Instantaneous Volume Imaging of Fuel Consumption Rate Distribution in Turbulent Rich and Lean Premixed Flames by Three-Dimensional Scanless Computerized Tomographic (3D-CT) Reconstruction Method with a 40-Lens-Camera

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ABSTRACT

In order to elucidate detail three-dimensional structure of turbulent flame, it is worth obtaining the whole shape of instantaneous reaction zone, namely, the distribution of fuel consumption rate of turbulent flame. Inferring local fuel consumption rate from chemiluminescence light emission has long been a common and largely accepted practice. In present study, therefore, the instantaneous three-dimensional distribution of the chemiluminescence light emission image of turbulent premixed “blue” flame is captured as a fuel consumption rate distribution by a newly proposed technique; "instantaneous three-dimensional scanless computerized tomography (3D-CT) technique" with a custom-made multi(40)-lens camera. The results for a propane-air fuel-rich-premixed turbulent flame show that the flame front is observed to be a thin wrinkled luminous region of 0.6 mm in thickness and that the cusps observed in horizontal cross-sections correspond to ridges of the three-dimensional flame front. It is also found that the luminosity distribution is quenched along the ridges by Lewis number effect. The maximum value of local fuel consumption rate is estimated to be 2.7 g/s/m^3. In this paper, fuel-lean case is also investigated.

INTRODUCTION

In order to elucidate detail three-dimensional structure of turbulent flame, it is worth obtaining the whole shape of instantaneous reaction zone, namely, the distribution of fuel consumption rate of turbulent flame. Inferring local fuel consumption rate from chemiluminescence light emission(e.g. C_2* and CH*. here the * denotes an electronically excited state) (Hurle et al., 1968, Ishino et al., 1993, 1996, Ikeda et al., 2000, Ducruix et al., 2000,) has long been a common and largely accepted practice. In present study, therefore, the chemiluminescence light emission image of premixed “blue” flame is focused, moreover, instantaneous three-dimensional scanless computerized tomography (CT) technique is proposed and accomplished for the turbulent propane-air premixed flames. First instantaneous two-dimensional images (projections) of an objective flame are simultaneously taken from forty horizontal directions with a custom-made multi-lens camera, which has forty lenses. Next four hundred horizontal CT images, which are reconstructed from the projections by MLEM (maximum likelihood expectation maximization)-CT algorithm, are vertically accumulated, resulting in an instantaneous three-dimensional distribution of visible light emission intensity and fuel consumption rate of the turbulent flame. The results for a propane-air fuel-rich-premixed turbulent flame show that the flame front is observed to be a thin wrinkled luminous region of 0.6 mm in thickness and that the cusps observed in horizontal cross-sections correspond to ridges of the three-dimensional

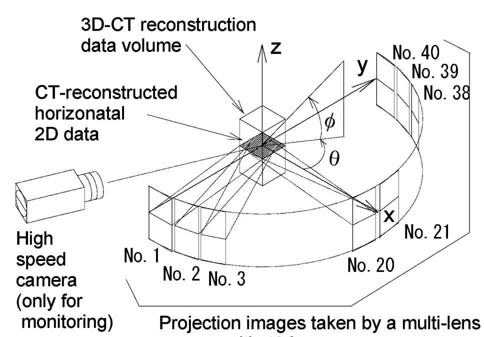
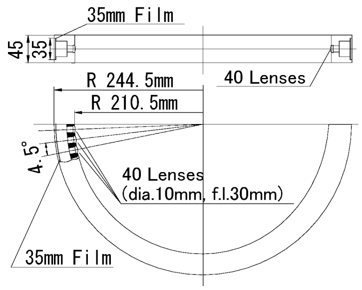
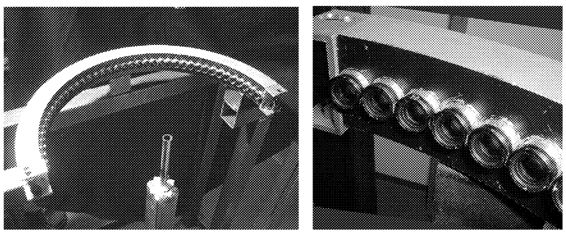


Figure 1: Concept of the proposed instantaneous Scanless 3D-CT technique



(a) Dimensions of custom-made multi-lens camera



(b) Appearance (left) and close-up (right) of multi-lens camera

Figure 2: Dimensions and appearance of a multi-lens camera which equipped with forty small high-performance lenses

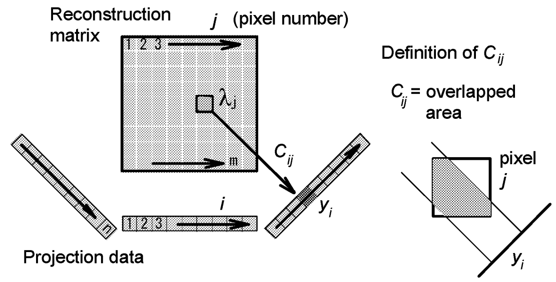


Figure 3: Notation and coordinate system for MLEM reconstruction (Yokoi et al., 2000)

flame front (Ishino and Ohiwa, 2004, 2005). It is found that the luminosity distribution is quenched along the ridges by Lewis number effect. The maximum value of local fuel consumption rate is estimated to be 2.7 g/s/m^3.

EXPERIMENTAL APPARATUS AND METHOD

Instantaneous 3D-CT Method

The schematic diagram of the experimental apparatus and coordinates system is shown in figure 1. The cartesian x-y-z coordinate and polar θ-ϕ coordinate system are also depicted in the figure. In this method, first, the pipe burner with a turbulent premixed flame is settled at the center of a custom-made multi-lens camera, which has forty lenses #1~#40. Instantaneous two-dimensional 'projection' images (#1~#40) of chemiluminescence of an objective flame are simultaneously taken from forty directions using the multi-lens camera. This simultaneous photographic technique is called as 'time-slice' photography. By use of MLEM-CT algorithm (Yokoi et al., 2000), instantaneous two-dimensional chemiluminescence distributions of each horizontal cross-sections are reconstructed from related sets of forty horizontal line data picked up from 'projections'. Instantaneous three-dimensional distribution is simply built up by accumulating vertically the numerous horizontal two-dimensional CT reconstructions. The objective turbulent flame is also monitored simultaneously by high speed CCD camera from the reverse direction of lens #33.

'Time-slice' Photographic Technique

Multi-Lens Camera. For 'time-slice' photography, a custom-made multi-lens camera is designed. Figure 2 shows the dimensions, appearance and close-up of the camera. The camera is equipped with forty small high-performance lenses (6 elements/5 group, focal length f = 30 mm, F number = 3.0, non-permeability to ultraviolet light). This semi-circular-arc shape of the camera can surround the objective flame over 180 degree for proper CT reconstruction. Very high-speed black and white negative panchromatic film (Fuji, Neopan 1600. sensitivity is up to 630 nm) is loaded along the circumference of the camera, and developed after exposure. A free-falling slit shutter (5 mm in slit size), which travels simultaneously in front of every lens, controls exposure time of 1.2 ms. In this system, although no interference filter for radical emission is used in order to ensure the fast-shuttering, the detection wavelength is limited to 400-600 nm by combination of the panchromatic film and the non-U.V. lenses used. In this investigation, therefore, detected flame images are treated as those of chemiluminescence.

Digital Image Processing. The developed negative film is digitized with a macro lens on a digital camera (Nikon, D1) to obtain the forty digital projection images of a turbulent flame. Alignment of each projection image is performed on the basis of burner rim position of each image. The pixel values of the digital images are still qualitative, because no compensation for the characteristic curve, which ensures the relation between exposure and density of negative film, has been made. In this experiment, however, the linear proportion between the pixel values and integrated emission intensity on the line of sight at the pixel is tentatively assumed.

CT Reconstruction

MLEM algorithm.(Yokoi et al., 2000) In present study, MLEM (maximum likelihood-expectation maximization) method (Dempster et al., 1977, Yokoi et al., 2000) is employed for CT reconstruction. This reconstruction method is a kind of iterative reconstruction methods. The iterative reconstruction has recently become be attractive as an alternative to conventional filtered backprojection algorithm, because of its quantitative capability. Figure 3 shows the notation and coordinate system for MLEM reconstruction. λ_j^k is the value of reconstructed image at the pixel j for k-th iteration, y_i the measured projection data at i-th pixel, and C_{ij} the detection

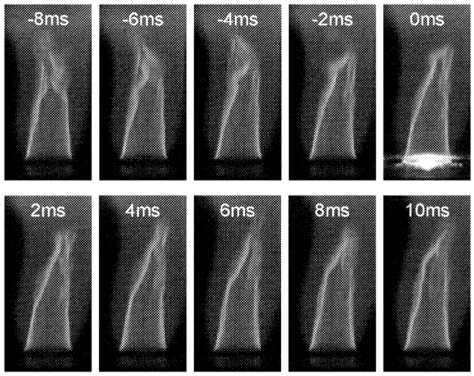


Figure 4: High speed photography (500 frame/s) of the observed turbulent fuel-rich premixed "blue" flame. The upper-right picture with flash light marker corresponds to the image recorded by multi-lens camera.

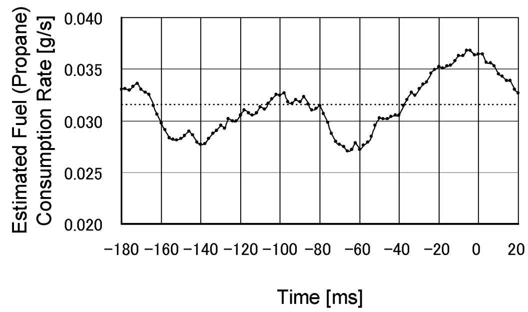


Figure 5: Time history of the estimated overall fuel consumption rate of the objective fuel-rich flame, which is evaluated from the total light emission from the flame. The fuel (propane) consumption rate at the timing of CT measurement, $t = 0$ ms, is estimated to be 0.0364g/s.

probability which represents as the overlapped area between i-th ray and pixel j. In MLEM reconstruction, for improvement of reconstruction image λ_j , the iteration is progressed by following expression:

$$\lambda_j^{k+1}=(\lambda_j^k/\Sigma_j C_{ij})\ \Sigma_i[y_i C_{ij} / \Sigma_j(C_{ij}\lambda_j^k)] \qquad (1)$$

where k is the iteration number. This algorithm converge to the maximum likelihood estimate of a probability distribution function from the observed data (Dempster et al., 1977, Yokoi et al., 2000).

In the reconstruction of present study, conventional backprojection image is progressed by eight MLEM iterative steps. The emission light is assumed to be parallel ray for simplification of calculation. This parallel-beam assumption can be made by assuming that the objective flame size is negligible compared to the distance between objective flame and lenses. Although inclusion of absorption term is possible in MLEM method, absorption is not considered in present investigation because the self-absorption at bands of CH, C_2 and HCO is very weak in small flames (Gaydon, 1974).

Data size. The forty projection images of 380 pixel (horizontal) x 550 pixel (vertical) produces 550 sheets of horizontal reconstructed image of 380 pixel x 380 pixel. It takes approximately 12 hours with Pentium 4 (1.7 GHz clock speed) PC to complete the reconstruction of 550 images. The pixel size corresponds to 0.12 mm. Therefore, the special resolution in the three-dimensional distribution is 0.12 mm x 0.12 mm x 0.12 mm, in each direction.

High speed photography

A high speed CCD video camera (Redlake, MotionScope PCI 1000S, 500 fps) monitors the turbulent flame behavior before and after exposure of multi-lens camera from the reverse direction of #33 lens of the multi-lens camera. A flash light inserts a time mark on high speed movie at the exposure of the multi-lens camera.

Objective Flames

Objective turbulent premixed flame is anchored on the top of the pipe burner of 16 mm in outer diameter and 14 mm in inner dia., which is located at the center of the lenses of the multi-lens camera. Commercial grade propane(96.4% purity) is used as fuel in this experiment. The equivalence ratio of the premixed mixture flow is set to be 1.43 and 0.9 in case of rich and lean condition, respectively. The average flow velocity and Reynolds number of the burner are 1.7 m/s and 1526. Turbulence of 0.09 m/s is promoted by a grid inserted in the pipe.

For propane-air rich flame, it is well known that dark ridges appeared along the flame surface (Lewis and Elbe, 1961). The high speed photography of the objective rich turbulent flame is indicated in figure 4. The

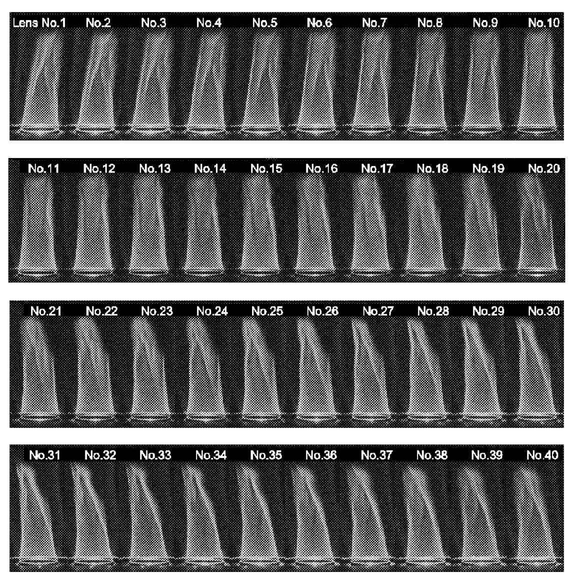


Figure 6: Complete set of the projection images of the objective rich turbulent flame

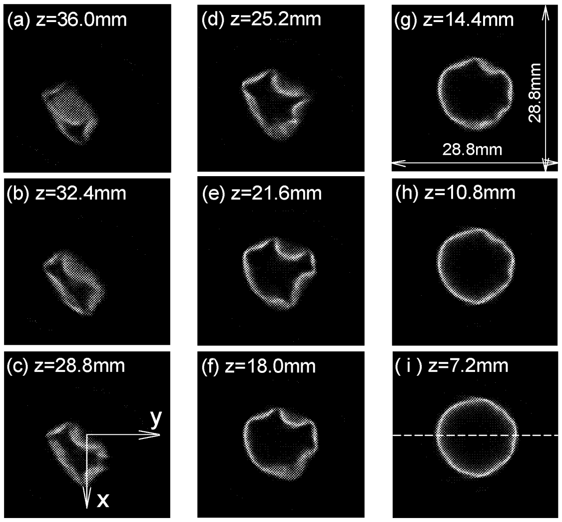


Figure 7: Samples of horizontal reconstruction of turbulent premixed flame of propane-air rich mixture: equivalence ratio=1.43

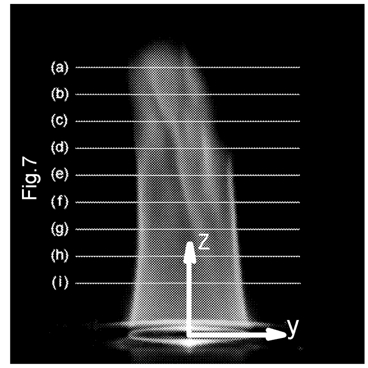


Figure 8: A $-x$ directional virtual image made of the 3D data. The lines gives the position information for figure 7.

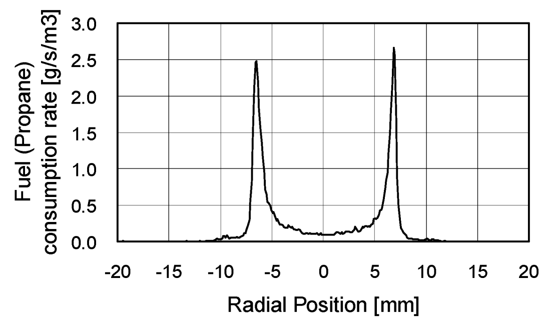


Figure 9: Fuel consumption rate distribution at the dashed line in figure 7(i)(z=7.2 mm).

flash-light-marked picture corresponds to the image recorded by multi-lens camera. Time history (figure 5) of the estimated overall fuel consumption rate of the rich flame evaluated from the total flame light emission measured from the high speed camera images. The fuel consumption rate at the timing of 3D-CT measurement, t = 0 ms, is estimated to be 1.04 l/min (0.0364g/s) in contrast with the time-average fuel flow rate of 0.90 l/min.

RESULTS AND DISCUSSION

Rich Propane-Air Flame

A complete set of projection images taken by multi-lens camera is shown in figure 6. Four hundred horizontal images are reconstructed from these projection images, and stacked them up in order to make three-dimensional distribution. First, selected horizontal reconstructions are indicated in figure 6. For reference, A $-x$ directional virtual image shown in figure 7, which is made of the 3D distribution, gives the information of sections of each figure. Figures 6(a)~(i) correspond to the tomographic images of z=36.0 mm, 32.4 mm, 28.8 mm, 25.2 mm, 21.6 mm, 18.0 mm, 14.4 mm, 10.8 mm and 7.2 mm in height from burner rim. Thin ring type distribution is observed at lower height (figure 6 (h) and (i)). In the middle region (figure 6 (d),(e)and (f)), it is found that flame front is folded, and the local fuel consumption rate are diminished at cusps, resulting from the so-called Lewis number effect. A set of horizontal reconstruction data proves that the 'cusps' in two-dimensional plane are ridges in three-dimensional space.

Local fuel consumption rates of each pixels are estimated by following values:

(1)instantaneous overall fuel consumption rate of 1.04 l/min (0.0364g/s) and

(2)the ratio of the whole sum of 3D-CT value of all pixels and CT value of each pixel

Figure 9 shows the reconstructed fuel consumption value distribution at the center line x = 0 mm of the data of z=7.2 mm (figure 7(i)). Maximum fuel consumption rate of 2.7 g/s/m^3 in fig 9, is considered to be almost same order of the value of 17g/s/m^3 of laminar flame of the same mixture(laminar burning velocity is assumed to be 0.2 m/s), if we take the blurred distribution in figure 9 into account. Half width at half maximum (HWHM) of high value region is measured as 5 pixel (approx.), that is 0.6 mm in width.

Figure 10 displays the various types of observation of three-dimensional distribution, where figure 10(a) is bird's eye view, figure 10(b) horizontal sectional view, and figure 10(c) a vertical sectional view. These types of display strongly help us to recognize the detail and total characteristics in turbulent flames.

Lean Propane-Air Flame

Propane lean flame is investigated in this section. A complete set of projection images is shown in figure 11. Three dimensional emission distribution of lean flame is reconstructed from these projection images by 3D-CT method as shown in figures 12, 13 and 14. Figure 13 depicts

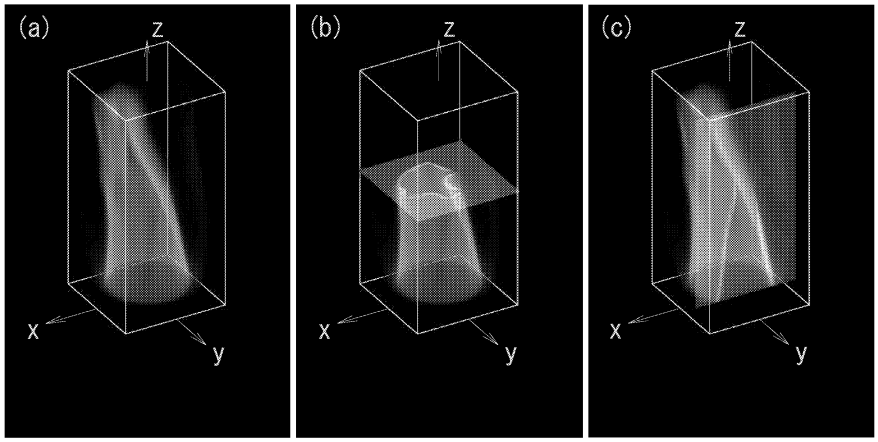


Figure 10: Various types of display of three-dimensional emission intensity distribution data set of the turbulent propane-rich flame. Figure (a): bird's eye view in directions of (θ, ϕ)=(60 deg, 30 deg), (b): horizontal sectional view at z=21.6 mm, and (c): vertical sectional view at y=4.8 mm.

the positions of horizontal cross-sections shown in figure 12. Figures 12(a)~(i) correspond to the images of z = 21.0 mm, 18.6 mm, 16.2 mm, 13.8 mm, 11.4 mm, 9.0 mm, 6.6 mm, 4.2 mm and 1.8 mm in height from burner rim. The horizontal reconstructions of figure 12 gives thin luminous region of flame surface. In contrast with propane-rich case, the lean flame surface exhibits diminution of light emission at concave region. Figure 14 displays the various types of observation of three-dimensional distribution, where figure 14(a) is bird's eye view, figure 14(b) horizontal sectional view, clearly showing the 3D relationship between instantaneous flame shape and its luminosity.

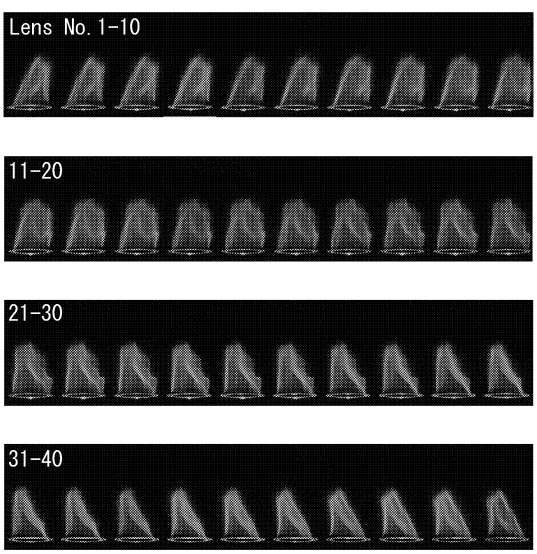


Figure 11: Sample of complete set of the projection images of the propane-lean turbulent flame

CONCLUSIONS

An advanced CT reconstruction technique for measuring an instantaneous three-dimensional distribution of fuel consumption rate of a turbulent premixed flame is accomplished for turbulent propane-air rich and lean premixed flames. It is found that flame front is folded, and the emission intensities and local fuel consumption rate are diminished at cusps of propane–rich flame surface, resulting from the so-called Lewis number effect. In case of

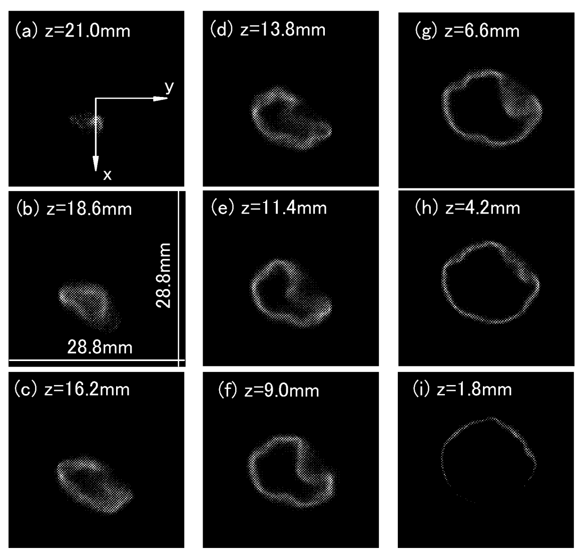


Figure 12: Samples of horizontal reconstruction of turbulent premixed flame of propane-air lean mixture: equivalence ratio=0.9

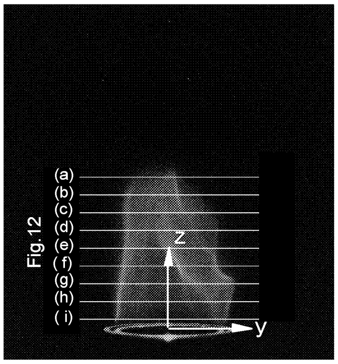
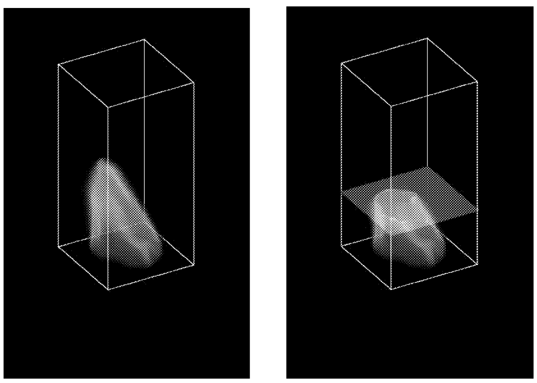


Figure 13: A $-x$ directional virtual image made of the 3D data. The lines gives the position information for figure 12.



(a)Bird's eye view (b)Horizontal cross-section

Figure 14: Various types of display of three-dimensional emission intensity distribution data set of the turbulent propane-lean flame. Figure (a): bird's eye view in directions of (θ, ϕ)=(60 deg, 30 deg) and (b): horizontal sectional view at z=10.0 mm.

propane–lean flame, emission intensity of concave regions of flame surface is diminished. Proposed technique has brought the high spatial resolution of 5 pixel (=0.6 mm) in 3D combustion measurement. Measurement of instantaneous distribution of local fuel consumption rate of a turbulent flame is succeeded. The maximum value of local fuel consumption rate is estimated to be 2.7 g/s/m^3 for rich flame.

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