



Experimental cross-correlation nitrogen Q-branch CARS thermometry in a spark ignition engine

R.D. Lockett^{*,1}, D. Ball, G.N. Robertson

Department of Physics, University of Cape Town, Rondebosch 7700, Republic of South Africa

ARTICLE INFO

Article history:

Received 26 July 2012

Received in revised form

8 January 2013

Accepted 20 February 2013

Available online 16 March 2013

Keywords:

CARS

Thermometry

Auto-ignition

Engine

Cross-correlation

ABSTRACT

A purely experimental technique was employed to derive temperatures from nitrogen Q-branch Coherent Anti-Stokes Raman Scattering (CARS) spectra, obtained in a high pressure, high temperature environment (spark ignition Otto engine). This was in order to obviate any errors arising from deficiencies in the spectral scaling laws which are commonly used to represent nitrogen Q-branch CARS spectra at high pressure. The spectra obtained in the engine were compared with spectra obtained in a calibrated high pressure, high temperature cell, using direct cross-correlation in place of the minimisation of sums of squares of residuals.

The technique is demonstrated through the measurement of air temperature as a function of crankshaft angle inside the cylinder of a motored single-cylinder Ricardo E6 research engine, followed by the measurement of fuel–air mixture temperatures obtained during the compression stroke in a knocking Ricardo E6 engine. A standard CARS programme (SANDIA's CARSFIT) was employed to calibrate the altered non-resonant background contribution to the CARS spectra that was caused by the alteration to the mole fraction of nitrogen in the unburned fuel–air mixture. The compression temperature profiles were extrapolated in order to predict the auto-ignition temperatures.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

Conventional nitrogen CARS thermometry normally involves the comparison of sets of referenced single-shot and/or averaged experimental broad-band nitrogen CARS Q-branch spectra obtained from a combustion environment, with a database of computed nitrogen CARS Q-branch profiles [1–6]. The quantitative comparison of experimental spectra with modelled spectra is normally achieved through a minimisation of the sum of squared differences. The database of spectral profiles is usually determined for a specified range of temperatures, pressure and gas composition, and consists of sets of spectra computed at discrete intervals over a wide range of temperature [3–5].

The use of a model computed database of CARS spectra in order to determine gas temperature distributions and/or profiles (as outlined above) in combustion environments is the most common methodology employed for CARS based gas temperature measurements. It has been employed in the experimental determination of temperature in many different combustion environments, including laboratory burners [7–10],

internal combustion engines [11–17], rocket and gas turbine combustors and exhausts [18–21], and furnaces [22–24].

Two surveys of many nitrogen Q-branch CARS thermometry experiments reported in 1996 and 2002 revealed that the typical relative precision achieved was approximately 3% (percentage standard deviation to mean ratio) for averaged spectra and approximately 10% uncertainty for single-shot measurements [25,26].

More recently, developments in nano-second (ns) CARS have focussed on the extension of capability to permit multiple-species measurement, together with temperature, and to higher pressures [27]. In addition, measurement accuracy and precision associated with rotational CARS has improved in the 300 K–1000 K temperature range, achieving an accuracy to rival or even surpass the accuracy achievable in vibrational CARS.

The precision achievable in nitrogen Q-branch CARS thermometry has improved to offer a minimum single-shot experimental uncertainty in measured temperature of approximately ± 15 K– ± 25 K (one standard deviation of CARS temperature distribution) in the 300 K–1000 K range of temperature, and approximately 2.5% relative uncertainty for single shot temperature measurements above 1000 K [27]. The improvement in CARS measurement precision has developed through improvements to rotational CARS, and the development and use of modeless dye lasers (which removes the spectral noise arising from dye laser mode competition) [28,29]. Of course, this level of precision applies to nearly perfectly heated calibrated

* Corresponding author. Tel.: +44 207 040 8812; fax: +44 207 040 8566.

E-mail address: r.d.lockett@city.ac.uk (R.D. Lockett).

¹ Present address: School of Engineering & Mathematical Sciences, City University London, Northampton Square, London EC1V 0HB, UK.

environments (calibrated heated cells, and calibrated flames). However, the complexities found in realistic combustion environments (engines, combustors, furnaces) results in reduced measurement precision.

The accuracy associated with the collisional models available for nitrogen, together with the variation in experimentally obtained nitrogen CARS spectra, results in a net minimum error of approximately 20 K in the range of temperatures and pressures of 500 K–1000 K, and 0.1 MPa–2.0 MPa, respectively [27]. An example of CARS measurement accuracy as a function of pressure was presented in the paper of Bood et al. [30]. They have presented rotational CARS temperature measurements conducted in a calibrated cell at 295 K, for pressures ranging from 0.1 MPa to 44 MPa, using various collisional models (modified exponential gap (MEG), energy corrected sudden approximation (ECS), and semi-classical collision (SCL) models). The results showed a difference of up to 10 K in the range of pressures from 0.1 MPa to 2.0 MPa, and up to 18 K in the range of pressures from 2.0 MPa to 7.5 MPa.

This was followed by the work of Afzelius et al. [31], which introduced improvements to S-branch Raman line-widths and included the effect of inter-branch interference to the models for the calculation of database CARS spectra. This led to an improvement in relative measurement error to approximately 2.5% at 295 K over the 1 MPa–7 MPa pressure range.

More recently, Kliewer et al. [32] have conducted an analysis of the accuracy of rotational CARS models (modified exponential gap (MEG) and energy corrected sudden approximation (ECS) models) in comparison with thermocouple measurements obtained from a calibrated high temperature cell at atmospheric pressure, in the temperature range of 300 K–1400 K. They showed that the rotational CARS models were capable of predicting the cell temperature with a relative error of approximately 2% in the temperature range of 600 K–1000 K.

These examples indicate that the smallest achievable relative error presently associated with the computational models employed for CARS thermometry is approximately 2%–3% in the temperature and pressure range of 295 K–1500 K and 0.1 MPa–7 MPa. This is particularly important in the context of measurements in the cylinders of internal combustion engines, which undergo varying temperature and pressure conditions over the range identified above.

A number of recent examples of CARS temperature measurements in engines have employed rotational CARS. Grandin et al. [33] employed rotational CARS in order to determine the temperature in the thermal boundary layer of an engine subjected to knocking and normal operation, in order to contrast the temperature profiles and heat transfer occurring during knocking and normal operation. Weikl et al. [34] employed rotational CARS in order to determine temperature and gas composition in a homogeneous charge compression ignition engine. The authors also employed a pulse stretching system in this study, which was developed earlier and reported elsewhere [35]. The use of a pulse-stretching CARS system for these engine measurements eliminated the possibility of optical damage to the windows, and improved the measurement precision, through an increase in signal-to-noise-ratio. They obtained standard deviations of approximately 50 K from the distributions of CARS temperatures obtained from the HCCI engine.

More recently, Birkigt et al. [36] have employed rotational CARS for the measurement of temperature in a motored and butane-fuelled firing engine, for the purpose of improving the determination of compression temperature. They were able to achieve standard deviations in the CARS temperature distributions of 17 K during motoring and 25 K during firing operation. This is to be compared with an achievable standard deviation of approximately 12 K in a calibrated oven.

As stated earlier, the comparison of the averaged spectra and sets of single-shot spectra is usually performed numerically using non-linear least squares techniques. However, there are some theoretical objections and practical limitations to the non-linear least squares method in CARS spectroscopy. Least squares minimisation is statistically valid only if the measurement variations are normally distributed and are uncorrelated. The practical limitations are encountered when the experimental data has a high noise level. The normal equations are non-linear, and therefore finding the least squares minimum is computationally time-consuming, and must satisfy rigorous convergence criteria. Experimental data with high noise levels will sometimes not satisfy the convergence criteria, and may lead to the discovery of many local minima occurring in the neighbourhood of the true minimum.

This paper presents a simpler and quicker numerical method of comparing sets of spectra. The method uses a normalised cross-correlation technique that is formally equivalent to the normalised non-linear least squares technique. The normalised cross-correlation function possesses useful Fourier transform properties, which facilitate fast computation of cross-correlations of many spectra, and provides an objective measure of goodness-of-fit during the comparison of spectra.

The cross-correlation function was derived for use in mathematical statistics, in order to identify correlations between apparently random variables (cross-covariance of probability density functions). It is also employed in acoustics and plasma physics as a means of comparing transmitted and reflected acoustic pulses with the source pulse for the purpose of determining time of flight, and the medium transfer function. It is capable of retaining useful phase information between two waveforms, and facilitates the determination of the speed of sound and the dispersion relation in a dispersive medium.

The cross-correlation function was employed by Lockett [37] to compare experimental CARS spectra with a spectral database for the determination of gas temperature. It was quickly realized that the cross-correlation function had useful Fourier properties, enabling the fast numerical comparison of many spectra. The use of Fourier techniques to compute the normalised cross-correlation for fast fitting of experimental vibrational CARS spectra was described in a short paper by Robertson and Roblin [38], where they discussed the potential benefits of fast computation of many normalised cross-correlations using dedicated Fast Fourier Transform (FFT) processors against the conventional Marquardt-Levenberg minimisation of sums of squares of residuals.

Schenk et al. [39] have since employed the cross-correlation technique in a comparative study of various fitting techniques to be employed in rotational CARS. They compared a Fourier analysis technique (FAT), cross-correlation, and four variations of weighted least squares techniques in fitting rotational CARS spectral profiles obtained from a calibrated heated cell. They concluded that the constant weighted and the inverse weighted least squares techniques provided the best options in terms of accuracy and precision. They found that the cross-correlation technique offered good applicability to experiments subject to strong optical distortions, as the technique proved robust to spectral shifts. It is interesting to note that the rotational CARS temperature measurements utilising all six of the fitting methods produced CARS temperature distributions with a mean uncertainty of 0.03 (approximately 3% variation from the cell temperature), and a standard deviation to mean temperature ratio of 0.05–0.07 (5%–7%).

This paper also introduces an alternative experimental methodology for conducting broad-band nitrogen CARS thermometry. The methodology consisted of creating a database of referenced broad-band nitrogen Q-branch spectra from inside a calibrated

Download English Version:

<https://daneshyari.com/en/article/735692>

Download Persian Version:

<https://daneshyari.com/article/735692>

[Daneshyari.com](https://daneshyari.com)