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Application of DFB Diode Laser Sensor to Reacting Flow (II) — Liquid-Gas 2-Phase Reacting Flow —

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Diode laser sensor is conducted to measure the gas temperature in the liquid-gas 2-phase counter flow flame. $C_{10}H_{22}$ and city gas were used as liquid fuel and gas fuel, respectively. Two vibrational overtones of H_2O were selected and measurements were carried out in the spray flame region stabilized the above gaseous premixed flame. The path-averaged temperature measurement using diode laser absorption method succeeded in the liquid fuel combustion environment regardless of droplets of wide range diameter. The path-averaged temperature measured in the post flame of liquid-gas 2-phase counter flow flame showed qualitative reliable results. The successful demonstration of time series temperature measurement in the liquid-gas 2-phase counter flow flame gave us motivation of trying to establish the effective control system in practical combustion system. These results demonstrated the ability of real-time feedback from combustor inside using the non-intrusive measurement as well as the possibility of application to practical combustion system. Failure case due to influence of spray flame was also discussed.

Key Words : Diode Laser Sensor, Liquid-Gas 2-Phase Flame, Combustion Measurement

1. Introduction

High temporal and sensitive measurements of gas-dynamic properties are strongly requested for high efficiency and low pollution combustion. To accomplish these requirements, we need an advanced in-process sensing technique that can measure the gas temperature and concentrations of major species faster and more accurately. Non-intrusive temperature and concentration sensors using lasers are attractive in many situations where measurements must be made in a hot and/or erosive environment such as in a flame. Thermocouple temperature measurements require a probe that is subjected to the hostile environment. Concentration measurements via sampling probe have similar problems. It is also difficult to make simultaneous temperature and concentration measurements with intrusive probes. Laser-based sensors are expected to resolve these difficulties. Vibrational and rotational spectra of gases using laser-based sensor can provide an excellent measure of pressure, temperature, and species concentration when the detailed dependence of the spectra on these variables are known. Near-infrared diode laser absorption sensors have been applied to in-situ measurement of gas temperature and species concentration in the combusting environment (Mihacea, R. M., et al., 1998b ; Sonnenfroh, D. M., et al., 1997). Applica-

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tions of diode laser have increased dramatically owing to their robustness, compactness, reasonable cost, compatibility with optical-fiber components, and relative ease of use. The target gases were H_2O (Arroyo, M. P., et., 1993 ; Allen, M. G., et al., 1996), NO (Mihacea, R. M., et al., 1998a), NO_2 (Mihacea, R. M., et al., 1996), CH_4 (Choi, S. I., et al., 1996 ; Nagali, V., et al., 1996), CO (Daniel, R. G., et al., 1996) and CO_2 (Mihacea, R. M., et al., 1998c). In practical combustion system, flame temperature and species concentration change with temporal and spatial. Furthermore, soot or floating materials sometimes exists in combustion-driven energy. Especially, droplets do exist for the liquid fuel combustion. Because the absorption method gives us path-averaged information, beam steering may restrict extension of path-length. Rapid combustion measurements, therefore, have been demonstrated in a variety of flow-field using scanned wavelength, diode laser absorption sensors (Arroyo, M. P., et., 1993 ; Arroyo, M. P., et al., 1994 ; Baer, D. S., et al., 1993). However, it is not cleared whether the absorption measurement using diode laser sensor is applicable to spray flame or not. In general, turbulent combustion field or spray combustion restricts wavelength sweep frequency and path-length of diode laser beam especially because of the non-uniformity in gas temperature and species concentration. Therefore, measurement of large line strength with high temporal resolution is needed for measurement of combusting field, which fluctuates temporally as well as spatially.

The objective, therefore, is to establish the non-intrusive temperature measurement method using diode laser absorption sensor and to demonstrate its possibility of application to the liquid fuel combustion environment.

2. Measurement Theory

The measurement technique is based on the absorption of monochromatic near-IR laser radiation. The transmission of a probe beam of light through absorbing medium follows the Beer-Lambert relation as follows

$$T=\left(\frac{I}{I_0}\right)_\nu=\exp(-k_\nu L)$$
$$=\exp\left(-P\sum_{j=1}^{K}X_j\sum_{i=1}^{N_j}S_{i,j}(T)\,\Phi_{\nu,i,j}L\right) \quad (1)$$

where. L is path-length in the medium, I_0 is the incident intensity of probe beam, I is intensity after propagation through a length L of the absorbing medium, and k_ν is spectral absorption coefficient at frequency ν. The spectral absorption coefficient (cm^{-1}) comprising N_j overlapping transitions in a multi-component environment of K species can be expressed as right hand term. P(atm) indicates the total pressure of the absorbing species, X_j is the mole fraction of j species, S_{ij}(T) (cm^{-2}/atm) is the line strength transition i and species j. and $\Phi_{\nu,i,j}$ (cm) is the respective line shape function of transition i at frequency ν. Its spectral integral over frequency is unity. The strategy for measuring the temperature of the gas is based on the intensity ratio of two-absorption line. The partial pressure of gas can be obtained from Eq. (1) if the temperature, line strength, and path-length are given. Line strengths and positions for absorption species at each temperature have been taken from HITEMP (high-temperature version of HITRAN) and HITRAN98. Detail explanation is described in previous study (Choi, G. M., et al., 2002).

This line-of-sight method may represent a significant problem and require complex reconstruction algorithms for measurement of unsteady flows such as liquid-gas 2 phase reacting flow. However, a reasonable estimate of the average value of gas mole fraction or temperature in the liquid fuel flames would provide useful information in present stage. Characteristics of selected H_2O transitions and experimental conditions are shown in Table 1 and Table 2.

Table 1 Characteristics of absorption transitions

Species	Transition Frequency (Wavenumber)	Line Strength (1200K) (cm^{-2}/atm)	Transition
H_2O	2049.94 nm (4878.193 cm^{-1})	1.08E-3	(021)-(010)
	1996.76 nm (5008.101 cm^{-1})	4.91E-4	(011)-(000)

Table 2 Experimental conditions

	Upper port	Lower port
Inlet velocity (m/s)	0.6	0.6
Fuel	n-decan	City gas
Equivalence ratio	0.56	0.7

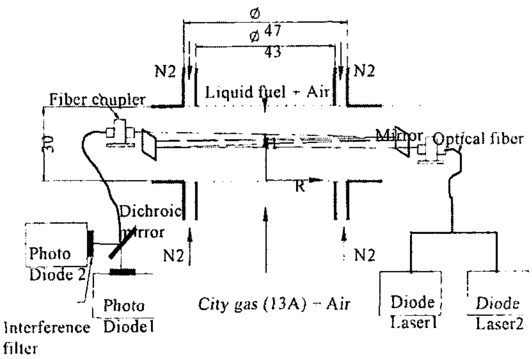

Fig. 1 Experimental schmatic for the in-situ combustion measurements

3. Experimental Setup

Figure 1 shows the experimental setup for absorption coefficient measurement using diode laser sensor system including liquid-gas 2 phase counter flow flame burner. There are two DFB lasers (5 mW), operating near 1996 nm and 2050 nm, respectively. The wavelengths of DFB lasers were scanned over selected H_2O transitions shown in Table 1. The repetition rate of sweeping frequencies was 1.5 kHz. The output of each laser was split into three fibers, one for direct absorption measurement, one for reference beam and one for fiber ring interferometer (FSR = 1.09 GHz). The direct absorption measurements are carried out using two optical fibers, one from diode laser source and the other from light collecting fiber, which is connected to beam splitter (1996/2050 nm), and electronics. The target flame is the liquid-gas 2-phase counter flow flame. From the upper port, n-decane ($C_{10}H_{22}$) with air is supplied, and from the lower port, city gas and air premixed mixtures are supplied. To stabilize the liquid gas 2-phase flame, liquid fuel is injected into the stable city gas and air-premixed counter flow flame. Liquid fuel is supplied by free fall from droplet chamber. We supplied relatively large droplet to the gaseous flame region in order to observe the interaction between droplets and gaseous flame in the wide droplet diameter range. The premixed liquid-air and city gas-air flows are supplied from the inner tube (43 mm diameter). On the other hand, nitrogen is supplied from outer tube (47 mm diameter) to protect mixing with surrounding air. This nitrogen jet also protects flame attachment in the burner rim. In present work, we set the distance between burner ports to 30 mm (40/s strain rate).

Counter flow flame without liquid fuel is formed at H = 12 mm, and the flame shape is almost 2-dimensional flat flame. Refraction surface is observed at h = 18 mm, which is estimated as the stagnation plane between the exhaust gas at high temperature and the air injected at the normal temperature from upper port. It is estimated that the exhaust gas from the premixed flat flame is accelerated by thermal expansion through combustion. The probe beams for the direct absorption measurements were reflected 5 times by mirrors to make high absorption path/volume ratio. Because the exhaust gas exists between flame front and stagnation plane, absorption coefficient measurement is carried out at H = 15 mm and 17.5 mm.

4. Results and Discussions

Figure 2 shows the single sweep of H_2O obtained from 2 dimensional premixed flame without liquid fuel in the counter flow burner. The residual shows the difference between the direct absorption data and the Voigt profile. The H_2O transition was (021)-(010) transition at 4878.193 cm^{-1}. Supplied equivalence ratio and position of measured cross section were 0.7 and H = 15 mm, respectively. The temperature obtained by diode laser absorption sensor was 1176.70 K. In present work, it is difficult to obtain precise species concentration because of the difficulty in the estimation of path-length. However, because the gas temperature is determined by the line strength ratio of two transitions, we can take path-averaged gas temperature.

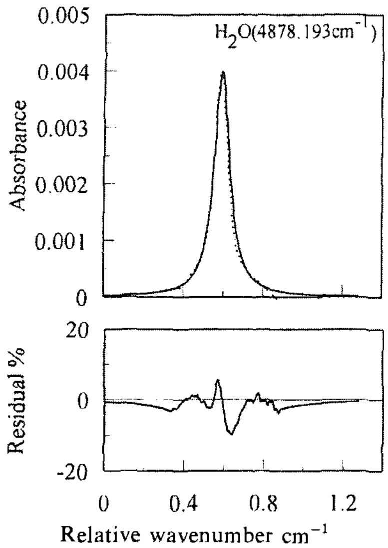

Fig. 2 Absorbance coefficients and residual distribution in the post flame of gaseous premixed flame

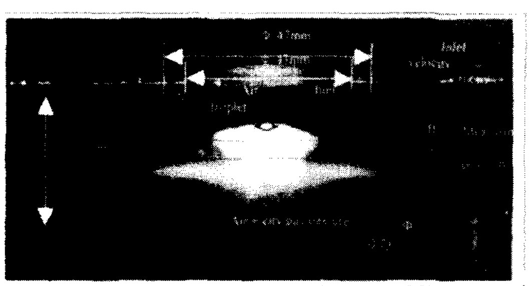

Fig. 3 Direct photography of liquid-gas 2-phase counter flow flame

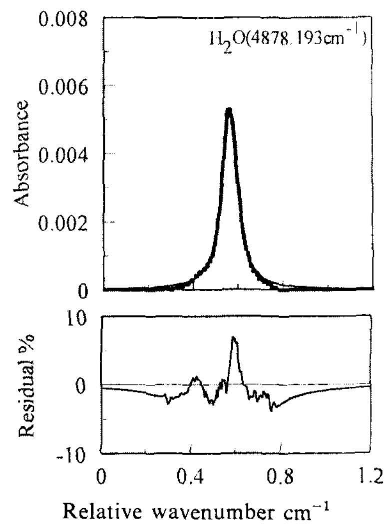

Fig. 4 Absorbance coefficients and residual distribution in the spray flame

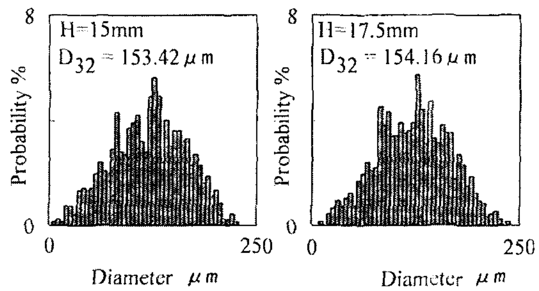

Fig. 5 Droplet diameter distributions

Figure 3 shows the direct photography of liquid-gas 2-phase counter flame, of which shutter exposure time is 1/15 second. Measuring cross section and experimental condition are also indicated in the photography. The gaseous flame shape is distorted due to intrusion of the fuel droplets and penetration of large droplets into the reaction zone. Luminous flames are observed near stagnation plane due to liquid fuel combustion.

Combustion of single droplet and droplet groups occur in high temperature region above gaseous flame in diffusion flame mode. Pre-vaporization of droplets occurs in approaching spray flow in the high temperature region. This pre-vaporization sustains the diffusion flame though 0.5 of the supplied equivalence ratio of $C_{10}H_{22}$-air mixture. The vaporization of droplets in the high temperature region works as the source of fuel vapor for burning in diffusion flame mode. No combustion reaction occurs inside the large droplet group, and burning in diffusion flame mode occurs at only the periphery.

Figure 4 shows the single sweep of H_2O obtained from liquid-gas 2-phase counter flow flame and residuals between the direct absorption data and fitted Voigt profile. Measurement plane is at H=15 mm(A), and the H_2O transition was (021)-(010) transition at 4878.193 cm^{-1}.

Figure 5 shows droplet size distribution at each measuring region. Droplet size was measured by PDA system. It was found that the droplets distributed in the wide range, and its averaged diameter was about 154 μm regardless of the difference of measuring region. Even though these droplets exist in the measuring region, diode laser absorption probe beam was detected at receiving optical equipment without large beam steering. Because the probe beam diameter was about 1 mm in present work, it was possible to measure the absorption coefficient of spray flame region where droplets, of which mean diameter is 154 μm, are floating in the reacting flow. However, relatively large discrepancy was observed at center frequency of single sweep between direct absorption data and fitted Voigt profile. This discrepancy is ascribed to beam steering due to droplets in the laser beam path. We used fitted Voigt profile for obtaining absorption coefficient integral in the measurement of temperature.

Figure 6 shows the time series temperature measured by diode laser sensors in liquid-gas 2-phase counter flow flame. At measuring position (A), the measured mean temperature and its RMS value were 1183.10 K and 18.52 K, respectively. On the other hand, at the measuring position (B), mean temperature and its RMS value were 1227.93 K and 22.76 K, respectively. The measured mean temperature as well as its RMS value at the B position was higher than those at A region. Higher mean temperature at B region is ascribed to thicker spray flame zone as shown in direct photography of Fig. 3. As the droplet group seems to burn in the diffusion flame mode, the temperature of liquid-gas 2-phase flame is not so higher than gaseous flame. We can confirm that the temperature measurement using diode laser absorption sensor is possible even in liquid fuel flame environment although it needs additional improvement for quantitative measurement.

We did not always succeed in absorption coefficient measurement in the liquid-gas 2-phase counter flow flame. There were failure cases in obtaining absorption coefficients.

Figure 7 shows time series temperature signals measured at B position. OH luminescence intensity and Mie scattering intensity of droplets were measured simultaneously. For simultaneous measurement of OH luminescence and droplet Mie scattering using a CCD camera, image-dividing optics was used. Ar^+ laser (central wavelength=

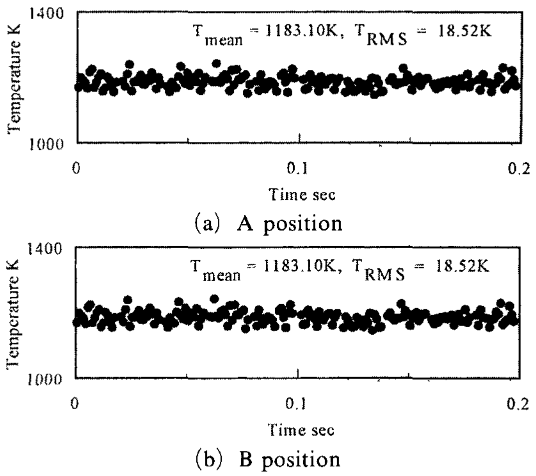

Fig. 6 Time series temperature signal measured by diode laser sensors in the spray flame region of liquid-gas 2-phase counter flame region

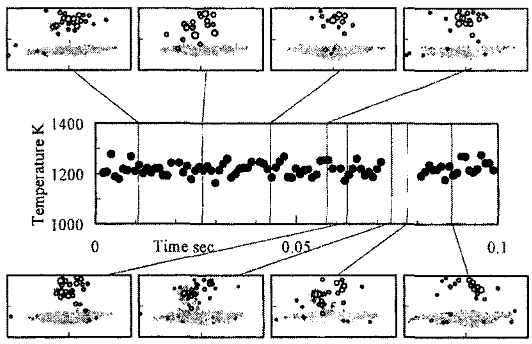

Fig. 7 Time series temperature signal with OH luminescence and droplet Mie scattering images in liquid-gas 2-phase counter flow flame

514.5 nm, 1 w) was used for the laser sheet Mie scattering technique. An unintensified 256×256 CCD camera recorded the images of Mie scattered light. The luminescence images of the OH radical were also recorded by same CCD camera.

Interference filter, of which central frequency was 308.5 nm, was used for OH luminescence images. In the images, gray region indicates OH luminescence. And circle and its size indicates the existence of droplet and its relative diameter, respectively. We can observe no temperature-plotted region between 0.07−0.08 second. We can not obtain line intensity of transitions from direct absorption signal in this region. In this region, OH luminous area was extended wider compared to other condition. These failures were ascribed to the large refraction of diode laser probe beam in the spray group combustion region above gases premixed flame. Additional investigation of diode laser absorption method is necessary to provide reliable information of the turbulent flame or spray flame.

5. Conclusions

Diode laser absorption sensor operating near 2.0 μm was developed. The system was applied to measure the gas temperature in the post flame of gaseous counter flow flame and in the spray flame of liquid-gas 2-phase counter flow flame. Diode laser absorption method succeeded in obtaining path-averaged temperature of liquid fuel combustion environment regardless of droplets of wide range diameter. The successful demonstration of time series temperature measurement in liquid-gas 2-phase counter flow flame gave us motivation of trying to establish effective control system in practical combustion system. Path-averaged temperature measured spray flame above liquid-gas 2-phase counter flow flame showed qualitative reliable results. It was found that these results demonstrated the ability of real-time feedback from combustor's inside using non-intrusive measurement as well as the possibility of application to practical combustion system. However, additional investigation of diode laser absorption method is necessary to provide reliable information of the turbulent flame or spray flame.

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