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Local fuel concentration measurement through spark-induced breakdown spectroscopy in a direct-injection hydrogen spark-ignition engine

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ABSTRACT

Quantitative measurements of local fuel concentrations were conducted in a direct-injection hydrogen spark-ignition research engine using the spark-induced breakdown spectroscopy (SIBS) technique. For SIBS measurements, a new sensor was developed from a commercially available M12-type spark plug with no major modifications to the electrodes. The new plug sensor showed better durability and required less maintenance when used in a hydrogen research engine. Emission spectra from the plasma generated by the spark plug were collected through an optical fibre housed in the centre electrode of the plug and resolved spectrally for atomic emissions of H_α, O(I), and N(I). The main focus of the present work was to characterise the effects of ambient pressure at ignition timing on spectral line emissions and to improve the accuracy of SIBS measurements by taking into account the pressure dependency of atomic emissions. A significant effect of the corresponding pressure at ignition timing was observed on spark-induced breakdown spectroscopic measurements and emission line characteristics. Retarded spark timing (i.e. higher ambient pressure at the ignition site) resulted in lower spectral line intensities as well as weaker background emissions. It is well established that with relatively higher pressure and density of atoms or molecules, the cooling of expanding plasma accelerates, and the collision probability increases, leading to both a weaker broadband continuum and atomic emissions. A "calibration MAP" representing the correlation of air excess ratio (relative air/fuel ratio) with both intensity ratio and pressure at ignition timing was created and subsequently used for quantitative measurements of local fuel concentrations for both port injection and direct injection strategies to demonstrate and explore the effects of pressure dependency of atomic emission on the accuracy of the SIBS measurements. Local stratification of the fuel mixture in the vicinity of the spark gap location associated with direct injection strategies was confirmed; the coefficient of variation of the local air excess ratio was relatively small for measurements made using the calibration map. This demonstrated that the measurement accuracy of local fuel concentrations through a spark plug sensor can be improved significantly when the pressure dependency of atomic emissions is taken into account.

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Introduction

Hydrogen has long been considered as one of the most promising energy carriers and investigated as a fuel for internal combustion engines (ICEs) due to its potential for high engine efficiency and greenhouse gas reduction [1–5]. There are some initiatives in Japan to move towards the "dream of a hydrogen-based society" and to accelerate the installation of hydrogen stations for fuel-cell vehicles that run on electricity, generated by burning hydrogen. Today, various governments, especially in Europe, the United States, Canada, and Japan, are taking leading roles in establishing and promoting low carbon electricity generation through cogeneration systems. Until now, hydrogen-fuelled cogeneration has been dominated by fuel cell applications, and the high cost of these systems has been a limiting factor for hydrogen's viability as a fuel for stationary power applications [6–9]. However, reciprocating hydrogen-fuelled engines that can offer an economic proposition comparable to natural gas and diesel could establish hydrogen-fuelled cogeneration system as a viable alternative. Obara et al. investigated a hybrid cogeneration system (HCGS) by combining a solid polymer membrane-type fuel cell (PEM-FC) and a hydrogen mixture gas engine (NEG) [10]. They reported improvement in power generation efficiency and reduction in carbon dioxide emission.

Much research has focused on hydrogen direct-injection spark-ignition (DISI) engines due to their high volumetric efficiency and potential to avoid knock, preignition, and backfiring, which have detrimental effects on engine performance and emissions [11–14]. Optimisation of spark timing, injection timing, and injection pressure, are important aspects of the development of hydrogen DISI engines [15] and can suppress backfiring and knocking, especially at higher engine loads. Oikawa et al. reported a "plume ignition combustion concept" (PCC) for hydrogen DISI engines, denoting the ignition of a rich mixture plume during or right after an injection event [16]. In their study, the injector was mounted close to the spark plug to achieve jet-guided combustion with the jet being directed towards the spark plug using high injection pressures (200 bar). This PCC combustion with late injection strategy was shown to substantially reduce NO_x emissions at high speed and under high load conditions while maintaining high thermal efficiency and power. A major challenge in the use of H_2-DI is in-cylinder hydrogen-air mixing. The local equivalence ratio near the spark plug at the time of the spark discharge is particularly important for successful ignition, because the jet-guided system generates a stratified fuel concentration near the spark plug in a DISI engine. In addition, the mixture distribution around the spark plug, together with fluid motion, strongly influences the combustion initiation, which subsequently affects the engine performance, efficiency, and emissions. Thus, a fundamental understanding of mixture formation processes is necessary to optimise DI-H_2 ICE operation. To better understand how to both achieve an optimal local mixture and control the large-scale stratification, a diagnostic tool for providing information on the mixture distribution in practical engines should be developed. Instantaneous fuel concentration measurements in production engines will greatly aid in engine design and optimisation.

There are several approaches to studying fuel concentrations in an SI engine, including infrared (IR) absorption, planar laser induced fluorescence (PLIF), Raman scattering, laser-induced breakdown spectroscopy (LIBS) and spark-induced breakdown spectroscopy (SIBS) or spark emission spectroscopy. A 3.392-μm He–Ne laser was used to obtain fuel concentrations for combustion diagnostics [17–26]. One of the members of our group was the first to investigate the possibility of measuring fuel concentration near the spark plug in a test engine [21]. Subsequently, Tomita et al. used an optical sensor with a pair of sapphire rods to pass laser light through the combustion chamber of a practical engine; they also discussed several of the factors that affected measurement accuracy [22,23]. Their sensor has also been applied to practical SI engines and direct-injection gasoline engines [24]. We developed an optical spark-plug sensor with a double-pass measurement length using an infrared absorption technique for measuring hydrocarbon fuel concentrations [25,27]. LIF measurements have been used widely because the LIF signal is relatively strong and provides two-dimensional fuel concentration information at a specified time [28–30]. Tomita et al. [28] applied the PLIF method to study the fuel concentration distribution in a transient hydrogen jet. Results showed that each transient hydrogen jet had different configurations and concentration distributions. Kaiser and White [30] performed an optical study of mixture preparation in a hydrogen-fuelled engine using a PLIF technique; their report favoured increased injection pressure and careful nozzle design. Ferioli et al. [31] used LIBS on engine exhaust gas to illustrate the ability of this technique to measure the equivalence ratio of SI engines, using the ratios of C/O and C/N atomic peaks derived from the measured spectra. Phuoc [32] used a laser-induced spark to measure the ignition and fuel-to-air ratio of CH_4-air and H_2-air combustible mixtures simultaneously using the measured spectral peak ratio H_α (656 nm)/O (777 nm). Shudo and Oba [33] measured the mixture formation characteristic with a hydrogen jet in a nitrogen-filled constant-volume chamber using LIBS techniques. We have also tried to measure the equivalence ratio using LIBS and discussed the accuracy of spatially, temporally, and spectrally resolved measurements [34,35]. However, IR absorption is not suitable for measuring the hydrogen/air ratio due to the lack of absorption bands at visible and infrared wavelengths. PLIF and LIBS require major engine modifications including optical access, which limit their application to production engines. Quantitative measurements of the cycle-to-cycle variations in the mixture strength at or near the ignition site are comparatively rare for practical hydrogen SI engines.

With SIBS, the signal detection and spectroscopy is similar to LIBS; however, spark generation occurs between two electrodes, in which the spark itself is used as the light source to estimate the equivalence ratio in the spark plug. SIBS can therefore be used in a combustion chamber with no engine modifications, because the plasma excitation can be implemented using a conventional spark plug. Spark-emission spectroscopy has been applied to measure the equivalence ratio in a DISI engine [36–38]. Ando and Kuwahara [37] and

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