Laser Induced Thermal Grating Spectroscopy (LITGS)によるトルエン/空気混合気の定量温度計測

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Quantitative Temperature Measurement of Toluene/air Mixture using Laser Induced Thermal Grating Spectroscopy (LITGS)

1. Introduction

Combustion in most internal combustion engines, such as gas turbine combustors, reciprocating engines and rocket motors, operates in high pressure environments to achieve high load combustion. To further improve combustors, it is essential to further our understanding of combustion phenomena at high pressure. Temperature is a key parameter in flames and many temperature measurement techniques have been developed. However, quantitative temperature measurement (especially at high pressure) by conventional laser diagnostics is, in general, difficult because of broadening of the absorption spectrum and an increase in the quenching rate. On the other hand, Laser Induced Thermal Grating Spectroscopy (LITGS) is anticipated as a laser diagnostics method that allows for quantitative temperature measurements at high pressure. LITGS has been attempted not only for non-reacting but also for reacting flows. Many other applications were described in a reviewed paper. Since LITGS signal intensity relates to the quenching process of excited molecules, it follows that the LITGS signal increases with an increase in pressure. Therefore, LITGS is a promising technique for the temperature measurements in high pressure flames. Previously, Latzel et al. obtained LITGS signal at high pressure (up to 40 bar). In this study, the accuracy of the derived temperature by LITGS for toluene/air mixtures at room temperature and pressures was investigated. Temperatures were evaluated for various pump energy and toluene mole fractions.

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2. Theory of LITGS

LITGS is laser diagnostics for the quantitative temperature measurement at the crossing point of two incident lasers. Figure 1 shows a schematic figure at the point where thermal grating is generated by two crossing beams. Two crossing pump beams generate an interference grating pattern at the crossing point. When the wavelength of these pump beams corresponds to the wavelength for molecular excitation of a species of interest, the species are exited and absorbed energy is subsequently released by collisional quenching as heat. The heat release generates a stationary temperature (density) perturbations across the interacting region. Rapid density changes also create an acoustic wave which propagates through the stationary density perturbations. These two density perturbations caused by stationary temperature perturbation and acoustic wave propagation interact with each other and lead to an increase and decrease in the overall amplitude of the density perturbation. When another beam, termed the ‘probe beam’, is introduced to the interaction region at the Bragg angle, Bragg diffraction occurs when the density perturbation is emphasized and it is detected as LITGS signal.

Figure 2 shows an example of LITGS signal. Since the oscillation frequency is caused by the propagation of the acoustic wave and its interaction with the stationary density perturbation, the oscillation frequency can be described by the speed of sound at the crossing point, \( a \), and the grating spacing, \( A \), as Eq. (1),

\[
 f_{osc} = \frac{a}{A}. 
\]

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

\[
 a = \sqrt{\frac{\gamma k_B T}{m}}. 
\]

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

\[
 T = \frac{m}{\gamma k_B^2} \frac{A^2}{f_{osc}^2}. 
\]

The grating spacing is determined by the wavelength and the incident angle of the pump beam. 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. Experimental setup

Figure 3 shows the schematic figure of the experimental setup in this study. The wavelength of the laser emitted from a pulsed Nd:YAG laser (Continuum, Surelite I-10) was converted to 308 nm by a dye laser (Sirah, Cobra-Stretch). The output
energy from the dye laser can be controlled between 1 - 12 mJ. The beam was separated by a 50/50 beam splitter and then introduced into the focusing lens having 500 mm focal length. A CW semiconductor laser with wavelength of 671 nm was used for the probe laser. The diffracted beam (LITGS signal) was introduced into a photomultiplier tube (PMT) and the signal was recorded by a PC oscilloscope (PicoScope 6000) at a maximum sampling rate of 5 GS/s and 8-bit precision.

Toluene vapour is used as the tracer species. Air flow rates were controlled by mass flow controllers (MFC, Alicat). One of the air flows was introduced into the toluene bubbler. It was assumed that the partial pressure of the toluene at the outlet of the bubbler was at the saturated vapour pressure. The toluene concentration can be controlled by the flow rates of two air lines. The toluene/air mixture was introduced to a tube of 22 mm diameter. The temperature inside the bubbler and the tube outlet of the tube were measured using a thermocouple. The temperature at the tube outlet remained at around 292 - 293 K throughout all experiments.

4. Experimental results

Figure 4 shows the relationship between the derived temperature from the LITGS signal, $T$, and mole fraction of toluene, $X_t$, for various incident pump beam energies. For low mole fraction cases, the derived temperature from the LITGS signal is close to the temperature measured by the thermocouple. However, the derived temperature increases as the toluene concentration increases. In addition, derived temperature also increases with an increase in the pump laser energy at a fixed $X_t$. The temperature rise may be attributed to an excessive amount of absorption of the pump beam energy into the medium.
A semi-empirical equation indicating the influence of the pump power and mole fraction on the derived temperature was evaluated considering Beer-Lambert's law. According to the Beer-Lambert's law, the absorbed irradiance by an absorbing medium, $\Delta I$, is given by Eq. (4),

$$
\Delta I = I_0 \left[ 1 - \exp \left( -\frac{\sigma P_0 N_A L X_t}{R T_0} \right) \right].
$$

(4)

Where, $I_0$, $\sigma$, $P_0$, $N_A$, $L$, $R$, $T_0$ were irradiance of the pump beam upstream of the absorbing medium, absorption cross section, pressure, Avogadro number, thickness of the absorbing medium, gas constant and the mixture temperature at the tube outlet measured by the thermocouple, respectively. In this study, the order of $\sigma P_0 N_A L X_t / (R T_0)$ was much smaller than unity, so Eq. (4) could be simplified to Eq. (5),

$$
\Delta I = K_{ab} I_0 X_t.
$$

(5)

Here, $K_{ab} = \sigma P_0 N_A L / (R T_0)$. Since the temperature rise by the incident laser is considered to relate to the absorbing energy, the temperature rise by the incident laser can be described by Eq. (6),

$$
\frac{\Delta T}{T_0} = K_{ab} K_{th} I_0 X_t.
$$

(6)

Where $\Delta T$ is the difference between the derived temperature and the temperature at the tube outlet and $K_{th}$ is the coefficient indicating the amount of energy used for temperature rise. The relationship between $\Delta T / T_0$ and $I_0 X_t$ is shown in Fig. 5. The results show that the $\Delta T / T_0$ increases with an increase in $I_0 X_t$. The line in the Fig. 6 shows the linear fit of the experimental results with the error bars falling over the fit. Eq. (6) shows the subsequent relationship between $\Delta T / T_0$ and the value of the irradiance of the pump beam and the concentration of the tracer molecule, which should remain small for highly precise temperature measurements.

5. Concluding remarks

In this study, laser induced thermal grating spectroscopy (LITGS) was attempted for the measurement of temperature in continuously flowing toluene/air jets. As a result, the following results were obtained:

1. The derived temperature increases with an increase in the toluene concentration and the incident laser energy because of the increase in the absorption of the laser energy to the absorbing media.
2. A semi-empirical equation showing the relationship between the temperature rise and the product of incident laser irradiance and toluene concentration is derived. The measured temperature increases with an increase in the value of the product of pump energy and concentration. The derived semi-empirical relationship between temperature rise and the product of the beam intensity and tracer concentration fits experimental data.
3. For a highly precise temperature measurements, the irradiance of the incident laser and mole fraction of tracer molecule should be small.

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References


