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Temperature measurements in a rapid compression machine using anisole planar laser-induced fluorescence

K.H. Tran [a,*], P. Guibert [b], C. Morin [c], J. Bonnety [b], S. Pounkin [b], G. Legros [b]

[a] Laboratoire Energétique, Mécanique et Electromagnétisme, Université Paris Ouest, 50 rue de Sèvres, 92410 Ville d'Avray
[b] Institut Jean Le Rond d'Alembert - CNRS UMR 7190, Université Pierre et Marie Curie (Paris 6) 2, place de la Gare de Ceinture 78210 Saint-Cyr-l'Ecole France
[c] LAMIH CNRS UMR 8201, UVHC, Le Mont Houy, 59313 Valenciennes Cedex 9, France

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ABSTRACT

Advanced combustion processes induced by self-ignition mechanisms in piston engines, such as Homogeneous Charge Compression Ignition (HCCI), especially need an accurate spatio-temporal temperature information because their phenomenology therefore their performances highly depend on the thermal conditions. The objective of this study is to measure the temperature distribution inside a rapid compression machine (RCM) along the compression stroke using anisole planar laser induced fluorescence. The present paper gives a new insight into the interpretation of RCM autoignition data. It also brings useful information for kinetics-related combustion research and combustion modeling. The anisole planar laser-induced fluorescence (PLIF) technique is applied, in order to observe the formation and the evolution of temperature heterogeneities in the combustion chamber prior to the auto-ignition process. Anisole is used as a novel tracer species, and the fluorescence signal's dependence on parameters, such as temperature, pressure and bath gas composition, is quantified in a high-pressure, high-temperature facility. Calibration of the fluorescence signal is defined under RCM-related temperature and pressure conditions and a protocol is proposed for post-processing of the PLIF image sequences, allowing the quantitative field temperatures to be determined at successive instants following compression. In order to gain a better understanding of the mixture process, Particle Image Velocimetry (PIV) measurements are analysed under the same conditions. The correlation between thermal and aerodynamic phenomena is determined. The temperature field is found to be non-uniform, with hot and cold centre positions resulting from recirculation inside the chamber, combined with heat transfer effects from the chamber wall.

1. Introduction

The present study describes temperature measurements in a rapid compression machine (RCM) using anisole as tracer for PLIF technique. This device is well suited to the study of combustion processes under similar conditions to those experienced in an IC engine, enabling the measurements of fuel ignition delays and the validation of kinetics mechanisms [1,2]. It is thus essential to characterise the RCM temperature fields, using a non-intrusive optical technique such as PLIF. Clarkson et al. [3] used PLIF to measure temperature fields in an RCM, with an acetone tracer under non-reactive conditions, and with DTBP (di-tert-butyl peroxide) decomposition, which forms acetone under reactive conditions. As their measurements were not calibrated, no quantitative data was reported. These authors observed a spatially non-uniform temperature field following compression, with a cold core. This consequence may affect chemical development and ignition delay measurements. The measurement of temperature distributions in an RCM using acetone PLIF, at different times along compression, was proposed by Mittal and Sung [4]. Thurber et al. [5] inferred temperature fields from the fluorescence signal by accounting for absorption phenomena and temperature effects. In-cylinder temperature imaging was also applied to the study of an IC engine, using toluene fluorescence at a single excitation wavelength and two-colour detection [6], and using 3-pentanone [7,8]. Löffler et al. [9] used acetone with the dual excitation wavelength technique, at 308/277 nm and 308/248 nm.

Similar approaches have been described in the literature. Strozzi et al. [10] used PLIF to characterise a two-dimensional temperature field in an RCM, with a single-excitation, two-colour detection technique, relying on the temperature dependence of toluene fluorescence established by Koban et al. [11], at atmospheric pressure and for the temperature range 300–950 K. These authors obtained temperature fields that clearly revealed a distorted structure, in particular at the boundary between the hot and cold zones. In-cylinder

* Corresponding author.
E-mail address: khtran@u-paris10.fr (K.H. Tran).

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temperature imaging using a shock tube or spray has also been applied to the study of IC engines. Kaiser et al. [12] studied the LIF imaging of toluene at an excitation wavelength of 248 nm, to determine the spatial fluctuations of gas temperature in an optically accessible engine. These fluctuations are due to wall heat-transfer during the compression stroke in a homogeneous mixture. Löffler et al. [9] presented calibration results from acetone fluorescence signal intensities in nitrogen, air, and an exhaust gas–air mixture, at temperatures ranging from 298 to 748 K and pressures ranging from 0.02 to 2 MPa, using 308 nm and 248 nm excitation wavelengths. From this data, inferred from single-shot images, temperature and exhaust gas concentrations in a spark ignition engine were accurately determined. The computed accuracy of the calibration data was 5.6%, and 3.2% for the signal measured under single wavelength excitation and for the signal ratio, respectively. The uncertainties in the measurements, made with an exhaust gas recirculation/air mixture, were slightly higher, as a consequence of small uncertainties in the mixing ratio: the errors were 6.9% and 5.1% for single wavelength excitation, and for the signal ratio, respectively.

Yoo et al. [13] used the PLIF technique to image temperature fields close to the walls of a shock tube. Two types of near-wall flow were considered: the sidewall thermal boundary layer behind an incident shock wave, and the end-wall thermal boundary layer behind a reflected shock wave. These thin layers were imaged at a high spatial resolution (15 μm/pixel), using fused silica walls and near-UV bandpass filters to accurately measure the fluorescence signals with minimal interference from scattering and reflection effects at the wall surfaces. Nitrogen, hydrogen or argon gases were premixed with 1–12% toluene, as the LIF tracer. The measured pressures and temperatures ranged between 0.01 and 0.8 bar, and 293 and 600 K, respectively. The temperature field measurements were found to be in good agreement with the theoretical values calculated using two-dimensional laminar boundary layer and one-dimensional heat diffusion equations, respectively. In addition, PLIF images were taken at various times, behind incident and reflected shock waves, in order to observe the development of the sidewall and end-wall layers, respectively. This demonstrated that this diagnostic strategy can be used to accurately measure temperatures at distances as close as 60 μm to the wall. The temperature measurement accuracy within the sidewall boundary layer is approximately ± 5 K. Cundy et al. [14] developed a high-speed transient temperature measurement technique using high-speed toluene LIF. They used single wavelength excitation at 266 nm, combined with detection within two spectral regions, yielding a self-calibrated, temperature-dependent signal ratio at temperatures between 373 and 873 K. These experiments were carried out in a well-stabilised heated nitrogen jet, to avoid signal reduction due to collisional quenching by oxygen. Although the sensitivity of the diagnostics suggested that the accuracy should increase with increasing temperature, the fluorescence signal decreased strongly, and the associated noise levels were higher with increasing temperature, such that the error actually increased. The standard deviation errors were computed as ± 8 and ± 25 K, at 373 K and 773 K, respectively.

The selection of the tracer is a crucial parameter of the LIF implementation. Among the potential tracers, small aromatic molecules, such as toluene [15] and naphthalene [16,17], are attractive [18] due to their high-fluorescence quantum yield (FQY). However, anisole can be a potential candidate for use as fluorescent tracer for gas-phase imaging diagnostics. Due especially to its high FQY, its large absorption cross-section, and its Stokes shift, anisole can deliver signal intensity up to 100 times stronger than conventional tracers such as toluene. This makes anisole a novel tracer alternative.

In the present study, quantitative temperature imaging was conducted in an RCM for the first time using the single excitation two-colour detection technique based on anisole fluorescence, including a prior calibration process over the range of experimental conditions met in the RCM. This calibration is necessary to obtain quantitative measurements in a large range of pressure and temperature. The experimental facilities and the image processing procedures are first outlined. A selection of two-dimensional temperature fields are then combined with the velocity fields measured inside the combustion chamber to highlight the key role of the hydrodynamic features on the thermal conditions met in a RCM.

2. Experimental set-up

2.1. PLIF model overview

The planar laser-induced fluorescence (PLIF) technique is well suited to this type of measurement, due to its sensitivity and ability to provide two-dimensional measurements with a high spatial resolution. The global expression governing the fluorescence signal S_f depends on terms that quantify the sensitivity of the signal to the pressure, temperature, composition of the gas mixture, optical matching of the absorption cross-section, and fluorescence quantum yield [5]:

$$S_f = \frac{E}{hc/\lambda}\eta_{opt} dV_c\left[\frac{XP}{kT}\right]\sigma(\lambda, T)\Phi(\lambda, T, P, X) \quad (1)$$

where E is the laser fluence, h is the Planck constant, c is the celerity, (hc/λ) is the energy of a photon at the excitation wavelength λ, η_{opt} is the overall efficiency of the collection optics, k is the Boltzmann constant, and dV_c is the collection volume. The terms characterising the tracer are σ, its molecular absorption cross-section, and Φ, its fluorescence quantum yield. The tracer mole fraction X, total pressure P, and temperature T define the experimental thermodynamic conditions.

In the case of a gaseous single phase, as described in the present study, three different LIF-based temperature measurement techniques can be used. The first of these is a single-excitation, single colour detection approach. It requires a homogeneous distribution of a tracer together with the use of a known reference temperature inside the volume probed. The second technique, referred to as single-excitation, two-colour detection, provides with temperature measurements in the case of an inhomogeneous tracer distribution. Finally, the third technique involves the use of a dual-excitation wavelength and two-colour detection. The latter approach allows both concentration and temperature values to be measured. The selection of one of the above techniques is driven by the thermodynamic quantities to be studied, depending on the selected tracer and the specific experimental conditions. In the current study, the single-excitation, two-colour detection technique was chosen, since it allows the temperature to be measured in a non-homogeneous seeded flow, provided the pressure is known.

In the general case, the function ratio S_f^* of the fluorescence signals detected in the two spectral bands $\Delta\lambda_1$ and $\Delta\lambda_2$ is expressed by:

$$S_f^* = \frac{E_1\eta_{opt}\lambda_1\int_{\lambda_{low1}}^{\lambda_{high1}}\sigma_{tracer1}(\lambda_1, T)\Phi_{tracer1}\left(\lambda_1, T, P, X_{ij}\right)}{E_2\eta_{opt}\lambda_2\int_{\lambda_{low2}}^{\lambda_{high2}}\sigma_{tracer2}(\lambda_2, T)\Phi_{tracer2}\left(\lambda_2, T, P, X_{ij}\right)} \quad (2)$$

The sensitivity of this ratio depends on the selected spectral wavelength bands $\Delta\lambda_1$ and $\Delta\lambda_2$, and on the selected temperature measurement technique. In the case of the single-excitation, two-colour detection technique under inhomogeneous conditions, the expression S_f^* can be simplified at a given pressure, as follows:

$$S_f^* = \frac{\eta_{opt1}\int_{\lambda_{low1}}^{\lambda_{high1}}\sigma(\lambda, T)\Phi\left(\lambda, T, P, X_{ij}\right)}{\eta_{opt2}\int_{\lambda_{low2}}^{\lambda_{high2}}\sigma(\lambda, T)\Phi\left(\lambda, T, P, X_{ij}\right)} = \frac{S_f^{\Delta\lambda_1}(T, P)}{S_f^{\Delta\lambda_2}(T, P)} \propto \frac{\Phi^{\Delta\lambda_1}(T)}{\Phi^{\Delta\lambda_2}(T)} = f(T) \quad (3)$$