

An In-cylinder Laser Absorption Sensor for Crank-angle-resolved Measurements of Gasoline Concentration and Temperature

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ABSTRACT

Simultaneous crank-angle-resolved measurements of gasoline concentration and gas temperature were made with two-color mid-infrared (mid-IR) laser absorption in a production spark-ignition engine (Nissan MR20DE, 2.0L, 4 cyl, MPI with premium gasoline). The mid-IR light was coupled into and out of the cylinder using fiber optics incorporated into a modified spark plug. The absorption line-of-sight was a 5.3 mm optical path located closely adjacent to the ignition spark providing spatially-resolved absorption. Two sensor wavelengths were selected in the strong bands associated with the carbon-hydrogen (C-H) stretching vibration near 3.4 μm , which have an absorption ratio that is strongly temperature dependent. Fuel concentration and temperature were determined simultaneously from the absorption at these two wavelengths. The two mid-IR laser wavelengths were simultaneously produced by difference-frequency-generation in a periodically poled lithium niobate (PPLN) crystal using one signal and two pump lasers. The pump lasers were modulated at different frequencies allowing frequency demultiplexing of the laser light transmitted through the spark plug probe, providing simultaneous absorption signals at the two mid-IR wavelengths. A model of the absorption cross section of gasoline was used to account for variation in the absorption signals as a function of fuel blend using the known fractions of olefins, aromatics, and paraffins. Validation experiments of this fuel and temperature sensor included comparison of in-cylinder data with more traditional exhaust gas diagnostics. For an engine operating at steady-state with a nominally homogeneous charge, measurements of air-fuel ratio (A/F) as a function of load agreed well with the air-fuel

ratios inferred from analysis of exhaust emissions; in-cylinder measurements performed with quite different fuel blends also agreed well with the exhaust diagnostics.

INTRODUCTION

Modern internal-combustion (IC) engine designs often optimize performance by the complex timing of fuel injection and/or valve actuation. Therefore a tool to measure crank-angle-resolved fuel concentration would be quite useful for the testing and validation of new gasoline engine designs. We report here the design and development of such a sensor and its first use to monitor the crank-angle-resolved fuel vapor concentration near the spark plug in a production, port-injection gasoline engine. The sensor monitors gasoline vapor using optical absorption by transitions in the C-H stretching vibrations of the component hydrocarbons in the gasoline blend.

Optical absorption has the potential to provide the needed crank-angle resolution, and the development of gasoline measurements by optical absorption has been an active area of research. Diode laser technology in the near-infrared is extremely well developed owing to investments by the telecommunications industry, and near-IR laser absorption has been used to monitor gasoline in the overtone vibrational features of the C-H stretch near 1.6 μm .¹ Unfortunately, these near-IR transitions are relatively weak, suggesting that stronger transitions would be useful for the short optical pathlength available in a piston engine. Gasoline is a blend of hydrocarbons, all of which have strong absorption features in the mid-infrared near 3.4 μm associated with their C-H stretching vibrational transitions. The hydrocarbon C-H

stretching region overlaps strongly with the 3.39 μm wavelength of an infrared HeNe laser, and this laser source has been used for a variety of successful absorption measurements of gasoline and gasoline surrogates. ^{2,3,4,5,6,7,8,9,10,11} Kawamura et al.⁵ used a constant value of the absorption cross section to make fuel-air equivalence ratio measurements in a motored engine. Tomita et al.⁷ also assumed a constant absorption cross section in measuring A/F next to the spark plug electrode in a fired engine. Kakuho et al.¹⁰ calibrated fired engine results to measurements at TDC of a motored engine supplied with a stoichiometric flow rate of air and fuel. However, the gasoline absorption cross section varies with temperature, and hence quantitative measurements of gasoline from absorption using a single laser require an independent source of crank-angle-resolved temperature and knowledge of the temperature dependence of the absorption for the particular blend of gasoline being used.

In the work reported here, four significant challenges were overcome to produce a sensor for quantitative, in-cylinder monitoring of gasoline vapor in a production IC engine: First, a quantitative absorption cross section model was formulated to account for the variation with composition of the specific gasoline blend used for testing. Second, this model of the absorption cross section was shown to account for the variation with temperature (and pressure). Third, an optical access scheme was created to let the sensor transmit light through a measurement volume inside the engine. Fourth, a new measurement strategy and associated hardware were developed to provide measurements of optical absorption of gasoline with a measurement bandwidth of $\sim 10\text{kHz}$ for crank-angle resolution. Although the solutions to each of these challenges have been published, we briefly review them below to provide a complete description of the sensor design. The fuel measurement results using this sensor in a production, port-injection gasoline engine (Nissan MR20DE, 2.0L, 4 cyl, MPI) are then described. First, measurements to validate the sensor performance were conducted with the engine operating with two quite different blends of premium grade gasoline. Second, the first crank-angle-resolved results of gasoline concentration are presented for this engine. A companion paper will report extension of this sensor to a direct injection engine where gasoline droplets produce optical scattering that interferes with the measurement of gasoline vapor absorption.¹²

MODEL FOR GASOLINE ABSORPTION

VARIATION OF ABSORPTION CROSS SECTION WITH BLEND

Quantitative optical absorption measurements rely on a known absorption cross section versus wavelength. Unfortunately like other practical hydrocarbon fuels, gasoline is a blend with wide variations in composition. For example, Fig. 1 illustrates the absorption cross section for two different premium gasoline blends, one with a high (39%) fraction of aromatic hydrocarbons and one with a low (6%) aromatic fraction. Note the abscissa is plotted in wavenumber (cm^{-1}) units where frequency, ν , is defined as the inverse of wavelength, $1/\lambda$ with λ in units of cm. For the mid-infrared light used by this sensor, when wavelength is reported directly, the units of microns (μm) are traditionally used. The value of the absorption cross section varies as much as a factor of two for these different blends of premium gasoline. This illustrates that quantitative absorption detection would either need to measure the absorption cross section for each blend used for engine testing or needs a model based on available composition data.

The relative fraction of structural classes (aromatics, olefins, paraffins) and oxygenates in a gasoline blend used at an engine research laboratory is routinely determined by two standard tests (ASTM D1319 and ASTM D4815). We investigated a wide range of gasoline blends and discovered that the contribution to the absorption cross section spectrum of gasoline from each structural class could be represented by a “class-averaged” absorption cross section spectrum. This allowed specification of the gasoline cross section spectrum from a sum of these class-averaged spectra weighted by the class composition of the gasoline blend. The cross section model was refined by using different absorption spectra for normal- and iso-paraffins and using a different ratio of these two types of paraffins for regular and premium gasoline. Details of the composition-dependent model for gasoline absorption cross section have been published in Klingbeil et al.¹³ This model was tested previously for 21 different gasoline blends that cover the full range of gasoline composition. This previous work found the errors in the absorption cross section predicted by the measured hydrocarbon class fractions and the model of Klingbeil et al. were less than 5%.

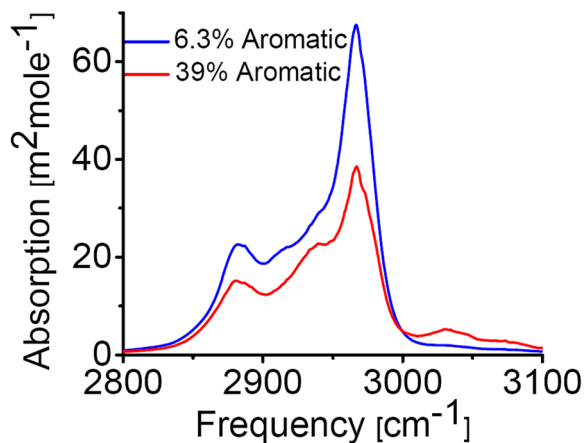


Figure 1. Absorption cross section in the C-H stretch region of the spectrum between 2800 and 3100 wavenumbers (3.571 and 3.226 μm) for two premium blends of gasoline with fractions of aromatic compounds of 6.3 and 39% by volume taken at 50C.

VARIATION OF ABSORPTION CROSS SECTION WITH TEMPERATURE

The absorption cross section spectrum is temperature dependent as illustrated in Fig. 2 for a sample of premium grade gasoline. The spectra were taken with Fourier transform infrared spectroscopy (FTIR) over a temperature range from 27 to 525 C. Note there is nearly a 30% drop in the peak value of the absorption cross section as the temperature increases. This temperature dependence provides an opportunity to determine the gas temperature from the ratio of measurements at two different sensor wavelengths. If the temperature-dependent class-averaged spectra are used in the composition-dependent model for gasoline absorption described above, we find that the temperature dependence of the gasoline absorption is modeled with only a slight increase in the uncertainty (5% to 8%).¹³ This temperature variation provides opportunity for simultaneous measurements of gasoline concentration and temperature. The ratio of absorption measured at two different wavelengths, marked by arrows in Fig. 2, is a sensitive function of temperature. This two-color method of simultaneous measurements of hydrocarbon fuel and gas temperature has been previously discussed in detail for n-heptane¹⁴ and n-dodecane.¹⁵ These previous publications validated the measured temperature and concentration against known values in shock-heated flows. Guidelines for wavelength selection to optimize temperature sensitivity were also discussed.

No significant variation of the gasoline absorption spectrum with pressure was found for measurements up to 10 atm. This is not surprising as the absorption spectrum is a superposition of many individual transitions which are more closely spaced than their spectral width. Thus, the net effect of pressure

broadening at any given wavelength in the absorption spectrum is expected to be quite small.

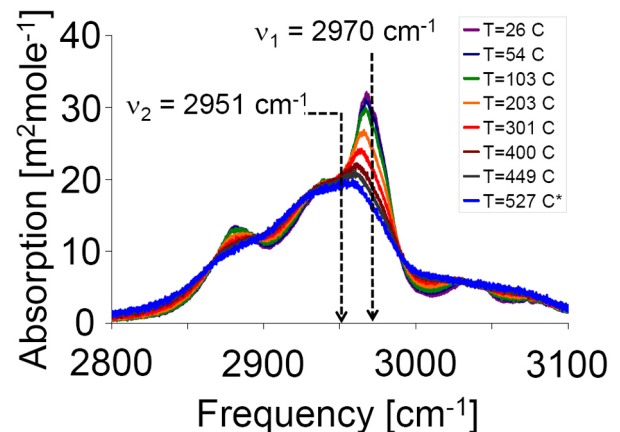


Figure 2. Temperature variation of the absorption spectrum of a premium grade gasoline blend in the region of the C-H stretch taken with FTIR; arrows mark attractive locations for two-color absorption measurements of concentration and temperature.

PROBE FOR OPTICAL ACCESS IN PRODUCTION ENGINES

Optical access of laser light in and out of the cylinder used the standard spark plug port of the production engine as illustrated in Fig. 3. A similar fiber-optic spark plug probe was reported previously for measurements of water vapor absorption to determine gas temperature and H₂O concentration.¹⁶ The water vapor sensing exploited the robust lasers and fiber optics available in the near-infrared. The current fuel measurements are in the mid-infrared, which is beyond the range of transmission in silica-based fibers. Thus, this new implementation used fluoride glass fibers; the laser input was by single-mode fiber. The laser light enters the cylinder through a sapphire window in the probe shown in Fig. 4, is reflected from a gold mirror, and exits the cylinder through the same window where it is collected onto a 200 μm core multimode fiber for transmission to the detector as illustrated in Fig. 3. The folded optical path has a length of 1.06 cm near the spark gap. The custom spark plug was matched to the same specifications as the standard plugs used in the production engine.