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Effect of ambient pressure on local concentration measurement of transient hydrogen jet in a constant-volume vessel using spark-induced breakdown spectroscopy

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ABSTRACT

We report an investigation of the effects of the ambient pressure on fuel concentration measurements of an injected jet of hydrogen using spark-induced breakdown spectroscopy (SIBS) in a constant-volume vessel. Measurements were carried out using hydrogen injected into a nitrogen environment with different ambient pressures, and the local concentrations were measured at various spark locations. The optical emission from the spark discharge at 501 nm (corresponding to nitrogen) and 656 nm (corresponding to hydrogen) was observed using SIBS. Spectrally resolved emission from the plasma was detected simultaneously using a spectrometer. The potential to determine the hydrogen/nitrogen ratio in the spark gap using was demonstrated. Spectral calibration was carried out using a hydrogen/nitrogen mixture, and hydrogen was injected at a pressure of 5.0 MPa into nitrogen with ambient pressures in the range 0.5–1.5 MPa. The results show an increase in the background radiation, as well as of the peaks corresponding to hydrogen and nitrogen atomic emission lines, as the ambient pressure increased. An increase in the density of nitrogen inside the chamber influenced the structure of the hydrogen jet, slowing the spray and reducing penetration, which altered the equivalence ratio at the location of the spark. When the spark occurred during injection, the behavior of the hydrogen jet was quasi-steady state; when the spark timing followed the injection, however, an unsteady state was observed.

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Introduction

Currently, the transport sector is largely dependent on fossil fuels, which leads to emission of pollutants including carbon dioxide, and much research interest has focused on the search for alternative fuels [1–5]. In particular, hydrogen has received much attention, and has potential for use in direct-injection spark ignition (DISI) engines because it has wide flammability range and a large volumetric efficiency [6,7]. However, there are significant challenges that must be overcome, particularly at high engine loads, including knocking, pre-ignition and backfiring [8]. These problems have so far inhibited reliable operation, and have limited the maximum output of a hydrogen DISI engine. Optimization of the spark timing and pressure is an important aspect of the development of hydrogen DISI engines [9], and can suppress backfiring and knocking, especially at higher engine loads.

An understanding of the mixing of the hydrogen jet with the in-cylinder gases is particularly important. There exist a number of approaches to study the fuel concentration in an SI engine, including infrared (IR) absorption [10,11], planar laser induced fluorescence (PLIF) [12–14], Raman scattering [15,16], and laser-induced breakdown spectroscopy (LIBS) [17–20]. However, IR absorption is not suitable for measuring the hydrogen/air ratio due to the lack of absorption bands at visible and infrared wavelengths, and PLIF and LIBS require major engine modifications, which limit their practical application. Here we investigate the mixing process of the injected hydrogen jet in a constant-volume vessel using spark induced breakdown spectroscopy (SIBS), which allows us to measure the equivalence ratio at various locations in space. With SIBS, the signal detection and spectroscopy is similar to LIBS; however, with SIBS spark generation occurs between two electrodes, where a plasma is generated to excite the sample. Furthermore, SIBS has potential to produce a higher temperature plasma, giving a stronger signal. SIBS can therefore be used inside the combustion chamber without any engine modifications, as the plasma excitation can be implemented using a conventional spark plug.

Hunter et al. [21] applied SIBS technique for the detection of Pb, Cr, Ba, Hg, and Cd in soils, as well as for monitoring airborne heavy metals, and were able to detect lead and chromium at both low and high concentrations [22]. Srungaram et al. carried out a comparative study of LIBS and SIBS to determine the detection range of the two techniques for mercury [23]. Fuel concentration measurements in internal combustion engines have been carried out using SIBS in a spark-ignition engine [24], and the results show that, for stratified operation with a fixed injection timing, later-than-optimal spark timing leads to incomplete combustion due to poor mixing and hence localized regions of excessively lean fuel/air ratio. However, the method still requires changing in the engine combustion chamber design for optical access from outside.

Effenberger et al. [25] reviewed the performance of LIBS in reduced pressure environments and with various gases other than air. Low pressures (<760 Torr) are favorable for LIBS due to an increased signal-to-noise (S/N) ratio; however if the pressure is too low, the spectra suffer due to a lack of plasma confinement. For pressures greater than 100 kPa, Phoc [18] found that the intensities of the Hα and O(I) triplets decreased as the pressure of the ambient gas increased. The effects of the ambient pressure on the emission intensity has been discussed by Iida [26] and Vadillo et al. [27], who identified three main factors: effects on the quantity of vaporized gas due to plasma shielding, changes in plasma temperature due to absorption of the laser radiation, and variations in the rate of plasma expansion. Although SIBS differs from LIBS, the same principles apply to the creation of the plasma.

We have previously investigated spectrally resolved emission spectra of plasmas generated using a spark plug via SIBS to measure the local fuel concentration of premixed CH_4/air [28]. The spark-plug sensor facilitated an investigation of a laminar premixed flame in a CH_4/air mixture. We further developed the spark-plug sensor to measure the local fuel–air concentration in the spark gap during ignition under stratified-charge conditions [29]. The SIBS system was able to directly characterize the equivalence ratio in the vicinity of the spark plug during discharge, and the accuracy was improved by increasing the spark plug gap to 1.5 mm, which increased the stability of spark discharge initiation [30]. We have previously measured the concentration of hydrogen injected into nitrogen with an ambient pressure of 0.5 MPa in a constant-volume vessel [31], which allowed us to characterize the spatial distribution of the equivalence ratio across the jet and along its axis. The purpose of previous paper is to develop and confirm the ability of SIBS sensor to measure fuel concentration. However in this paper, to understand the mixing process of direct injection of a hydrogen jet, we investigate the spatial distribution of the hydrogen concentration at higher ambient pressures up to 1.5 MPa. It is able to obtain an empirical formula for deriving the equivalence ratio for ambient pressure using the SIBS sensor.

Experimental procedure and conditions

Experimental setup

The experiment was carried out in two stages. The first was to study the relationship between the ratio of the intensities of the atomic emission lines of hydrogen and nitrogen, I_H/I_N, and the equivalence ratio of hydrogen and nitrogen at various ambient pressures to calibrate the SIBS system. The second was to measure the local fuel concentration of the hydrogen jet at different ambient pressures of nitrogen. Fig. 1 shows the experimental apparatus used in this study. A constant-volume vessel equipped with a SIBS sensor was used, and a swirl-type direct-injection (DI) injector with a single orifice that was 1.0 mm in diameter was installed at the top of the vessel. The experimental set-up is described in detail in Ref. [31].

Fig. 2 shows the SIBS sensor, which was developed using a commercially available spark plug with an optical fiber installed at the center. An optical UV-grade quartz fiber with a core diameter of 1000 μm and an outer diameter of 1250 μm was used to collect the light. The spark-plug gap was 1.5 mm, which provides a stable spark discharge. The optical fiber had a numerical aperture (NA) of 0.20, and covered the area