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Structure and Dynamic Behavior of Combustion Visualized by 2-D Laser Diagnostics

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***Abstract*:** This paper describes studies of structure and dynamic behavior of combustion by use of laser-aided two-dimensional flame visualization. Attentions are given to the recent development of the laser sheet imaging techniques of velocity, temperature and concentration and its application to flame visualization. Visualization of turbulent diffusion flames by use of RIV (Rayleigh scattering Image Velocimetry) and OH-PLIF conducted by the authors are presented together with the short review of laser diagnostics of combustion.

***Keywords*:** flames visualization, 2-D laser diagnostics, measurements of velocity, temperature and species concentration.

1. Introduction

Combustion is a complex phenomenon combined with many processes such as flow, mixing, reaction, heat release and heat transfer. The combustion field is a multi-component system of high temperature. Some of the species are unstable radicals whose concentration is very small but plays important roles for the combustion. The flow field is sometimes turbulent and velocity, temperature and species concentration are time-dependent with rapid change of the state. There are many items which should be measured in the flame for combustion researches. They are flow velocity, temperature, species concentration of many kinds of gas species and so on. Development of the measuring methods by use of laser have stimulated the experimental researches of the flame structure. Laser light scattering techniques have been developed and used including Mie scattering, Rayleigh scattering, Raman scattering and laser-induced fluorescence. Books (Eckbreth, 1996; Taylor, 1993) and Review articles (Daily, 1997; Masri et al., 1996; Laurendeau, 1988; Kohse-Hoinghaus, 1994) describe the principles and demonstrate the availability and usefulness for the flame measurements. Importance of planar imaging of flames by use of laser techniques was demonstrated (Hanson, 1986). The experiments also encouraged the numerical simulation and analysis of the flame for the better understanding of the flame properties and structure.

This paper describes short reviews of recent advances in laser diagnostics of combustion and some of authors' results paying attention to two-dimensional visualization of flames for structural studies and dynamic behavior of the flames.

2. Detection Items and the Methods

The state of the combustion field is described mainly by the flow velocity, temperature and species concentration. They are the main items for the measurements. Numerous species prevail in the combustion field. They are components of the fuel, oxidizer, major combustion gas species, intermediate species such as radicals, air pollutants and soot. Tracer or additives such as particles or species added in the flow can be the items to be detected.

Non-intrusive laser-aided measurements, using Mie, Rayleigh and Raman scattering and laser-induced fluorescence (LIF) methods, as well as laser Doppler velocimetry (LDV), particle imaging velocimetry (PIV) and particle tracking velocimetry (PTV) have been used in many experiments for combustion researches. With the development of the laser source and detector, the methods have been extended from one point measurement to two-dimensional measurement, from single species to multi-species measurements and single variable to multi-variable measurements. Two dimensional, simultaneous and instantaneous temperature and concentration measurements together with velocity have been developed.

3. Visualization and Measurements

3.1 Flame Visualization and Velocity Measurement by Mie Scattering

The laser-light sheet (LLS) methods have been developed and used to visualize a two-dimensional instantaneous image of the flame. The visualization can be made by detecting two-dimensional profiles of species concentration, temperature, velocity, gas density or particle density added or generated in the flame (Hanson, 1986).

A thin laser-light sheet affords illumination of a specific plane by Mie scattering from paraffin oil droplets (Chao et al.,1992) or particles of TiO_2 (Lasheras et al., 1992; Chen et al., 1988; Chin et al., 1991) or soot (Shioji et al., 1993).

Laser light sheet (LLS) shots were used on vertical and horizontal cross sections in the flame for the visualization of turbulent eddies in an ethylene jet diffusion flame (Shioji et al., 1993). Tracer particles are soot formed in the interface between fuel and air. It was found that a very thin sooting particle layer rolls up several times and constitutes a large eddy. Such eddies are observed on every cross section, and they are unexpectedly coarse.

Joint Mie-scattering and Planar-Laser-Induced-Fluorescence (PLIF) technique has been employed to study the impact of jet-shear-layer development upon flame behavior (Chen, 1991). Mie-scattering is from TiO_2 particle generated by the chemical reaction between added $TiCl_4$ vapor in the gaseous fuel (propane and methane) and H_2O of combustion product. OH is detected by PLIF induced by UV laser sheet of 283 nm wave length. Mie scattering and OH-PLIF signals are observed simultaneously by a single CCD Camera system. Studies of the images indicate the flame/flow interaction and the observation of different types of flame zones and local extinction.

Laser Doppler velocimeter has been widely used to measure velocity and its fluctuation at one point in the flame. Two velocity components were measured by the two-color LDV. Two velocity components were detected together with temperature to get turbulent heat flux in the flame by correlating velocity and temperature fluctuation (Takagi et al., 1984).

Instantaneous two-dimensional velocity profile measurements have been made by Particle Imaging Velocimetry (PIV). A sequence of two-dimensional images of Mie scattering from TiO_2 particles illuminated by an argon-ion laser sheet was taken every 0.2 ms by use of a high speed camera (Shioji et al., 1993). The temporal difference of seeded particle profiles was estimated by cross-correlation between two images to get two dimensional instantaneous velocity profiles.

Particle tracking velocimetry (PTV) was used to obtain the instantaneous two-dimensional velocity field (Lewis et al., 1988). A pulsed copper-vapor laser was used to get high pulse repetition rate and the capability to control the pulse rate. These measurements are combined with the two-dimensional images of Mie scattering from TiO_2 seed particles, soot luminosity and laser-induced fluorescence from OH in the flame with a periodic vortical motion induced by acoustic excitation of the fuel stream. Local strain rate was estimated from the velocity profiles. These measurements reveal the interaction phenomena of the flame and vortex such as the local extinction by the high strain rate.

3.2 Flame Visualization by Rayleigh Scattering and Temperature/Velocity Measurements

(1) Turbulent diffusion flame

Figure 1 shows a schematic view of the optical apparatus for the simultaneous measurement of two-dimensional temperature and velocity profiles using the Rayleigh scattering image velocimetry (RIV). A Nd:YAG laser (Spectra-Physics, PIV400) produced two pulses (λ = 532 nm, 400 mJ) separated by a 20 μs interval time. It was focused to the measuring volume by a cylindrical lens (f = 500 mm) and made laser sheet with 0.2 mm of width

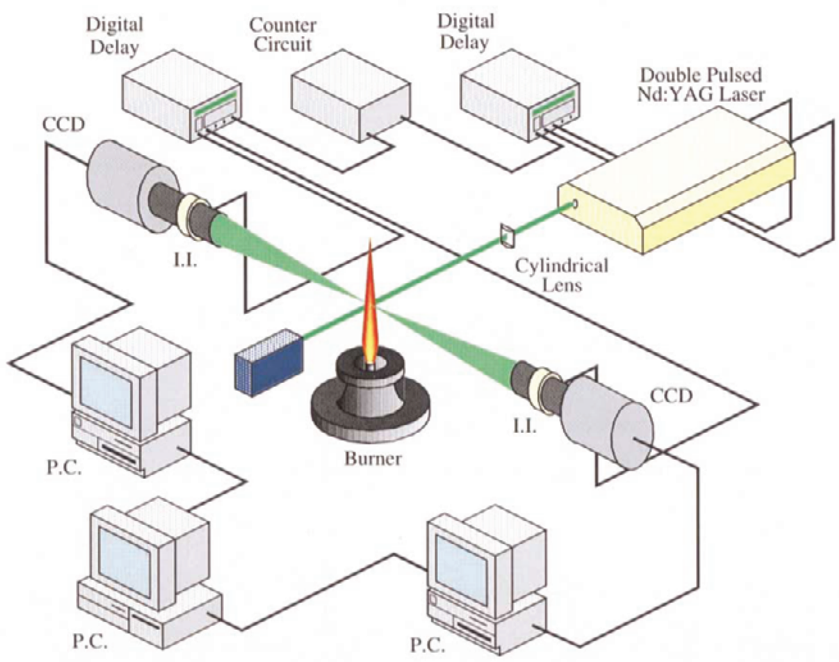


Fig. 1. Schematic view of the optical apparatus for the simultaneous measurement of two-dimensional temperature and velocity profiles using the Rayleigh scattering image velocimetry (RIV) (Komiyama et al., 1996).

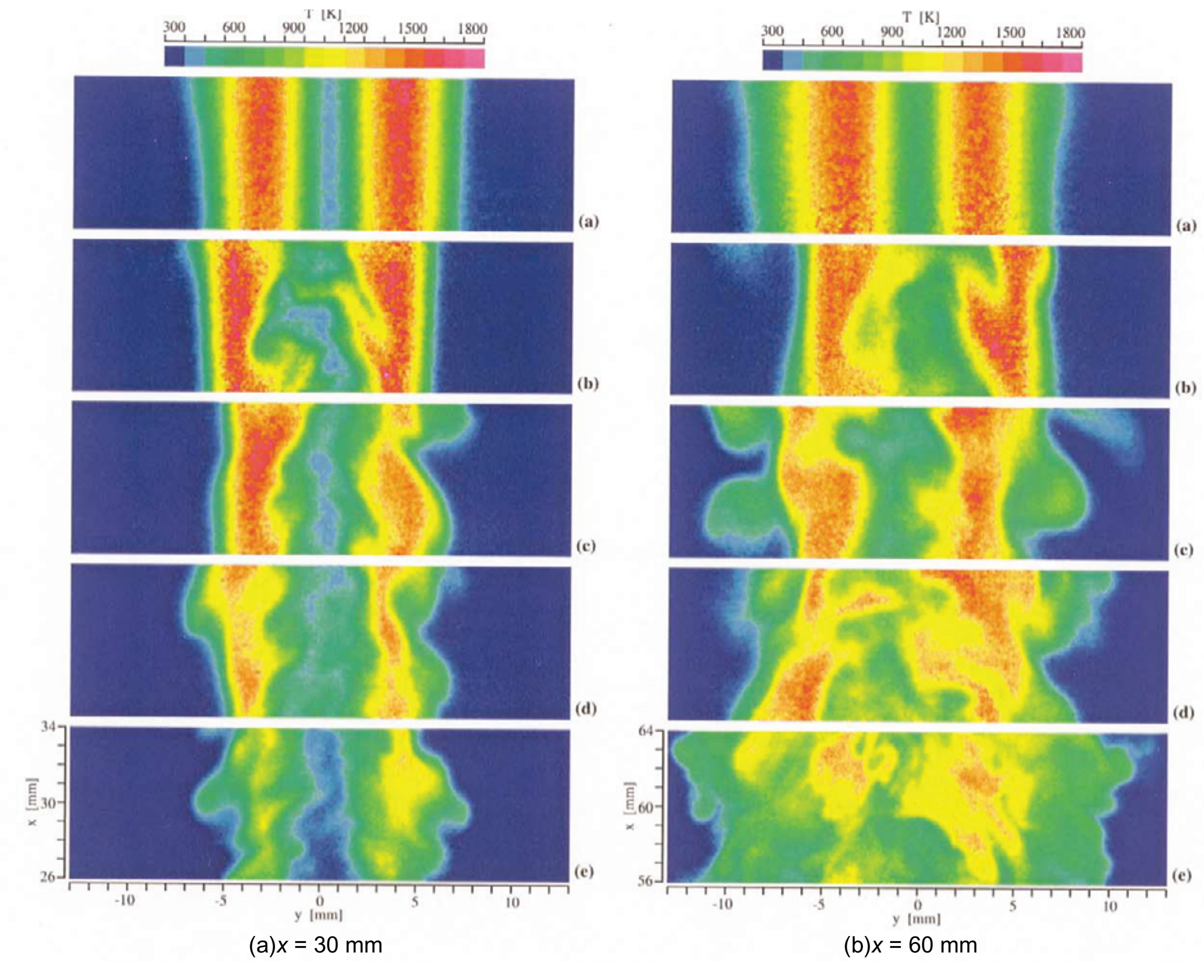
and 10 mm of vertical length at the measuring area. The Rayleigh scattering light emitted from the gas molecules in the measuring volume was collected at right angle to the incident beam by each lens (*f* 1.2) and introduced to each CCD camera (Photometrics, MXC200L) which has 512 × 512 square pixels with a single image intensifier (Hamamatsu-Photonics, C4273). Pulse generators (Stanford Research System, DG535) and a counter circuit were used to synchronize Rayleigh scattering to each laser pulse with gate time of each image intensifier, and to get two Rayleigh scattering images separated by 20 μs. The measuring area was 26 mm (laser light direction) × 10 mm (vertical direction) which corresponds to 500 × 190 pixels on the CCD camera. The temperature is measured by the laser Rayleigh scattering method which postulates that the absolute temperature is inversely proportional to Rayleigh scattering intensity when the Rayleigh scattering cross section is constant. The fuel is selected to be a mixture of H_2 30% and $N_2$70% by volume fraction because the Rayleigh scattering cross section of the burnt gas changes only slightly as compared with that of air. The cross section of the burnt gas at unity equivalence ratio is 2% less than that of air. The temperature ambiguity due to the non-uniform Rayleigh scattering cross section is estimated to be at most 50 K. The duration time to detect the Rayleigh scattering intensity was set to be 1 μs which is short enough to eliminate the influence of chemiluminescence.

Two-dimensional velocity vector was obtained by Rayleigh scattering image velocimetry (RIV) method (Komiyama et al., 1996). Two instantaneous Rayleigh scattering images was taken with small time interval τ. The cross-correlation technique was employed to obtain the velocity vector for each location. The small area at $t = t_0$, the reference matrix, was searched over an interrogation window at $t = t_0 + \tau$. The corresponding matrix was identified by the maximum coefficient of the cross-correlation between the reference matrix and the small area in the interrogation window. The displacement of local inhomogeneous

Rayleigh scattering images during the interval time, τ was measured by this method. The velocity vector was evaluated from the displacement and interval time, τ between the reference matrix and the corresponding matrix. Flame propagation speed could be negligibly small in the turbulent diffusion flame, and so we assumed displacement of the Rayleigh scattering images equals to that of the fluid elements in the small area. The interval time between the laser pulses was set to be typically 20 μs. The shorter interval time decreases spatial displacements of the Rayleigh scattering images and the number of erroneous velocity vectors by the cross-correlation technique. But it made difficult to determine slow-fluid velocity when the displacement became less than 1 pixel on this CCD camera. The size of the reference matrix was set to be 23 × 23 square pixels which corresponds to 1.2 × 1.2 mm square.

The measurements were carried out in diffusion flames formed when the gaseous fuel was ejected into the surrounding air flow through a round stainless steel nozzle with an inner diameter of 4.2 mm and an outer diameter of 6.0 mm. The typical flame condition was that the average velocity of the fuel at the exit of the nozzle was 40 m/s and the Reynolds number corresponds to 8000. The surrounding clean air was effused at 1.7 m/s from the exit which has an inner diameter of 50 mm after flowing through a filter to get rid of humidity and small particles. This prevents Mie scattering by small particles.

Figure 2 shows the two-dimensional temperature profiles measured by Rayleigh scattering which visualizes the flame configuration and temperature behavior. The vertical axis, x, in Fig.2 is the axial distance from the fuel nozzle tip and the horizontal axis, y is the radial distance from the centerline of the flame. L, TA, TB, TC and TD denote the Reynolds number conditions as noted in the figure caption. Reynolds number is evaluated at the exit of the fuel nozzle. Flame L of low Reynolds number is a laminar diffusion flame where the temperature profiles are laminar-like and low temperature fuel flow at the central part (y = 0 mm) is surrounded by high temperature reaction zone. In the flame TA, disturbance of the temperature pattern arises in the central part of the flame, but the outside part of the flame seems laminar-like. The laminarization phenomena due to the existence of the flame (Takagi et al., 1980) seems to occur in this flame. In the Flame TB and TC, turbulence occurs at the outside part of the flame and large scale bulge is observed. High temperature region is distorted and almost continuous, but the temperature becomes low partly which seems to indicate local quenching. The Flame TD is of high Reynolds number and a pilot flame was formed surrounding the fuel nozzle rim to anchor the flame. The flame temperature becomes low and quenched region increases.



(a)x = 30 mm (b)x = 60 mm

Fig. 2. Flame visualization by temperature profile measured by Rayleigh scattering of diffusion flames of different Raynolds number. ((a), (b), (c), (d) and (e) correspond to Renumber of 1000, 4000, 8000, 12000, 17000, and to average fuel nozzle exit velocity of 5, 20, 40, 60, 90 m/s. The flame of (a), (b), (c), (d) and (e) are named as flame L, TA, TB, TC and TD, respectively.)

Figure 3 shows a pair of instantaneous two-dimensional temperature profiles measured by the Rayleigh scattering method. The lower profile (Fig. 3(b)) was taken 20 μs after the upper profile (Fig. 3(a)). In this study, 1150 K is selected as one of the standard temperatures to discriminate the flamelet pattern. We call the distorted high temperature layer as flamelet. Based on our computation for a steady planar counterflow diffusion flame of the same fuel, 1150 K is the minimum flame temperature under which the flame extinguishes. Figure 4 shows the flamelet which is indicated as white and light gray areas from Fig. 3. Figure 4(a) corresponds to Fig. 3(a) and Fig. 4(b) to Fig. 3(b), respectively. The flamelet is almost continuous and it does not have constant radial width along the downstream, but has various kinds of width in the measuring area. Significant temperature depression was recognized in the thin flamelet in the center of a circle (left) and of a square (right) area where the temperature of the thin flamelet tends to decrease with respect to time and it almost reaches local extinction in Figs. 4(a)(b).

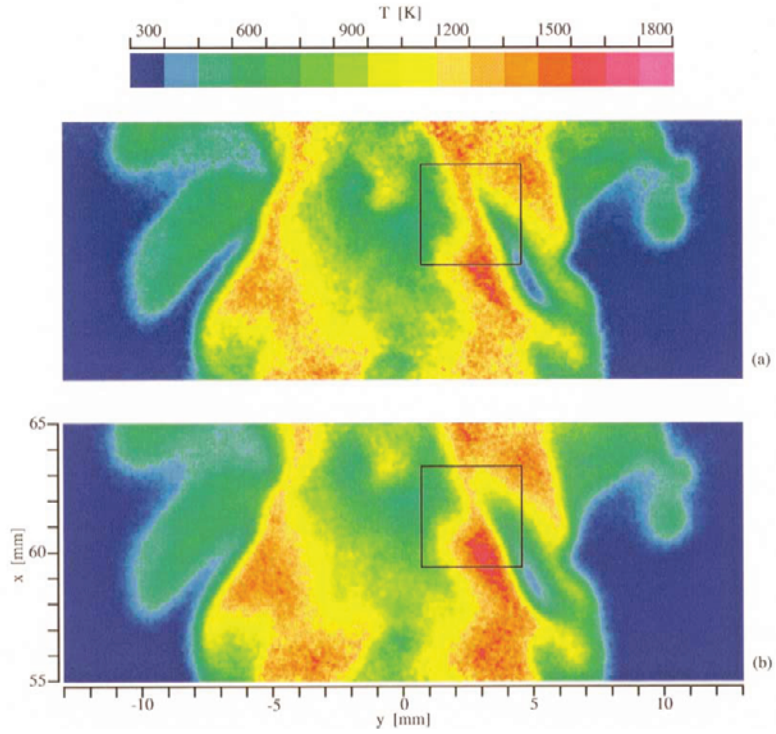


Fig. 3. Instantaneous two-dimensional temperature profiles measured by the Rayleigh scattering method. The measurements were made between x = 65 mm (top of the profile) and x = 55 mm (bottom) downstream from the exit of the nozzle. The lower profile (b) was taken 20 μs after the upper profile (a) (Komiyama et al., 1996).

Figure 5 shows an instantaneous two-dimensional velocity vectors derived from the two instantaneous two-dimensional Rayleigh scattering profiles (Figs. 3(a)(b)) based on the Rayleigh scattering image velocimetry (RIV) as noted above. The lines represent equi-temperature contours where the interval of the lines is 260 K. The velocity vectors have higher speed at the inside of the flamelet than the outside, and have large spatial fluctuations.

By use of the two-dimensional velocity field, we can estimate the vorticity, shear strain rate, expansion rate, and the (flame-surface) normal component of strain rate tensor in the flame stretch rate. Attention is focused on the flamelet in the center of a square area in Figs. 3(a)(b) and Figs. 4(a)(b) where the width of the flamelet becomes thin. It was shown by the computation based on the measured velocity fields that shear strain rate is negative and high and the normal component of strain rate tensor is positive and high in this flamelet region. This flamelet inclines toward the centerline (upper part of the flamelet lies in the inner part near the flame axis, y = 0 mm) in Fig. 4. The thin flamelet in the center of the circle area in Fig. 4 also inclines toward the centerline (y = 0 mm). The similar tendency is often recognized at two-dimensional temperature profiles with the similar flow conditions. It was noted that the flamelet in the center of a square area receives positive and high strain rate because the high-velocity fluid flows inside of the shear layer and low-velocity fluid flows outside. And so the inclination of the flame toward the centerline tends to stretch the flame and make the flamelet thin which should induce the temperature decrease to reach local quenching.

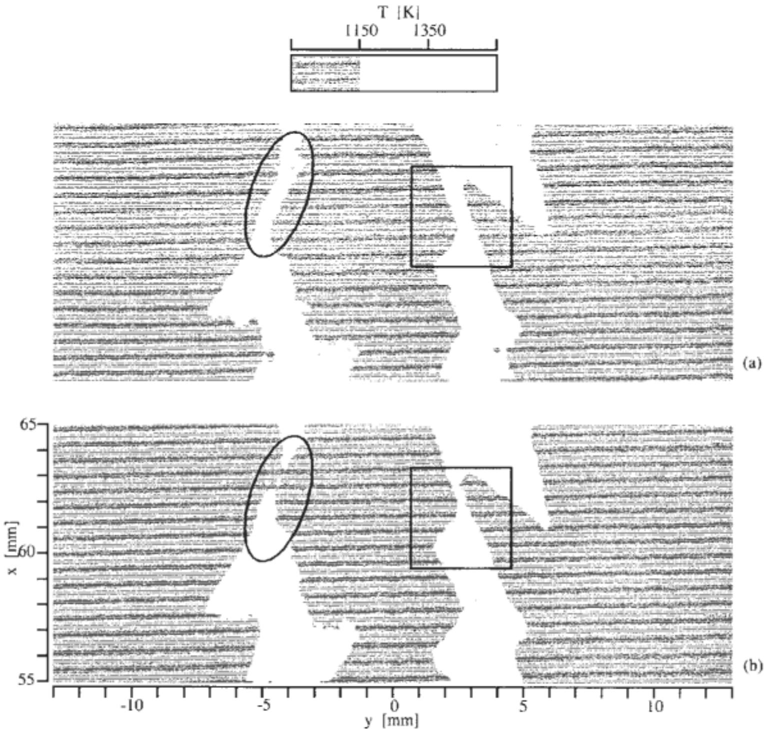


Fig. 4. Profile of flamelet region. A white area is higher than 1350 K, a light gray area is from 1350 to 1150 K and a dark gray area is lower than 1150 K. (a) corresponds to Fig. 3(a), and (b) to Fig. 3(b) (Komiyama et al., 1996).

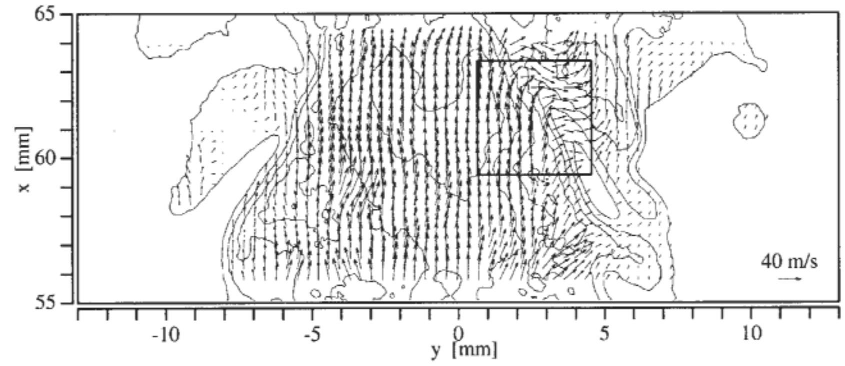


Fig. 5. Instantaneous two-dimensional velocity vectors by the RIV method. The lines represent equi-temperature contours where the interval between two lines is 260 K (Komiyama et al., 1996).

Single-shot Rayleigh scattering profiles have been obtained in the development zone of a turbulent diffusion flame of a diluted hydrogen jet issuing into a coflowing air stream (Stepowski et al., 1992). The temperature profiles were converted to get mixture fraction and scalar dissipation rate by use of an algorithm involving a strained flame library assuming flamelet model. The occurrence of local and intermittent extinctions due to the action of turbulent stretch are presumed.

The two-dimensional time-resolved Rayleigh scattering technique for mapping the temperature field was applied to a nonpremixed-hydrogen flame was presented (Fourguette et al., 1986)and to a large-scale industrial combustor (Kampmann et al., 1993).

Two-dimensional temperature measurements are almost exclusively made by Rayleigh scattering method because its scattering intensity is relatively intense as compared with other scattering such as Raman scattering. But, the scattering light wavelength is the same with that of the incident laser light. That is the reason why the temperature measurement by Rayleigh scattering cannot be combined with the velocity measurements by PIV or

PTV method which uses the Mie scattering of the same wavelength with Rayleigh scattering. This is the reason why the RIV method described above without seeding particle is useful for the simultaneous measurements of two-dimensional velocity and temperature profiles in the flame.

(2) Strained laminar flame

Two-dimensional temperature measurements were used for observing the temperature behavior of the locally strained steady diffusion flames (Takagi et al., 1996). The flame was counterflow diffusion flames strained by impinging micro air or fuel jet. Two-dimensional temperature measurements by Rayleigh scattering method together with corresponding numerical analysis revealed the effects of preferential diffusion and the flame curvature on the flame extinction. The similar measurements and computation were made of the unsteady locally strained diffusion flames (Yoshida et al., 1998), to reveal the local flame quenching and reignition phenomena and the effects of unsteadiness of the flame.

Flame vortex interaction has been investigated by use of Rayleigh scattering method and LIF together with numerical simulation (Gord et al., 1998; Katta et al., 1998).

3.3 Flame Visualization by Laser-induced Fluorescence and Concentration/Temperature/Velocity Measurements

Species concentration measurements are made by laser-induced fluorescence (LIF) and Raman scattering. LIF has a large scattering cross section and can be applied to the detection of small concentration species and applicable to two-dimensional species concentration measurements. LIF method needs the laser light which can excite the species of interest and so, the laser light wavelength must closely overlap a resonant transition of the species. The species detected by LIF and the wavelength used for the species excitation (Seitzman et al., 1993) are OH:(248, 285, and 308 nm), CH:(431 nm), C_2:(517 nm), O_2:(193 and 248 nm), NO:(193 and 227 nm), NH:(336 nm), CN:(388 nm), NO_2:(532 nm), acetone:(285 and 308 nm), biacetyl:(351 and 420 nm).

Optical arrangement was set up combining RIV method of Fig. 1 with apparatus to detect two-dimensional OH concentration by LIF (Miyafuji, 1997) so that two-dimensional profiles of temperature, velocity vector and OH concentration can be detected simultaneously.

The measurements were carried out in turbulent diffusion flames formed by the same condition as noted in Fig. 2.

Figure 6 shows instantaneous and simultaneous two-dimensional temperature, OH concentration and velocity vectors profiles which show typical flamelet behavior of the flame TB of Fig. 2. The instantaneous two-dimensional velocity vectors were obtained by RIV method described above. OH concentration was detected by the OH-LIF method. The trace of the flame surface is obtained by maximum radial OH concentration at every axial position.

We pay attention to the square area C where flame surface (reaction zone of OH peak) shifts much outside as compared with the temperature profile in Fig. 6(a). OH concentration on the flame surface that inclines toward the centerline in the area C is locally reduced in Fig. 6(c). The flame surface in the area C is pushed outward by the convection motion in Fig. 6(d). Figure 7 shows temperature and OH concentration profiles at the cross section C-C that passes the center of the area C. The radial position of the right hand side peak of OH concentration profile is located prominently outside as compared with the temperature peak and the peak temperature and OH concentration are significantly low as compared with those of the laminar flame. It was estimated from the velocity profiles that the flame surface in the center of the area C has high and positive normal component of the strain rate tensor and receives high flame stretch, where temperature and OH concentration are significantly reduced along the flame surface. On the other hand, the temperature and OH concentration keep relatively high along the flame surface which locates downstream of the area C.

Combination of PIV for velocity and LIF for OH were made to study the relationship between vorticity/strain and reaction zone structure in turbulent nonpremixed jet flames (Rehm et al., 1998). PIV and LIF of fuel were used to study turbulent premixed flame (Frank et al., 1996).

Two-dimensional LIF measurements of combined OH and Acetone added to the fuel were used to study the unsteady stretch and history effects on turbulent flames (Mueller et al., 1998) and to study high-speed reacting mixing layers (Seitzman et al., 1994). Two-dimensional Mixture fraction imaging in turbulent nonpremixed methane flames was measured by N_2 Raman, CH_4 Raman and Rayleigh scattering (Fielding et al., 1998). Two-dimensional mixture fraction and other scalars in turbulent flames were measured by simultaneous fuel Raman and Rayleigh imaging (Kelman et al., 1994). CH and CH_4 and temperature images were obtained and used to study the stabilization of lifted turbulent flames (Shefer et al., 1994a) and temporal evolution of turbulence chemistry

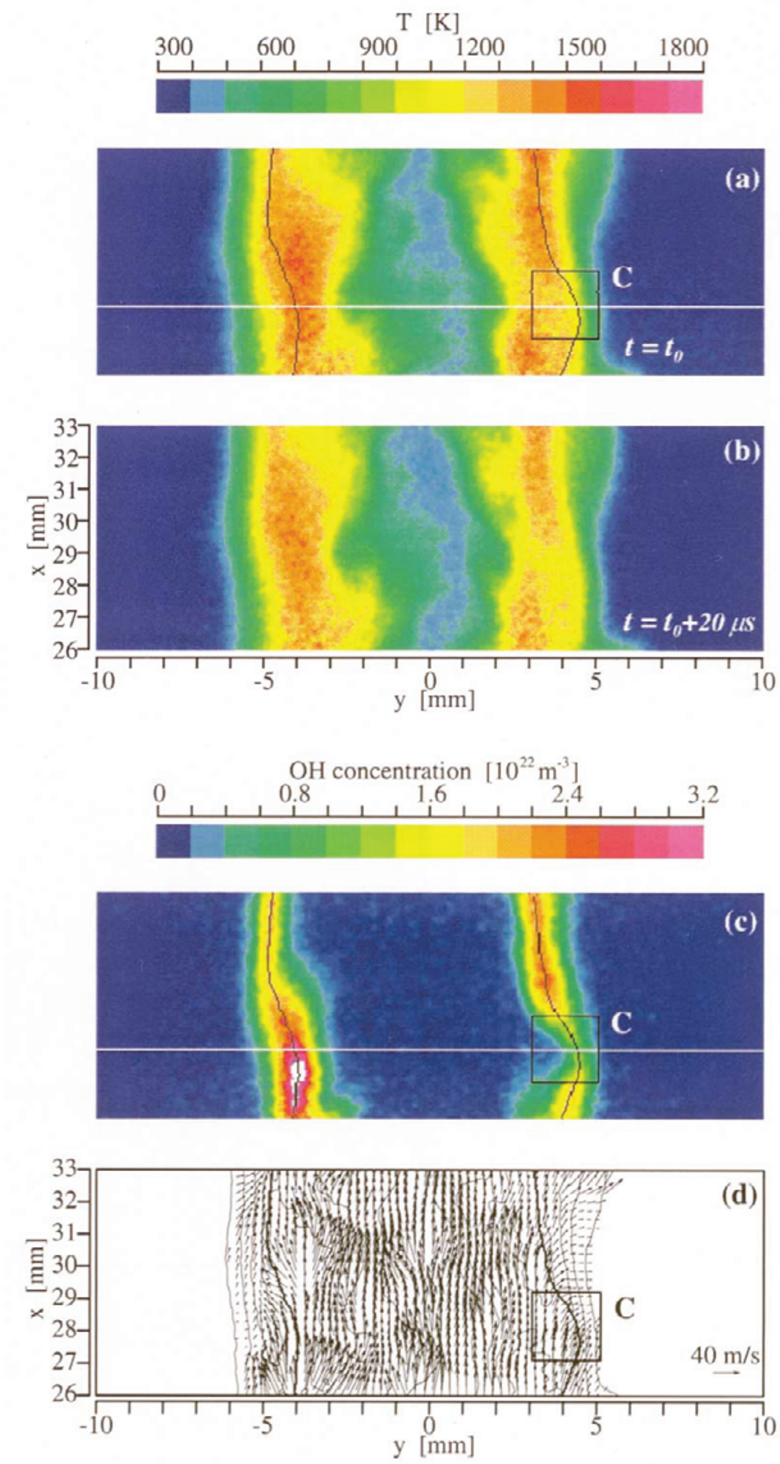


Fig. 6. Instantaneous and simultaneous two-dimensional temperature ((a) and (b)), OH concentration (c) and velocity vectors profiles (d) of the flame TB in Fig. 2. The solid lines in Figs. (a), (c) and (d) represent the flame surface obtained by tracing the maximum OH concentration at every axial position. The lower figure (b) was taken 20 μs after the upper figure (a) (Miyafuji,1997).

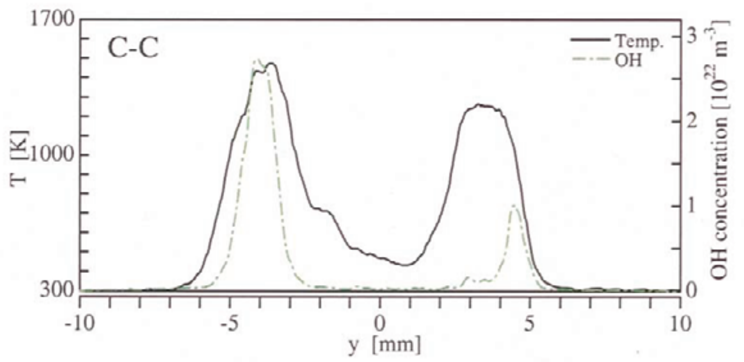


Fig. 7. Radial profiles of temperature and OH concentration at the cross section C-C of Fig. 6(a). Dark solid line is temperature and light chain line is OH concentration (Miyafuji, 1997).

interaction (Shefer et al., 1994b). OH-LIF and temperature by Rayleigh scattering imaging was used to study turbulent diffusion flames (Kelman et al., 1997), and to study the highly turbulent lean premixed flames (Dinkelacker et al., 1998).

Simultaneous planar LIF images of the OH and CH radicals were obtained in piloted turbulent methane diffusion flames (Starner et al., 1992). The results give the flame is locally interrupted and extinguished some 10-30 diameters from the nozzle and is re-lit further downstream. The images reveal thin, tendril-like structures of CH closely wrapping around the rich side of the OH profiles. Air dilution of the flame substantially thickens the OH reaction zone to the lean side. Comparisons with laminar flame calculations indicate that whilst flamelet concepts may be applicable to the inner reaction zone where CH is produced and consumed, they are not valid for the thickened recombination zone.

The planar LIF of OH and CH was used to study the time evolution of a vortex-flame interaction (Nguyen et al., 1996). The planar distributions of OH, CH and CH_4 concentration in a lifted turbulent CH_4-jet flame were measured by using combined LIF and spontaneous Raman scattering (Schefer et al., 1990). Simultaneous imaging of these species provides information on flame zone chemistry and its relationship to the turbulence structure. The two-camera imaging system is used for CH/CH_4 and OH measurements. For CH and CH_4 measurements, a flash lamp-pumped dye laser was tuned to produce a 431.5 nm beam. The ultraviolet laser radiation for excitation of the OH molecule was provided by a frequency-doubled, Nd:YAG-pumped dye laser. The detailed substructure of the large-scale coherent vortices in the mixing layer of annular diffusion flame (Gutmark, 1988) or laminar toroidal vortex interacted with a laminar premixed flame (Roberts et al., 1993) was studied by imaging OH radical by use of the planar Laser-Induced-Fluorescence (PLIF) visualization technique.

Planar imaging of OH-LIF were applied to a turbulent nonpremixed flame (Seitzman, 1990; Johnson, 1993), a laminar nonpremixed flame in unsteady vortical flow (Lewis et al., 1988), visualization of turbulent flame kernel growth and fractal characteristics (Gorgeon et al., 1993). Plane imaging of CH_4 concentration in turbulent jet flames by Raman scattering (Schefer et al., 1988) and plane imaging of parent fuel fraction in non-premixed flames by LIF are presented (Tait et al., 1992). Simultaneous temperature and NO concentration imaging was obtained by a PLIF technique in turbulent nonpremixed flames (Namazian et al., 1994).

Simultaneous, time-resolved point measurements of NO, major species, mixture fraction, temperature and OH were obtained in turbulent jet flames of pure hydrogen and helium-diluted hydrogen, using the combination of spontaneous Raman scattering, Rayleigh scattering and laser-induced fluorescence (Barlow et al., 1994). The data were systematically taken of scatter plots of measured temperature, major species mole fractions, and OH mole fraction versus the measured mixture fraction. The evidence of differential diffusion effects on temperature and significant OH overshoot were indicated. The differential diffusion effect is less in the downstream region and less than that in the laminar flame.

Simultaneous Raman/Rayleigh/LIF point measurements were made in piloted turbulent jet diffusion flames of diluted propane (Starner et al., 1990). It was indicated that measured H_2, CO and OH have peaks that are 2-3 times above those of predicted laminar flames and departure from partial equilibrium of the water-gas shift reaction and reactions in H_2-O_2 system.

Raman-Rayleigh-LIF measurements was applied to piloted diffusion flames of nitrogen-diluted methane near extinction (Barlow et al., 1990a). Mass fraction of OH and H_2 in the turbulent flames are higher than predicted by steady strained laminar flame calculations and OH, O_2 and H_2 approach partial equilibrium for temperatures above 1600 K on the lean side. Raman-Rayleigh method was applied to bluff-body stabilized turbulent nonpremixed methane and methanol flames close to blowoff and temperature and the mass fractions of fuel, CO, CO_2, H_2, H_2O, O_2 and N_2 (Masri et al., 1992a). It was found that bluff-body stabilized flames close to extinction show similar characteristics to pilot-stabilized free jet-flames of the same fuel. Raman-Rayleigh (and LIF) method was applied to turbulent diffusion $CO/H_2/N_2$ flames (Masri et al., 1998; Drake, 1986; Starner et al., 1991), CO/H_2 (Correa et al., 1988), hydrogen (Barlow et al., 1994; Cheng et al., 1992) jet flames, methanol flames (Masri et al., 1992b), methane flames (Hartick et al., 1992; Starner et al., 1990a; Starner et al., 1990b). Multi-species concentration measurements in CO/N_2 diffusion flames at one-point by CARS have been reported (Boyack et al., 1990).

4. Conclusion

Two-dimensional laser-aided flame visualization and the measurements of velocity, temperature and species concentration have been developed and extensively applied to combustion researches to enhance the understanding of the combustion phenomena such as microcopic flame structure, flame dynamics and transient effects, vortex-flame interaction, local flame quenching and reignition, flame curvature effects with respect to preferential diffusion. Instantaneous and simultaneous 2-D measurements of velocity together with multiple scalar profiles would be conducted to reveal the flame-flow interaction. Three-dimensional measurements would be developed and applied to understand three-dimensional phenomena as in turbulent flames.

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