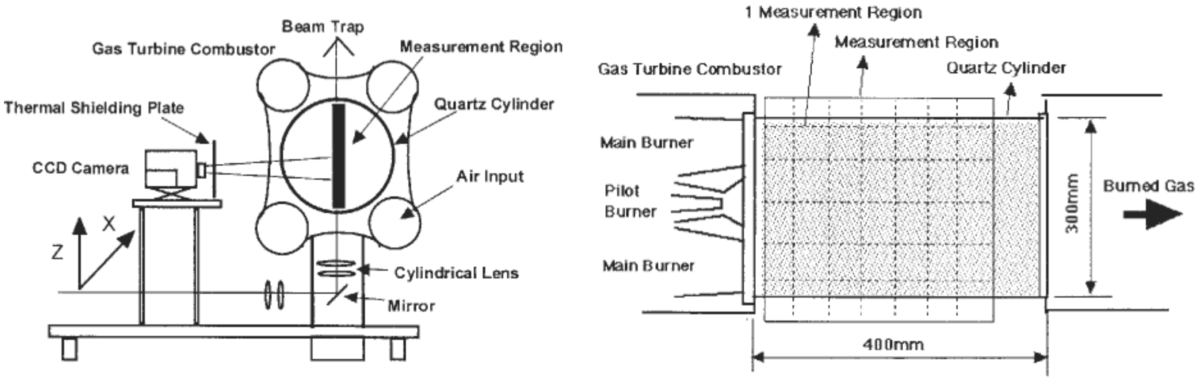


Fig. 3. Visualization of OH, CN, NH, NO and temperature using different color bars.



(a) Optical Setup

(b) Measurement Region

Fig. 4. Experimental setup for gas turbine measurement.

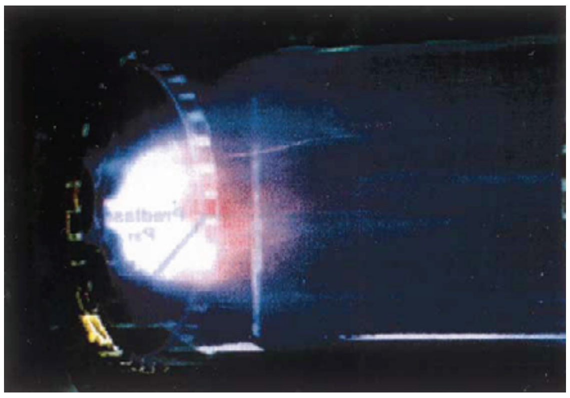
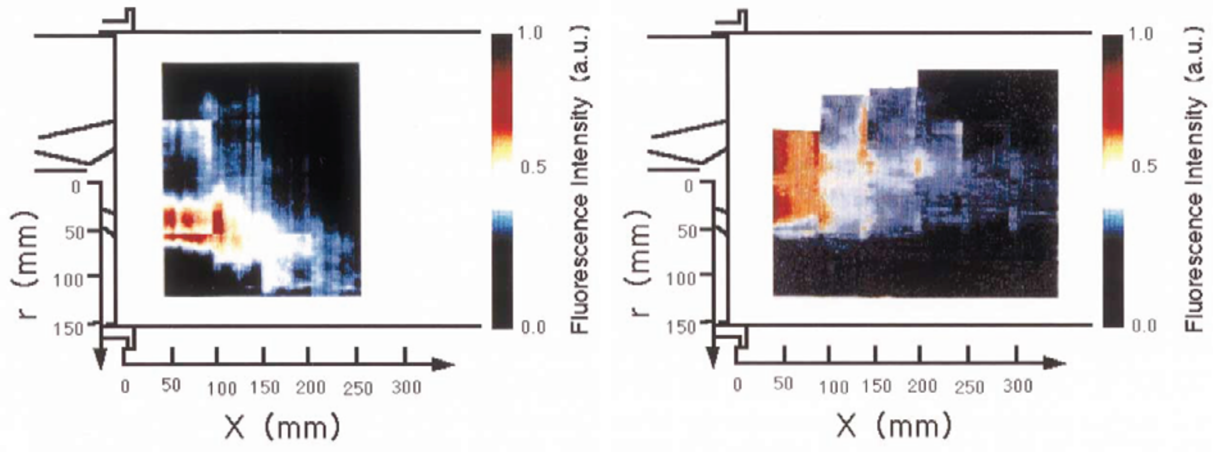


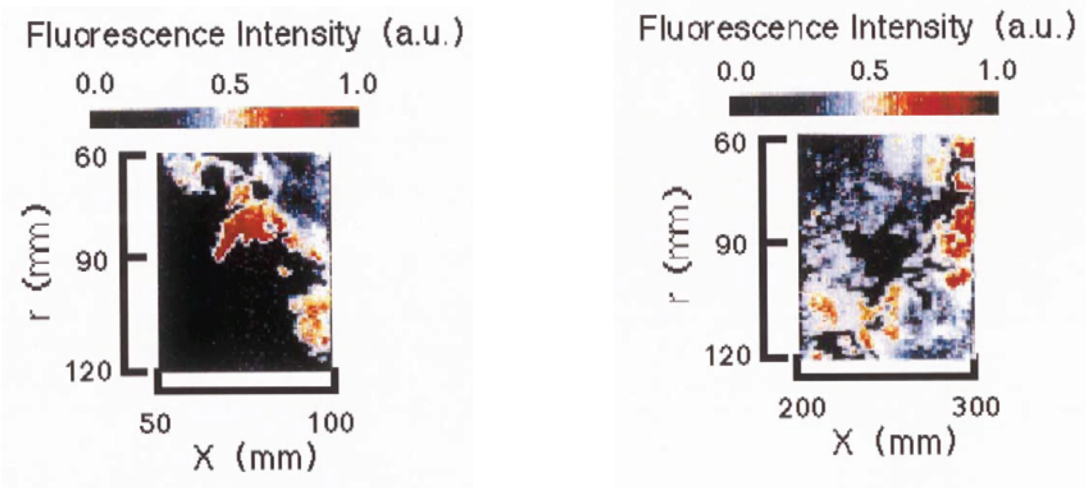
Fig. 5. Photograph of a gas turbine flame at 0.1 MPa.



(a) OH

(b) NO

Fig. 6. Time averaged OH and NO distributions inside a normal burner.



(a) X=50-100mm

(b) X=200-300mm

Fig. 7. Single shot OH distributions inside a normal burner.

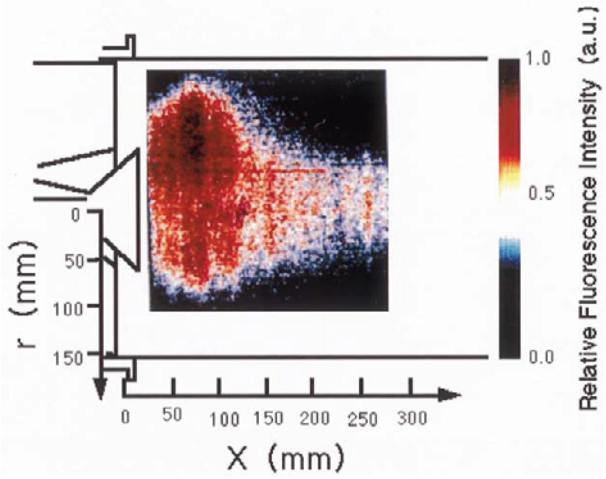


Fig. 8. Time averaged NO distribution inside the improved burner.

4. Diesel Engine

A schematic of the diesel engine measurement section is outlined in Fig. 9 (Nakagawa et al., 1997). The combustion test system was equipped with windows for the laser sheet incident at the side of the combustion chamber and with an observation window at the top of the piston to measure signal light in a single cylinder motoring engine. The fuel used was a mixed fuel (50:50 in volume ratio) of n-tetradecane and i-octane to minimize production of exhaust particles. Injection of the fuels into the combustion chamber was made by an in-line fuel pump for diesel engines. The suction air was made oxygen-rich in order to minimize formation of particles obstructive to laser measurement and to maximize formation of NO. Blower induced pressurization and heating of the suction air were carried out to raise temperature and pressure during compression. The fluorescence signal was collected through a UV lens and detected using two CCD cameras. Synchronization of the system was based on engine rotation, and measurement at any crank angle could be achieved by sending a signal with an adequate time delay relative to the motoring rotation to the laser and the CCD cameras.

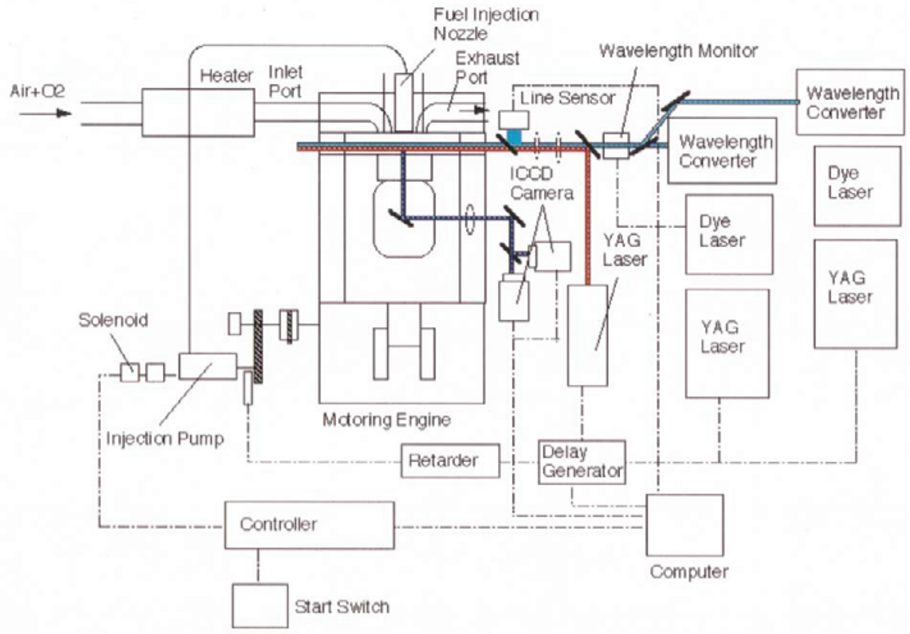


Fig. 9. Experimental setup for diesel engine measurement.

Measured results are shown in Fig. 10. From the upper block, Figure 10 shows, respectively, the direct flame images taken by a high-speed camera, laser-induced OH fluorescence intensity, laser-induced NO fluorescence intensity, laser-induced soot luminescence intensity, and temperature. Signals were integrated through five cycles of the combustion process.

The observed results show that combustion was initiated nearly at the timing of the top dead center, and a luminous flame is no longer observed at 30 degrees after top dead center. OH is present outside the region where the flame luminescence is observed, and it is recognized that the reaction process is still taking place at timing of 40 degrees after top dead center where the flame luminescence is no longer observed. The NO distribution is located slightly outside the flame luminescence, in almost the same region as that of OH and high temperature, and its presence in this region tends to increase during the latter period of the combustion process. This fact corresponds to the formation process of NO estimated from an extended Zeldovich mechanism, whereby formation of NO is slightly delayed relative to heat release. Soot formation occurs in the fuel-rich region in the flame center and shows a trend similar to that of flame luminescence.

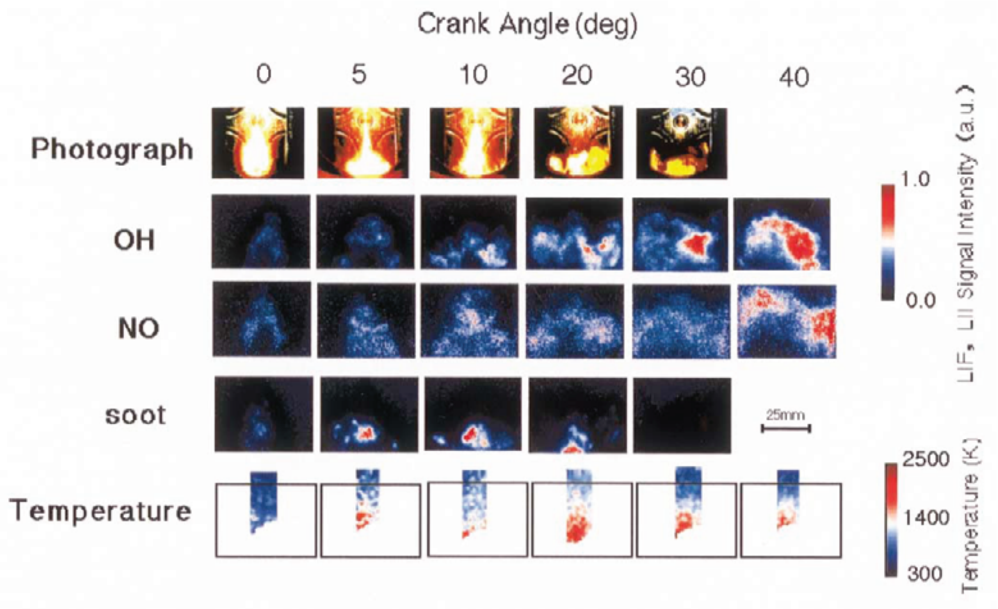


Fig. 10. Direct flame images, OH, NO, soot, and temperature in diesel engine combustion.

5. Large Scale Industrial Burner

LIF has been applied to various fields of combustion, but its application has been limited to small scale combustion phenomena. In this study, the delay time of a fluorescence signal was employed to resolve the measurement point inside a large scale combustor featuring a burner with recirculation of exhaust gas. This method is usually employed in the laser radar technique. The delay time of the fluorescence signal is related to the distance between the measurement point and the detector. The two-line NO LIF method was used to obtain temperature information inside the combustor.

The experimental setup for a large scale industrial burner measurement is outlined in Fig. 11. The test system was equipped with a window in the exhaust chamber, and the laser beam was introduced from this window. The fluorescence signal was also detected through the same window using a large diameter collection mirror. Resolution of 1 m inside the combustor can be achieved using a dye laser with 5 ns pulse duration. A PMT with 0.5 ns response was used as a detector and the measured signal was transferred for further analysis. The laser beam direction was controlled using a computer-controlled 3 axis stage.

The result is shown in Fig. 12. The high temperature region appeared at 4-5 m from the burner and temperature decreased gradually toward the exhaust. This technique allows greater than 25 m remote sensing ability with 1 m special resolution. Several burners of this type are used in a given thermal plant, and individual burner adjustment is an important factor for plant operation. This technique has the potential to be an excellent tool not only for burner optimization but also for plant monitoring operations.

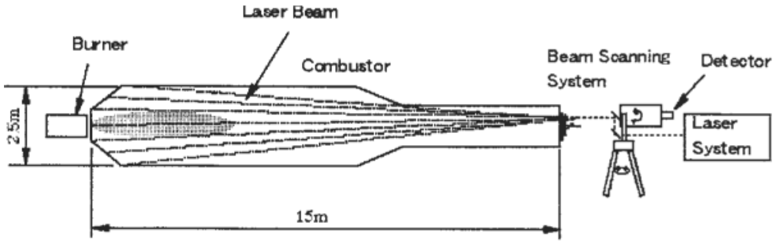


Fig. 11. Experimental setup for large scale industrial burner measurement.

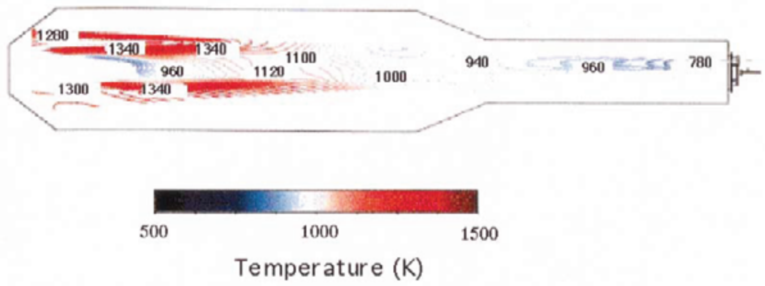


Fig. 12. Temperature distribution in a large scale industrial burner.

6. Conclusion

LIF was applied to several industrial combustors and results were obtained which are not feasible with conventional diagnostics. These results were used in the understanding of reaction phenomena and in the development of new generation combustors. LIF will play a significant role in the clarification of practical combustion mechanisms and in the improvement of practical combustors in various fields.

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Author Profile

Yoshihiro Deguchi: He is a senior research engineer in applied physics. He has worked at Mitsubishi Heavy Industries, Ltd. Nagasaki Research & Development Center for 10 years in laser technology. He is involved in developing laser diagnostics such as laser induced fluorescence, laser induced breakdown spectroscopy, and laser Raman spectroscopy for the application of these techniques to industrial fields. He received a doctorate in mechanical engineering from Toyohashi University of Technology in 1990.

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Toshimitsu Ichinose: He is a research manager for power systems. He has worked at Mitsubishi Heavy Industries, Ltd. Nagasaki Research & Development Center for 17 years in coal, oil and gas combustion technologies. He has worked on the development of high efficiency and low pollutant combustors for boilers, incinerators, etc., and is handling wide-ranging researches on with new types of next generation combustors.

Mitsuru Inada: He is an assistant chief research engineer in combustion and heat transfer. He has worked at Mitsubishi Heavy Industries, Ltd. Takasago Research & Development Center for 20 years in combustion technology, and has been engaged in developing low BTU gas fuel combustors and low NO_x combustion systems for high temperature gas turbines. He did research on detonation initiation at McGill University in Canada for one year.