In-cylinder Chemical Species Tomography for CI Engines

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High-speed Chemical Species Tomography (CST) using near-IR absorption has recently been demonstrated in a multi-cylinder gasoline SI engine running on retail fuel. Many of the inherent advantages of the CST technique would be even more marked in CI engines, for example in HCCI engines where mixture preparation involves residual species, and in diesel engines where gross inhomogeneities over large spatial scales are the norm. On the basis of practical experience of CST in engines and in laboratory systems, this paper explores the potential for these applications of the technique.

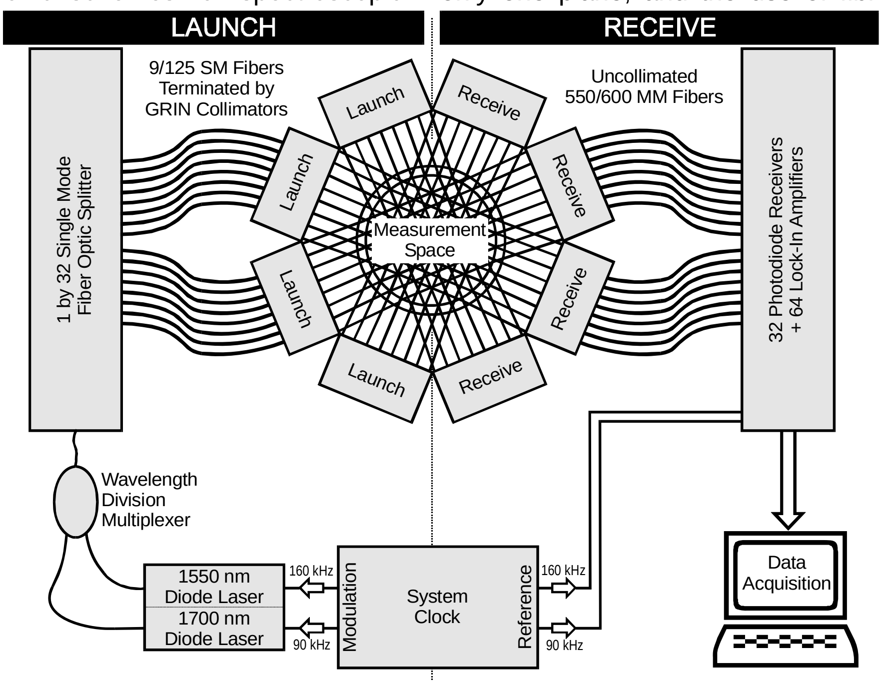
Introduction

There is a long-term trend towards greater premixing of fuel and air in compression ignition (CI) engines. The most extreme case is the Homogeneous Charge Compression Ignition (HCCI) engine [1]. Even in the “conventional” diesel engine, injection sequences now lead to complex mixture development processes. Moreover, the creation of engine-out pollutant species is of critical importance. These trends demand in-cylinder imaging of chemical species in a variety of CI engine types.

The technique of Chemical Species Tomography (CST) has recently emerged due to the maturing of Near-Infra-Red (Near-IR) opto-electronic technologies that were initially used in the communications industry: diode lasers, optical fibres with mixers and splitters, and photodiodes. The keys to exploiting these technologies are low noise opto-electronic schemes for spectroscopic measurements, and beam array design for adequate spatial resolution. For high-speed imaging of hydrocarbon fuel in a gasoline SI engine cylinder, the Manchester group has developed an implementation of Near-IR CST (Fig. 1) that has allowed, to date, up to 32 simultaneous path-integral measurements through the measurement subject [2-4]. This paper discusses the application of CST to CI engines in projects that are now underway.

Key Features of Near-IR CST

This technique offers direct sensitivity to the target species, thus avoiding the use of artificial dopants. The Manchester system is based on continuous-wave diode lasers and photodiodes that are inherently capable of rapid operation, enabling high-speed continuous imaging. The tomographic approach requires optical access to the cylinder in only one plane, and the use of fibre-based tech-



For clarity, fibers are only shown for 2 (of 4) 8-beam projections

Fig. 1: Schematic diagram of first-generation Near-IR CST system.

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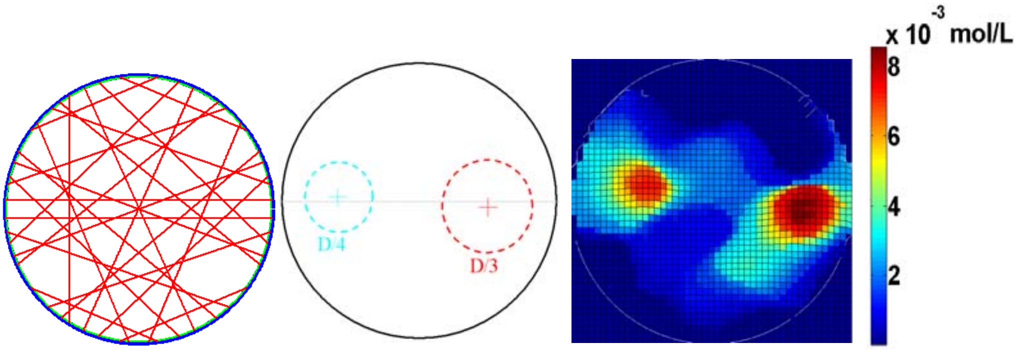

(a) (b) (c)

Fig. 2: (a) The 25 beams used in lab tests; (b) A double-plume phantom; (c) IMAGER reconstruction performance.

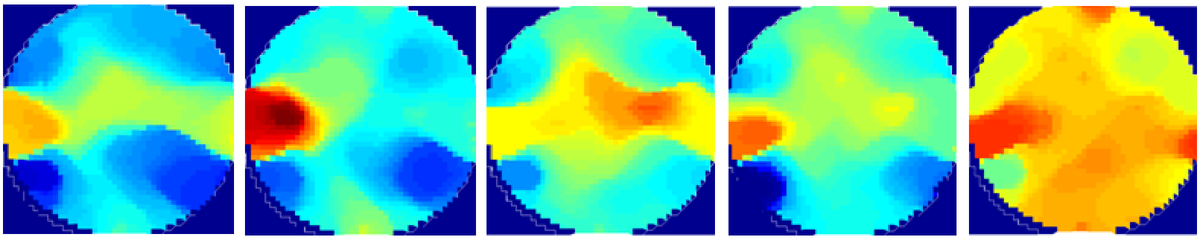
ºBTDC 42 39 36 33 30

Fig. 3: Tomographic images showing the development of fuel distribution in the period from 42˚ to 30˚ before TDC, obtained using a 21-beam subset (1500rpm/1.5 bar BMEP load).

-ologies allows relatively small-scale and robust optical access. The Manchester system offers great robustness to sprays and soot by launching absorbed and reference wavelengths (λ_1 and λ_2 respectively) along each beam path, where the reference wavelength undergoes only scattering and beam-steering.

The first-generation system illustrated in Fig. 1, using simultaneous measurements along 32 beam paths, enabled the laboratory demonstration of high-speed CST of propane [3, 4] and iso-octane [5] at 3500 frames per second (fps). A second-generation system has been developed by the IMAGER consortium (Manchester, Roush Technologies Ltd. and AOS Technology Ltd.) for application to multi-cylinder SI gasoline engines (with λ_2 = 1651nm), and implemented on a 4-cylinder Ford Duratec PFI engine with 2.0 L capacity (89mm bore) [6]. The IMAGER system is compatible with GDI sprays by the use of faster laser modulation, and incorporates a unique OPtical Access Layer (OPAL) that houses the launch and receive optics for 27 beams that are irregularly arranged relative to each other. The balance between number and geometry of beams must be carefully optimized, particularly in terms of angular sampling [7]. Fig. 2 shows some laboratory test results for propane plumes passing through the measurement plane [7]. Fig. 3 shows example images obtained when the engine was operated under conditions where a homogeneous fuel distribution was expected at ignition (15 ºBTDC) [6].

Fuel Sprays and CST

The first-generation system achieved considerable success in imaging iso-octane fuel in a laboratory GDI set-up, despite operating at marginally low laser modulation frequencies [5]. In particular, it was found that the coarse features of a GDI spray could be imaged by using the attenuation of the reference wavelength only.

Fig. 4 illustrates this capability, clearly showing the hollow spray cone, which would be enhanced using model-dependent image reconstruction algorithms that are now available. In-cylinder spray-shape imaging may thus be achievable in running CI engines, with effectively simultaneous measurement of gaseous fuel distribution and its inhomogeneity. Such a study of CI engine combustion is to be explored in a new project with Shell in single-cylinder engines.

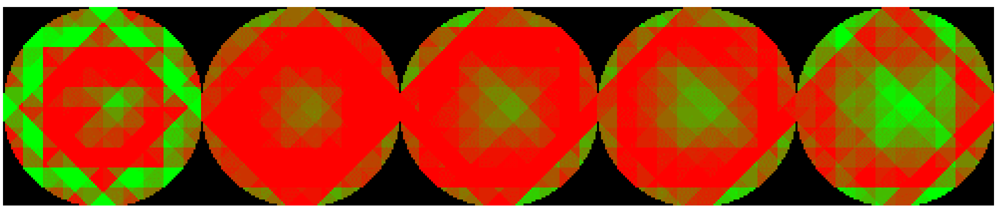
2.94 5.29 7.65 8.82 11.76 (ms after SOI)

Fig. 4: Tomographic images of the GDI spray cone after a 4ms iso-octane injection (red=high scattering).

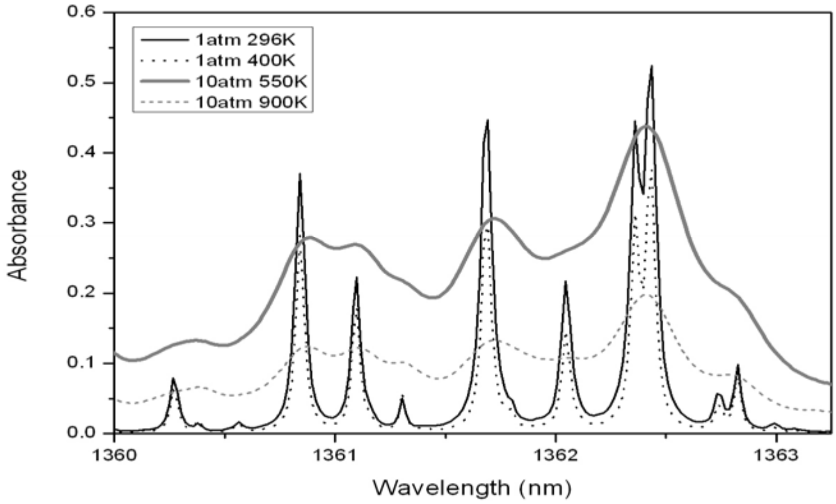

Fig. 5: Calculated spectra of water at conditions relevant to HCCI (10% mole fraction water, pathlength 80 mm).

CST for HCCI research

The combination of HCCI and variable 2/4-stroke operation is being researched by a consortium of several universities, with Ricardo plc and Innospec Ltd. [8]. The Manchester CST technique is being adapted to image mixing between combustion residuals and the fresh fuel/air charge, by imaging the distributions of both water and hydrocarbon fuel. For small molecules such as water, extensive databases of spectroscopic parameters are available, e.g. in HITRAN [9], which are helpful for early-stage development of measurement systems.

However, the IR transitions of interest can demonstrate complex behaviour as a function of temperature and pressure. This is illustrated in Fig. 5, for the case of H_2O under various conditions relevant to HCCI operation: Whilst very strong absorption is observed, the relatively narrow lines at low (i.e. intake) pressure show considerable temperature dependence, even over a range of only 100K. At high pressure (i.e. approaching ignition), each absorption feature is composed of the broadened lineshapes of several vibrational-rotational transitions and strong temperature dependence is still evident.

The choice of absorption wavelength for in-cylinder water measurement and imaging is tractable, nevertheless, and also presents the potential to measure and image the distribution of temperature as well as concentration.

Conclusions

The development of Near-IR CST for engine in-cylinder applications has reached the stage where it can be applied confidently to single- and multi-cylinder gasoline SI engines for fuel imaging. In the multi-cylinder case, robust fibre-based optical access has been demonstrated.

The challenges posed in adapting CST to CI engines are significant, but are strongly motivated by the potential it offers for advances in the underlying knowledge of CI engine processes that determine combustion behaviour. Initial CI applications are focused on single-cylinder optical engines.

In both engine types, there is great scope to extend substantially the utility of the CST technique to provide unique insights to help optimise engine environmental performance.

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