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Quantitative Temperature Measurement of High Pressure $CH_4/O_2/N_2$ Laminar Flames Using Laser Induced Thermal Grating Spectroscopy (LITGS)

HAYAKAWA, Akihiro[1], LOWE, Steven[2], TAKEUCHI, Kiyonori[1], YAMAGAMI, Tomohisa[1]*, KUDO, Taku[1], GAO, Yi[2],
HOCHGREB, Simone[2], KOBAYASHI, Hideaki[1]

[1] *Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai, Miyagi 980-8577, Japan*
[2] *University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, United Kingdom*

Abstract : Laser diagnostics for quantitative measurements of temperature are important in high pressure and high temperature environments. In this study, Laser Induced Thermal Grating Spectroscopy (LITGS) is employed for oxygen enriched $CH_4/O_2/N_2$ laminar flames at elevated pressure. The wavelength of the pump beam was set for OH excitation. LITGS is a promising laser diagnostic for quantitative measurements of temperature at high pressure because the magnitude of LITGS signal increases with pressure due to higher quench rates and stronger density perturbations in more dense mixtures. As a result, LITGS signal can be successfully acquired at 0.5 MPa for various equivalence ratios. The derived temperature was close to the adiabatic flame temperatures for each condition and the maximum derived temperature was higher than 2600 K. Therefore, LITGS is also a promising diagnostic for quantitative temperature measurements in high temperature flames, such as rocket motors.

Keywords : Laser diagnostics, LITGS, Temperature, Quantitative measurement, High pressure

1. Introduction

Internal combustion engines, such as rocket motors, reciprocating engines and gas turbine combustors, operate under high pressure conditions. Therefore, it is essential to understand combustion characteristics at high pressure in order to improve combustion systems. Temperature is a key parameter in flames and as a result, a number of temperature measurement techniques have been developed. However, quantitative temperature measurements in high pressure environments by conventional laser diagnostics is, in general, difficult because of the increase in chemiluminescence, quenching rate, broadening of the absorbing spectrum etc.

On the other hand, Laser Induced Thermal Grating Spectroscopy (LITGS) is a promising diagnostic for quantitative temperature measurements at high pressure [1]. LITGS signal increases with an increase in pressure because LITGS signal intensity relates to the quenching process of excited molecules. Latzel et al. [1] could measure flame temperatures in CH_4/air mixtures up to 40 atm. Sahlberg et al. [2] obtained LITGS signals at atmospheric pressure using infrared absorbing spectrum of ethylene and H_2O.

The purpose of this study is to develop LITGS for high pressure and high temperature flames.

2. Theory of LITGS

LITGS provides quantitative temperature measurements at the crossing point of two incident pump lasers. Figure 1 shows a schematic of the point where a grating pattern is generated by two crossing incident lasers. Two crossing pump beams generate an interference grating pattern at the crossing point. When the wavelength of the pump beams is set to the specific wavelength for molecular excitation of a species of interest, the molecules in the regions of high intensity within the grating absorb incident energy from the short laser pulse. The absorbed energy is subsequently released by collisional quenching as heat. The heat release generates a stationary temperature (density) perturbation across the interacting region. Rapid density changes also create an acoustic wave that propagates through the grating towards normal direction of the grating pattern and the acoustic wave generates a dynamic density perturbation. These two density perturbations interact with each other and lead to an increase and a decrease in the overall amplitude of the density perturbation. When another beam, called the probe beam, is introduced to the interaction region at the Bragg angle, Bragg diffraction occurs when the density perturbation from the stationary thermal grating and the standing acoustic wave constructively interfere and it is detected as LITGS signal.

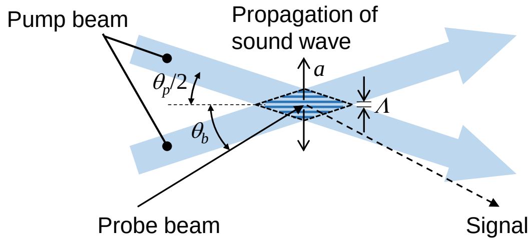

Fig. 1 Schematic of LITGS. Here, θ_p is incident angle of the pump beams and θ_b is the Bragg angle.

Since the oscillation frequency of the resulting signal, f_{osc}, is caused by the propagation of the acoustic wave and its interaction with the stationary density perturbation, the oscillation frequency is related to the speed of sound at the crossing point, a, and the grating spacing, Λ, as Eq. (1) [3],

$$f_{osc} = \frac{a}{\Lambda} . \tag{1}$$

Here, the speed of sound can be described by Eq. (2),

$$a = \sqrt{\frac{\gamma k_B T}{m}} . \tag{2}$$

where, γ, k_B, T and m are the specific heat ratio, the Boltzmann constant, temperature and the mean molecular weight, respectively. From Eqs. (1) and (2), the temperature can be described as a function of the oscillation frequency, as Eq. (3),

$$T = \frac{m}{\gamma} \cdot \frac{\Lambda^2}{k_B} f_{osc}{}^2 . \tag{3}$$

The grating spacing can be determined by the wavelength of the pump beam and incident angle. As shown in Eq. (3), if the mean molecular weight and the specific heat ratio are known, the temperature at the crossing point can be derived from the oscillation frequency of the measured LITGS signal.

3. Experiment

Figure 2 shows a schematic of the experimental setup in this study. High pressure combustion experiments were carried out using the high pressure combustion test facility at the Institute of Fluid Science, Tohoku University. Details of the test facility was described elsewhere [4]. A Nd:YAG laser (Spectra-physics, GCR-250) and a dye laser with a frequency doubler (Lumonics, HD500+HT1000) were employed to obtain a pump laser beam at a wavelength of 282.929 nm for OH excitation. The energy of the laser for OH excitation is about 11 mJ. The laser beam was separated by a 50/50 beam splitter and then the beams is introduced to a focusing lens having 1000 mm focal length. A CW

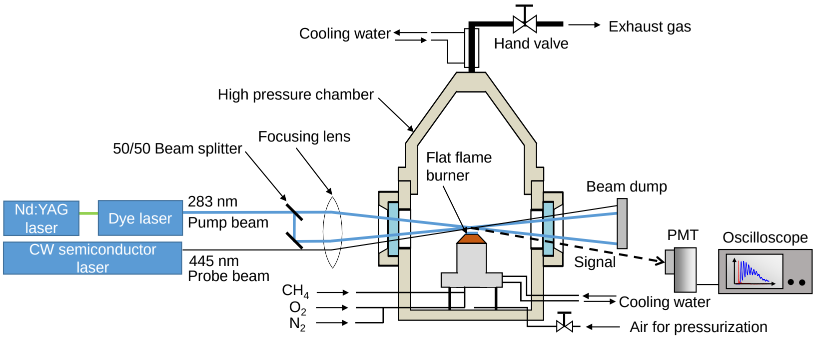

Fig. 2 Experimental setup for high pressure LITGS measurement.

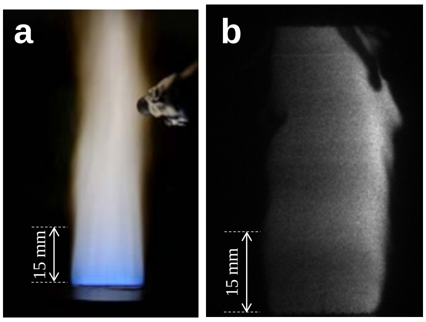

Fig. 3 Flame images: (a) direct photograph; (b) OH-PLIF.

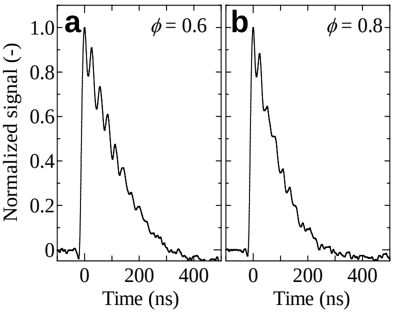

Fig. 4 Example of LITGS signal: (a) $\phi = 0.6$; (b) $\phi = 0.8$.

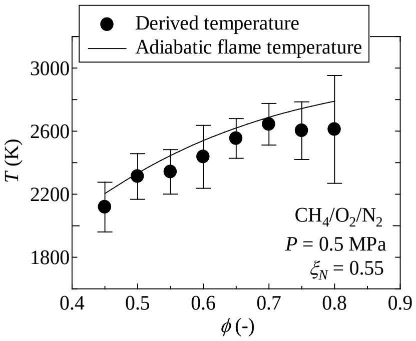

Fig. 5 Relationship between derived temperature, T, and ϕ.

semiconductor laser whose wavelength is 445 nm (RGB laser system, NovaPro PB 445-1000 MM) was employed as the probe beam. The power for the probe beam was set to 810 mW. The beams pass through the chamber are stopped by a beam dump. The diffracted signal was detected by a photo multiplier tube (PMT, Hamamatsu photonics, R928). The LITGS signal was acquired using an oscilloscope at a sampling rate of 5 GS/s and 150 MHz bandwidth (GwInstek, GDS-3154). At least 30 single shots of LITGS signal were acquired for each condition.

A flat flame burner was employed in this experiment. The burner is designed as a calibration burner for high pressure and high temperature flames and the details are described elsewhere [5]. The diameter of the burner outlet is 19 mm. The burner has 240 holes of diameter 0.7 mm. The measurement point was 15 mm downstream from the center of the burner outlet. CH_4 is used as fuel, O_2 is used as oxidizer and N_2 as a diluent. The flow rates are controlled using an orifice flow meter and a mass flow meter. The equivalence ratio, ϕ, was varied from 0.45 to 0.8. The dilution ratio, ξ_N, is determined as the molar ratio of N_2 in the $N_2 + O_2$ mixture, and was set to 0.55 in this study. The dilution ratio used is smaller than the value 0.79 corresponding to air, so the mixture examined in this study was oxygen enriched. The unburnt mixture temperature was set to 298 K and the pressure, P, was set to 0.5 MPa.

Figure 3 shows an instantaneous direct photograph and OH-PLIF images of the $CH_4/O_2/N_2$ flame at $\phi = 0.8$. As shown in Fig. 3a, intense chemiluminescence can be observed 15 mm downstream of the burner outlet. As shown in Fig. 3b, OH-PLIF can be detected at the measurement point, confirming the existence of OH in the region at which the LITGS thermal grating is written. The laser attenuation is also observed in Fig. 3b.

Figure 4 shows representative LITGS signals for conditions where $\phi = 0.6$ and 0.8. The LITGS signals shown in Fig. 4 were smoothed using a moving average filter and the signals were normalized by the maximum value of the LITGS signal. As equivalence ratio increases, the LITGS signal decays faster and the amplitude of local peak becomes small, especially after the second local peak. The degree of thermalization of the medium decreases with the increase in equivalence ratio due to a decrease in the amount of collisional quenching as a result of an increase in flame temperature and corresponding decrease in density.

Figure 5 shows the relationship between derived temperature and equivalence ratio at $P = 0.5$ MPa and $\xi_N = 0.55$. Here, the values of γ and m used were obtained from the mixture composition at the equilibrium state. The derived temperature from the LITGS signal, T, was close to the adiabatic flame temperature and the maximum acquired temperature was higher than 2600 K. This result demonstrates that LITGS has the potential for quantitative temperature measurements in flames that operate in high pressure environments, such as a rocket motor.

4. Conclusions

Laser Induced Thermal Grating Spectroscopy (LITGS) has been employed for quantitative measurements of temperature in oxygen enriched $CH_4/O_2/N_2$ flames at high pressure. As a result, LITGS signals has been obtained successfully at 0.5 MPa and the derived temperature was close to the adiabatic flame temperature. In addition, temperatures over 2600 K can be evaluated successfully. Therefore, the potential for LITGS measurements in high temperature flames is demonstrated.

Acknowledgements

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References

1. H. Latzel, A. Dreizler, T. Dreier, J. Heinze, M. Dillmann, W. Stricker, G.M. Lloyd, P. Ewart, Appl. Phys. B. 67: 667-673 (1998).
2. A. -L. Sahlberg, D. Hot, J. Kiefer, M. Aldén, Z. Li, Proc. Combust. Inst. 36: in press (2016).
3. B. Williams, M. Edwards, R. Stone, J. Williams, P. Ewart, Combust. Flame. 161: 270-279 (2014).
4. H. Kobayashi, Exp. Thermal Fluid Sci. 26: 375-387 (2002).
5. K. Takeuchi, Y. Nunome, S. Tomioka, T. Tomita, T. Kudo, A. Hayakawa, H. Kobayashi, Proc. 54th Symp. (Japanese) Combust. (2016) (in Japanese).