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Quantum cascade laser assisted time-resolved measurements of carbon dioxide absorption during combustion in DME-HCCI engine

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HIGHLIGHTS

- QCL light transmissivity during the absorption of CO_2 is correlated with ROHR.
- Experiments show CO_2 absorbance increase only when second peak of ROHR is maximized.
- In-cylinder CO_2 concentration during DME-HCCI combustion was measured about 4 vol%.

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ABSTRACT

We conducted experiments to investigate in-cylinder light absorption by carbon dioxide (CO_2) during homogeneous charge compression ignition (HCCI) engine combustion. The combustion was fuelled with dimethyl ether. An *in situ* laser infrared absorption method was developed. We used an optical fibre spark plug sensor and the light source was a 4.301 μm quantum cascade laser (QCL). We applied Lambert–Beer's law in the case of a single absorption line of CO_2. We were able to measure the transient CO_2 formation during the HCCI combustion inside the engine cylinder. Our experiments showed that the laser light transmissivity level decreased with the intensity of the infrared (IR) signal. We compared the change in the transmissivity to the spatially integrated HCCI flame luminosity level and observed significant correlations between the flame luminosity level, heat release rate and transmissivity. Time-resolved experiments showed that the CO_2 absorbance increases when the second peak of the rate of heat release (ROHR) is maximised. After combustion, the CO_2 concentration was approximately 4 vol%, which agrees with the amount of CO_2 formed during complete combustion.

1. Introduction

Homogeneous charge compression ignition (HCCI) engines have received much attention due to their high combustion efficiency and low nitrogen oxide (NOx) and particulate matter (PM) emission rates. Recent studies on HCCI-based combustion engines have focused on four-stroke engines using conventional or alternative fuels, including dimethyl ether (DME) fuel [1–4]. In HCCI engines, DME fuel exhibits very strong low-temperature kinetic reactions, making it suitable for compression ignition engines. It is a promising alternative fuel due to the fact that it will not contribute to the air-pollution problems caused by soot and NOx [5], which are emitted by conventional fuels. To improve understanding of the DME oxidation mechanism in an HCCI engine, we conducted experimental kinetic studies to characterise the combustion. One effective way to investigate the DME reaction mechanisms is to use spectral analysis to determine the major active species, especially CO_2 and CO [6–9]. A number of studies have examined CO_2 and CO absorption in a constant volume vessel or reactor. However, few studies have examined CO_2 formation and absorption under normal engine conditions. Schultz et al. [10] investigated the impact of ultraviolet (UV) absorption by CO_2 in high-pressure combustion applications. They measured the absorption cross section of CO_2 at combustion temperatures corresponding to wavelengths of 190 nm and found that the measured absorption cross section had a pronounced temperature dependence in the case of CO_2, and that to analyse the absorption by hot combustion products, significant corrections to the UV combustion measurements must be made. Farooq et al. [11] performed high-pressure measurements of CO_2 absorption at wavelengths near 2.7 μm. They concluded that in this wavelength range, as the spectra broaden and blend at high densities, access to discrete transitions

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is not possible. This makes it difficult to avoid H_2O interference. Hall and Zuzek [12] used broadband infrared radiation from a tungsten halide lamp to analyse the density of CO_2 in the cylinder of a spark-ignited (SI) engine. The CO_2 was measured by the attenuation of the infrared radiation, which occurs due to the excitation of the 2300 cm^{-1} infrared vibrational–rotational absorption band. Kawahara et al. [13] used infrared laser absorption to conduct cycle-resolved residual gas concentration measurements inside a heavy-duty diesel engine. They were able to quantify the CO_2 concentration in the residual gas and estimate the internal exhaust gas recirculation (EGR) ratio. Residual gas concentrations, especially CO_2 and H_2O, have also been measured *in situ* using infrared absorption techniques [14,15]. Francqueville et al. [15] measured the CO_2 concentration across the combustion chamber in a spark-ignited engine. Grosch et al. [16] performed infrared spectroscopic concentration measurements of CO_2 and gaseous H_2O in environments that are difficult to measure directly using a fibre optical sensor. The mixture of CO_2 and H_2O was analysed spectrally at a wavelength of about 3700 cm^{-1} for temperatures up to 573 K and pressures up to 1800 kPa. An optical absorption sensor was used to make quantitative in-cylinder transmission measurements.

Optical absorption-based sensors are used to analyse mixture formation in spark-ignited engines. Using these sensors, it is possible to access the cylinder without modifications such as optical windows. As a result, the thermodynamic and mechanical properties of the engine being studied will not be changed by the apparatus, enabling measurements to be made under realistic conditions. The in-cylinder mixture was analysed using optical absorption-based sensors in conjunction with gas sampling probes. Little progress has been made towards the development of practical absorption-based sensors for CO_2 measurements in high-pressure combustion environments. Most previous high-pressure CO_2 sensors used robust telecommunications diode lasers and optical fibre technology in the near-infrared (NIR) 1.3–1.6 μm wavelength region. These sensors accessed weak vibrational bands of CO_2 by direct absorption [22] and used direct absorption spectroscopy [17–19], wavelength modulation spectroscopy (WMS) [20,21], or NIR hyperspectral sources. To explore the challenges of optical sensor design for high-pressure applications [23], high-pressure measurements of CO_2 absorption have recently been performed near 2.0 μm.

The work presented in this paper is motivated by the need for an *in situ* absorption-based diagnostic for measuring transient CO_2 concentrations in HCCI engine cylinders. Understanding the transient CO_2 formation process may help resolve problems related to knocking combustion [24] and exhaust gas formation [25]. This also aids the design of efficient HCCI engines with precise ignition timing control and a variable valve timing system [26,27]. The objective of this study was to measure transient CO_2 formation during DME-HCCI combustion. By combining spectroscopy and QCLs, we were able to determine the CO_2 light absorption. Our aim was to characterise the time-resolved spectrum of CO_2 formation. CO_2 formation is a representative indicator of thermal ignition and fuel oxidation during HCCI combustion.

2. Experimental setup and procedure

We used an optical compression–expansion test engine with a single cylinder and a compression ratio of 9.0, as shown in Fig. 1 and Table 1, to study DME-fuelled HCCI. The engine crank was driven externally by a 2000 W induction motor and rotated at a constant rate of 600 rpm. The DME was premixed with gas at a ratio of 20% oxygen to 80% argon at molar proportions equivalent to $\phi = 0.30$. Argon was used instead of nitrogen for two reasons: firstly, to increase the in-cylinder temperature at the end of compression by decreasing the heat capacity of the in-cylinder gas–fuel mixture; and secondly, to initiate HCCI combustion at a significantly lower compression ratio than that used in conventional HCCI engines. The DME—O_2—Ar fuel mixture was supplied to the mixture tank, where it was heated to the temperature T_{in} = 293 K, 303 K and 310 K and maintained at pressure P_{in} = 65 kPa. While the motor was on, the intake valve remained open, and the fuel mixture was sucked into the cylinder and pushed back into the mixture tank. When the thermocouple reading in the mixture tank stabilised, a valve closure signal was sent to a solenoid that activated the valve stopper. The intake valve was closed at around bottom dead centre (BDC), and the fuel mixture was compressed, autoignited, and combusted. Changes in the gas pressure were measured during the compression and expansion strokes using a KISTLER 6052B pressure transducer. Concurrently, sequential HCCI-DME combustion images were recorded by a high-speed camera (MEMRECAM GX-8; Nac Image Technology Inc., Simi Valley, CA, USA) at 10,000 frames per second with a resolution of 640 × 640 pixels. CO_2 absorption was measured by directing laser light from the QCL to the spark plug sensor via optical fibres, and then to the infrared (IR) detector. A QCL is a semiconductor laser that emits light in the mid- to far-infrared portion of the electromagnetic spectrum. Unlike typical interband semiconductor lasers, which emit electromagnetic radiation through the recombination of electron–hole pairs across the material band gap, the QCL is unipolar and laser emission is achieved via intersubband transitions in a repeated stack of semiconductor multiple quantum well heterostructures [28]. A QCL was used as the light source due to its strong absorption, and because no other gas needs to be introduced to the burned gas or fresh mixture. The centre-wavelength of the QCL at 4.301 μm, shown in Fig. 2, coincides with the absorption line of CO_2. This absorption line is caused by the C—O vibrational-rotational band, estimated using the HITRAN database to occur at temperature 900 K [29]. The

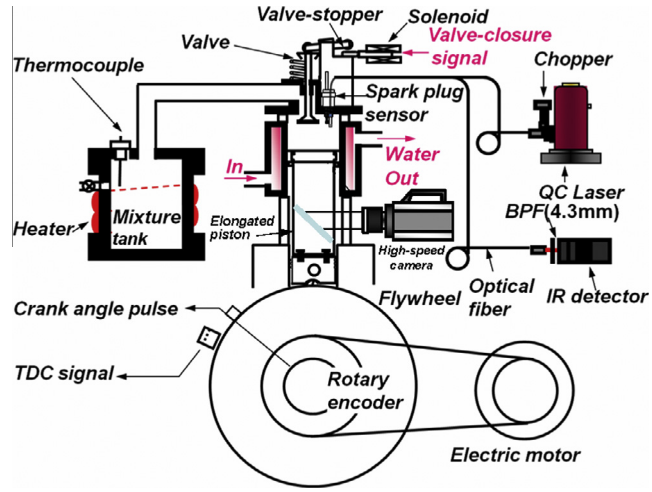

Fig. 1. Schematics of a compression-expansion test engine.

Table 1
Test engine specification.

Bore	78 mm
Stroke	85 mm
Connecting rod length	153 mm
Displacement volume	406.2 cm^3
Compression ratio	9.0:1
Combustion chamber	Pancake type
Engine speed	600 rpm
Valve closure time	180°BTDC