

In-Cylinder Temperature Measurements Using Laser Induced Grating Spectroscopy and Two-Colour PLIF

Blane Scott, Christopher Willman, Ben Williams, Paul Ewart, and Richard Stone
University of Oxford

David Richardson
Jaguar Land Rover Limited

ABSTRACT

In-cylinder temperature measurements are vital for the validation of gasoline engine modelling and useful in their own right for explaining differences in engine performance. The underlying chemical reactions in combustion are highly sensitive to temperature and affect emissions of both NO_x and particulate matter. The two techniques described here are complementary, and can be used for insights into the quality of mixture preparation by measurement of the in-cylinder temperature distribution during the compression stroke. The influence of fuel composition on in-cylinder mixture temperatures can also be resolved. Laser Induced Grating Spectroscopy (LIGS) provides point temperature measurements with a pressure dependent precision in the range 0.1 to 1.0 % when the gas composition is well characterized and homogeneous; as the pressure increases the precision improves. The well-established method of Two-Colour Planar Laser-Induced Fluorescence, TC-PLIF allows 2-D temperature distributions to be determined from measurement of fluorescence signals at two different wavelengths. However, the challenge with PLIF is making the qualitative temperature measurements quantitative, so simultaneous LIGS measurements have been used for *in situ* calibration.

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INTRODUCTION

Within internal combustion engines, the in-cylinder temperature has a profound effect on many processes including mixture preparation, pollutant formation and combustion performance. The formation of NO_x and particulate matter is highly sensitive to local in-cylinder temperatures and the rates of chemical reactions that dominate combustion are also highly temperature dependent. In gasoline engines, sites of auto-ignition that can lead to engine knock are dictated by the temperature of the unburned gas during compression [1]. Knock can be particularly damaging in modern, highly boosted Gasoline Direct Injection (GDI) engines, potentially leading to catastrophic failure [2]. For these reasons, the reliable measurement of in-cylinder temperature with high accuracy and precision is of great interest to engine manufacturers, especially for model validation, and in particular when emissions or auto-ignition are being modelled.

Conventional methods for in-cylinder temperature measurements involve the use of fast response thermocouples that can physically affect the measurement environment and provide limited spatial resolution. Therefore, non-intrusive optical and laser-based methods have been developed for in-cylinder gas thermometry. Many of these techniques measure the temperature of a gas at a single 'point' in the combustion chamber. This is usually a small volume of gas in the

order of cubic millimetres where two or more laser beams interact. However, 2D or 3D measurements are desirable in order to identify any temperature structure that may be present.

Planar Laser Induced Fluorescence (PLIF) is a well-established laser-based technique that can provide 2-D measurements of in-cylinder temperature, air-fuel distribution and fuel concentration [3]. To quantify PLIF measurements, external calibration is required at known conditions of pressure, temperature and composition. However, these conditions are difficult to replicate under fired conditions, leading to greater measurement uncertainties.

In this work, Laser Induced Grating Spectroscopy (LIGS) has been used for in-cylinder gas thermometry, providing point temperature measurements with high precision. This technique has been shown to achieve measurement uncertainties in the range of 0.1 to 1 % [4]. The precision of the measurements is shown to increase with pressure, which is a clear advantage for engine applications.

In the following sections the LIGS and PLIF techniques are described and their advantages and limitations are discussed. The engines and optical setup used in this work are then described. Preliminary measurements with LIGS demonstrate its ability to resolve small variations in temperature during engine warm-up. Finally, LIGS

measurements are used to calibrate 2-D PLIF temperature distributions *in situ* under motoring and firing conditions for varying air-fuel ratios.

OPTICAL DIAGNOSTICS FOR IN-CYLINDER THERMOMETRY

The use of optical diagnostic techniques to measure engine-relevant parameters such as temperature and composition within combustion environments has been thoroughly reviewed [5], [6], [7], [8]. Two techniques which have seen widespread application to thermometry in internal combustion engines are Planar Laser-Induced Fluorescence, PLIF, and Coherent Anti-Stokes Raman Scattering, CARS.

PLIF thermometry utilises the temperature dependence of either the absorption spectrum for 2-line excitation PLIF [9], [10], [11], or the fluorescence spectrum for 1-colour [12], [13] or 2-colour detection PLIF [12], [14], [15], [16] of a molecular tracer such as toluene, acetone or 3-pentanone. In-cylinder thermometry with PLIF has demonstrated precisions of 2-5 % [11], [13], [14], [16] for 2-dimensional measurements with a spatial resolution of the order of 100 μm . With suitable choices of tracer, PLIF thermometry may also be extended to perform simultaneous compositional measurements [3] e.g. for exhaust residuals [17] or fuel/air ratio [10], [18]. Each PLIF technique requires calibration in order to accurately derive temperature from the recorded signals, typically by performing measurements under conditions of known composition, pressure and temperature.

CARS is a four wave mixing technique probing the thermal populations of rotational or vibrational energy levels within a target species. The spectrally resolved signal contains many peaks, whose relative intensities encode information about the Boltzmann population of the levels involved. Fitting a theoretical spectrum to the signal permits the derivation of temperature. For an in-depth review of CARS see reference [19], CARS also features in a review of nonlinear optical techniques applicable to combustion diagnostics [20].

Vibrational levels of CARS target molecules such as N_2 that have large energy gaps have very small thermal populations at temperatures around 300 K. Accordingly, vibrational CARS is typically employed for measurements at elevated temperatures, becoming most sensitive above 1000 K. Single-shot CARS can be performed by replacing the narrow bandwidth Stokes beam, scanned in frequency over time, with a broadband laser. The precision of such measurements is typically limited by noise arising from the modes of the broadband Stokes laser competing for gain, leading to fluctuations in spectral intensity. Use of a modeless broadband laser eliminates this source of noise and can improve the precision of CARS for flame temperature measurements to around 2 % [21], [22], [23].

At temperatures below 1000 K, the closely spaced rotational energy levels of the ground vibrational state have significant thermal populations. Rotational CARS is therefore suited to performing measurements at temperatures relevant to the in-cylinder conditions of this work, during the compression stroke prior to ignition.

Precisions of 3 - 5 % have been achieved with rotational CARS [24], [25], [26], [27] and evaporative cooling effects have been studied [28], [29].

As is the case for both CARS and PLIF measurements, temperatures derived from optical methods which rely on an intensity measurement are susceptible to noise arising from fluctuations in laser pulse energy or spectral intensity, scattered light and other background light sources. In contrast, the LIGS technique derives temperature from the frequency of temporal oscillations in the signal intensity. Noise fluctuations that perturb the intensity of the signal typically have little effect on the derived oscillation period. As such, temperature measurements with LIGS are inherently less sensitive to intensity fluctuations. Combined with the fact that frequencies can be measured with high precision, LIGS temperature measurements can have significantly higher precision than alternative optical methods.

LIGS thermometry has been performed in many combustion environments, including premixed methane/air flames [30], in high-pressure sooting flames [31], in combustion engines [4] and in flash-boiling sprays [32]. Assuming the conditions of a given environment are known, the accuracy (deviation from the nominally 'correct' value) and precision (variability in the results of repeated measurements under identical conditions) of the LIGS technique may be quantified. Measurements in a static pressure cell under optimal conditions of high pressure (40 bar) and low temperature (300 - 400 K) have demonstrated the potential of LIGS to measure temperatures with both high accuracy (0.42 %) and high precision (0.16 %) [33]. The quoted accuracy of 0.42 % was determined by comparison of the mean temperatures derived from 20 individual LIGS signals at each of 9 temperatures across the 300 - 400 K range, to the temperatures reported by a two-point calibrated K-type thermocouple mounted in the wall of the cell. The quoted precision of 0.16 % represents the standard deviation of the residuals of the 180 derived temperatures about the corresponding mean temperatures.

The above work uses resonant absorption of the pump beams to produce thermal gratings. By selecting a pump wavelength away from resonance with any absorption features of the gas mixture, electrostrictive gratings can be used to perform LIGS measurements. The theory and experimental application of electrostrictive gratings have been summarized in [34], [35] and the optimal accuracy (< 1 %) and precision (0.5 %) of electrostrictive LIGS measurements has been evaluated [36]. While the non-resonant nature of electrostrictive gratings permit measurements in air [37], the lower pump pulse intensities required for thermal LIGS and ready availability of absorbing species in a combustion engine environment motivate the use of thermal LIGS in this work and electrostrictive LIGS will not be further discussed.

Laser-Induced Grating Spectroscopy, LIGS

For a detailed description of the underlying physics of LIGS, the reader is referred to the review of four wave mixing techniques [20] and the two established theoretical descriptions of LIGS grating formation [38], [39], [40], [41]. To summarise, the LIGS technique can be understood as follows.



LIGS thermometry derives temperature from a measurement of the sound speed in a gas. Absorption of energy from a pair of laser pulses perturbs the local density to form a thermal grating and generates acoustic waves, which modify the density perturbation over time. Directing a probe beam onto the grating and recording the scattered signal allows the evolution of the grating to be monitored and used to derive the local sound speed and therefore temperature.

To form the grating, two short duration laser pulses (1 - 10 ns) of wavelength ' λ ' are crossed at a small angle, θ , to create an interference pattern of high and low intensity fringes separated by the grating spacing, Λ ,

$$\Lambda = \frac{\lambda}{2\sin(\frac{\theta}{2})} \quad (1)$$

The target molecules are electronically excited at the high intensity fringes and deposit this energy, via collisional quenching with the surrounding gas molecules, in the form of heat. This localized heating perturbs the local temperature and pressure, leading to two distinct density perturbations. Firstly, the temperature rise creates a 'thermal grating' with minima of density at the high intensity fringes. Secondly, the rapid increase in pressure leads to counter-propagating sound waves which sum to form a standing wave. The acoustic oscillations modulate the density perturbation of the thermal grating as the standing wave moves in and out of phase with the stationary thermal grating contribution.

The evolution of the grating can be recorded by scattering a probe beam off the grating onto a detector. The intensity of the scattered signal depends on the magnitude of the periodic density perturbation and therefore is modulated at a frequency, f_{osc} , determined by the local sound speed, c_s ,

$$f_{osc} = \frac{c_s}{\Lambda} \quad (2)$$

The probe wavelength, λ_{probe} , may be freely chosen provided the beam is incident on the grating at the Bragg-scattering angle, ϕ_B , defined by,

$$\lambda_{probe} = 2\Lambda \sin \phi_B \quad (3)$$

The scattered signal forms a coherent laser-like beam, aiding in discrimination of the signal from incoherent sources of intensity noise, and follows the temporal evolution of the grating: a single-sided, exponentially decaying signal modulated at a frequency given by ' f_{osc} ' [Figure 1].

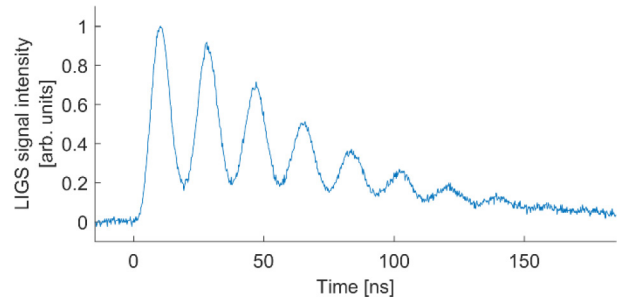


Figure 1. Temporal evolution of a typical single-shot LIGS signal for excitation at time zero, recorded in a static cell at 1.7 bar.

The decay rate of a LIGS signal depends on the diffusion rate of the gas molecules and therefore decreases with increasing pressure. At higher pressures, the longer signals contain a greater number of oscillations, allowing the oscillation frequency to be determined with increased precision.

Measurement of the oscillation frequency allows the sound speed to be determined, given knowledge of the grating spacing, Λ . The isentropic sound speed is then related to temperature, for the case of an ideal gas, by,

$$c_s = \sqrt{\frac{\gamma k_B T}{m}} \quad (4)$$

where γ is the ratio of specific heats at constant pressure to constant volume, m is the mean molecular mass and k_B is Boltzmann's constant. Given knowledge of the local gas composition, γ/m can be calculated and temperature can be derived from a measured oscillation frequency,

$$T = \frac{m\Lambda^2}{\gamma k_B} f_{osc}^2 \quad (5)$$

As the intensity of the signal does not feature directly in the derivation of temperature, only via measurement of the oscillation frequency, the precision is not directly limited by intensity noise.

The main sources of uncertainty in a LIGS temperature measurement are instead the grating spacing, Λ , and the local gas composition, γ/m . Derivation of Λ from measurements of f_{osc} under known temperature and composition is more accurate than geometric calculation of Λ and once known, the fixed value of Λ can be applied to further measurements.

For in-cylinder measurements, unknown variation in the amount of exhaust residuals, air and fuel at the LIGS measurement region leads to uncertainty in the derived temperature due to the dependence on the mean value of γ/m . The derived temperature is relatively insensitive to the exchange of exhaust residuals for a stoichiometric fuel/air mixture [4] as the respective γ/m ratios differ by only 6 %.

The error associated with e.g. assuming zero residuals when the actual value is 10% would be an error in the derived temperature of 0.6%. In contrast, the γ/m value for a typical fuel/air mixture is 1.04, and the error associated with assuming a value of 1.0 would be an error in the derived temperature of 0.6%.

two-component gasoline surrogate fuel used in this work is a factor of 4.4 smaller than that of air. Uncertainty in the fuel concentration therefore dominates the error in derived temperature. Previous work with the AJ133 engine placed an upper limit of 23% variability in the fuel concentration and this leads to uncertainty in temperature owing to compositional variations of less than 1.3% [42].

The derivation of temperature from a LIGS signal relies on the measurement of the frequency of the acoustic oscillations, for which there are two alternative approaches. Firstly, the Fourier transform of the recorded signal may be used to determine the frequency content of the signal. The resulting power spectrum of a LIGS signal contains a peak centred at the frequency of the acoustic oscillation, allowing rapid determination of ' f_{osc} '. Secondly, a theoretical LIGS signal may be fitted to the experimental data, determining the oscillation frequency as that which provides the best fit to the data. In this work, both the Fourier transform approach and fitting to a computational model developed previously [33] based on the theory of Paul et al. [40] were used.

Two-Colour Planar Laser-Induced Fluorescence, TC-PLIF

The populations of rotational and vibrational energy levels within a molecule are temperature-dependent and for certain molecules this leads to a fluorescence spectrum which varies with temperature. In the case of toluene, the fluorescence spectrum shifts to longer wavelengths as temperature is increased. The ratio of fluorescence intensities S_1/S_2 emitted over two different spectral windows, $\Delta\lambda_1$ and $\Delta\lambda_2$, therefore varies with temperature. This 'signal ratio' from two different wavelength regions (hence Two-Colour PLIF) can be calibrated to provide a measurement of temperature [14], [16], [43], [44], [45].

The fluorescence signal, S , (photons per pixel) detected during PLIF measurements is given by,

$$S = \frac{E}{h\nu} V_p n_{tr} \sigma \phi \frac{\Omega}{4\pi} \eta_{opt} \quad (6)$$

where E is laser fluence, h is Planck's constant, ν is pump laser frequency, V_p is the excitation volume imaged onto one pixel, n_{tr} is tracer number density, σ is the absorption cross section of the tracer at the pump wavelength, ϕ is the fluorescence quantum yield of the tracer, Ω is the solid angle subtended by the collection optics and η_{opt} is the transmission efficiency of the collection optics [11] [46]. The 'signal ratio' of TC-PLIF is given by,

$$\frac{S_1}{S_2} = C \frac{\phi(\Delta\lambda_1, T)}{\phi(\Delta\lambda_2, T)} \quad (7)$$

where ϕ is the fluorescence quantum yield as a function of wavelengths within a spectral window and temperature ($\Delta\lambda_i$, T) and C is a constant. The ratio method removes the requirement to measure several experimental parameters, such as tracer number density and laser fluence, since they are identical for both S_1 and S_2 and therefore

cancel during calculation of the ratio. This is advantageous for environments where the tracer number density is unknown or varies across the measurement region. This also removes the need for the tracer to co-evaporate with the base fuel, as required when considering fuel/air ratio measurements. The relative merits of this two-colour detection scheme and the detection of the total fluorescence intensity (one colour method) have been evaluated recently by Peterson et al. [12].

Practical application of the TC-PLIF technique involves exciting tracer molecules within a plane using a sheet of laser light and imaging the resulting fluorescence onto separate cameras, using filters to define a different spectral window for each camera. The two images are registered and the ratio of intensities at each pixel, potentially after spatial averaging to reduce noise at the expense of spatial resolution, provides the 'signal ratio'.

The TC-PLIF 'signal ratio' is typically calibrated in terms of temperature to remove the requirement for an accurate model of the fluorescence quantum yield, ϕ , by preliminary measurements under known conditions over the range of pressures, temperatures and compositions that are likely to occur for a given experiment. Such calibration methods can be very effective where the conditions of the experiment are well defined and match the calibration conditions [47]. Difficulties arise if there is any uncertainty in how the calibration conditions apply to the unknown conditions within the engine cylinder.

This issue is potentially resolved by calibrating the TC-PLIF 'signal ratio' *in situ* using an independent thermometry technique. In this work, this is achieved by simultaneously measuring the temperature at a well-defined location within the TC-PLIF images, ensuring that the calibration and measurement conditions are identical by definition. The accuracy of the TC-PLIF calibration is therefore reliant on the accuracy of the LIGS temperature measurement.

APPARATUS AND EXPERIMENTAL PROCEDURE

Optical Engine

Two single-cylinder DISI optical engines have been used for the results presented in this work. The first optical engine, based on a Jaguar Land Rover AJ133 engine (specifications listed in Table 1), was used for the data presented in the "Engine warm-up measurements" and "Temperature measurements over engine cycle" sections. A stainless steel section with four windows of 16 mm effective aperture at each quadrant was installed between the cylinder head and liner to provide optical access to the combustion chamber. A standard, flat-topped piston blocked the windows after 45 crank angle degrees before top dead centre (45° BTDC), restricting measurements to before this point. For the results shown in the "Temperature measurements over engine cycle" section, a piston with a rectangular slot was manufactured to allow the transmission of the pump and probe beams when the piston was at top dead centre, which allowed measurements to be made for a full cycle. The 'slotted' piston crown was shaped to compensate for the missing volume to maintain the same compression ratio as the