A Mid-Infrared Laser Absorption Sensor for Carbon Monoxide and Temperature Measurements

by

Jeremy Vanderover

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Examining Committee:

Matthew Oehlschlaeger, Thesis Adviser

Michael Jensen, Member

Linda McGown, Member

Zvi Rusak, Member

Rensselaer Polytechnic Institute
Troy, New York

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ABSTRACT

A mid-infrared (mid-IR) absorption sensor based on quantum cascade laser (QCL) technology has been developed and demonstrated for high-temperature thermometry and carbon monoxide (CO) measurements in combustion environments. The sensor probes the high-intensity fundamental CO ro-vibrational band at 4.6 µm enabling sensitive measurement of CO and temperature at kHz acquisition rates. Because the sensor operates in the mid-IR CO fundamental band it is several orders of magnitude more sensitive than most of the previously developed CO combustion sensors which utilized absorption in the near-IR overtone bands and mature traditional telecommunications-based diode lasers. The sensor has been demonstrated and validated under operation in both scanned-wavelength absorption and wavelength-modulation spectroscopy (WMS) modes in room-temperature gas cell and high-temperature shock tube experiments with known and specified gas conditions. The sensor has also been demonstrated for CO and temperature measurements in an atmospheric premixed ethylene/air McKenna burner flat flame for a range of equivalence ratios (Φ = 0.7-1.4).

Demonstration of the sensor under scanned-wavelength direct absorption operation was performed in a room-temperature gas cell (297 K and 0.001-1 atm) allowing validation of the line strengths and line shapes predicted by the HITRAN 2004 spectroscopic database. Application of the sensor in scanned-wavelength mode, at 1-2 kHz acquisition bandwidths, to specified high-temperature shock-heated gases (950-3400 K, 1 atm) provided validation of the sensor for measurements under the high-temperature conditions found in combustion devices. The scanned-wavelength shock tube measurements yielded temperature determinations that deviated by only ±1.2% (1-σ deviation) with the reflected shock temperatures and CO mole fraction determinations that deviated by that specified CO mole fraction by only ±1.5% (1-σ deviation). These deviations are in fact smaller than the estimated uncertainties of 2.5-3% in both sensor determined temperature and CO.

Enhancement of the sensor sensitivity can be achieved through use wavelength-modulation spectroscopy (WMS). Similarly, under WMS operation the sensor was

applied to room-temperature gas cell (297 K, 0.001-1 atm) measurements, which indicate that the sensor sensitivity in WMS operation is approximately an order-of-magnitude greater than that achieved in scanned-wavelength mode, and high-temperature shock-heated gases (850-3400 K, 1 atm), which validate the sensor for sensitive thermometry at combustion temperatures. In WMS mode the temperature measurements show 1-σ deviation of ±1.9% with the reflected shock conditions. High-temperature CO concentration measurements require calibration to scale the measured WMS-2*f* peak height with a simulated WMS-2*f* line shape. However, using single point calibration for each CO containing mixture studied resulted in fairly good agreement (1-σ deviation of ±4.2%) between measured and simulated WMS-2*f* peak height. In other words, CO mole fraction determinations (proportional to peak height) were achieved with deviation of ±4.2% with specified CO mole fraction.

Sensor measurements made at a 1 kHz acquisition bandwidth in an atmospheric pressure ethylene/air flat-flame produced by a McKenna burner for equivalence ratios from 0.7 to 1.4 were in excellent accord with thermocouple measurements and chemical equilibrium predictions for CO based on the thermocouple temperatures for rich conditions. At lean conditions sensor temperature determinations are lower than thermocouple determinations by around 150 K due to the cool flame edge and sensor CO measurements are greater than those predicted by chemical equilibrium due to super-equilibrium CO in the cool flame edge.

The CO sensor developed and described herein and validated in room-temperature cell, high-temperature shock tube, and flat-flame burner measurements has potential for a vast array of measurements in combustion, energy, and industrial gas sensing applications. It has unsurpassed sensitivity due to the use of the fundamental CO band at 4.6 μm and provides kHz acquisition bandwidths necessary for high-speed measurements in these systems.

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