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Single-Ended Infrared-Laser-Absorption Sensing of Gas Properties

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Abstract: This paper presents the design and application of a compact, single-ended laser-absorption sensor for measuring temperature and H_2O in high-temperature combustion gases. The sensor employs two fiber-coupled, near-infrared diode lasers and a fiber bundle for pitching the laser light and collecting the light that is backscattered off a native surface. The transmitting and receiving end of the sensor is housed within a 1/8" NPT pipe fitting along with a 6 mm diameter lens to increase the collection efficiency. These attributes enable the sensor to be directly integrated into a sealed, high-temperature environment without windows. The sensor was demonstrated with measurements of temperature and H_2O mole fraction in a burner using calibration-free wavelength-modulation-spectroscopy techniques with a measurement bandwidth up to 25 kHz.

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1. Introduction

Single-ended laser-absorption-spectroscopy (LAS) sensors have become a practical tool for characterizing combustion environments with limited optical access [1]. Recently, single-ended LAS sensors have been used to characterize low-pressure burners [2, 3], flames [4, 5], rotating-detonation engines [6], and internal-combustion engines [7]. These sensors operate by pitching laser light through a test gas and collecting it using either optical probes (e.g., sapphire rods) protruding into the gas or via backscattering off embedded reflectors or native surfaces. The amount of light absorbed by the gas is then calculated and used to determine gas properties via absorption spectroscopy models.

The work presented here builds upon that of Goldenstein et al. [4] who used a fiber-bundle-based design to measure gas temperature, pressure, and H_2O or CH_4 mole fraction at stand-off distances from 10 cm to 10 m. Here, a fiber bundle was integrated into a compact and rugged housing capable of withstanding direct exposure to high-temperature environments (i.e., no windows are required) while sealing the test environment from the ambient. The following sections present the architecture and initial demonstration of this single-ended LAS sensor in a propane-air burner.

2. Experimental Setup

Distributed-feedback diode lasers near 1392 and 1343 nm were used to provide two-color measurements of gas temperature and H_2O mole fraction using both scanned- and fixed-wavelength-modulation-spectroscopy techniques employing $1f$-normalized $2f$ detection (see [8] for more details). In all experiments, the lasers were frequency multiplexed at 160 and 200 kHz via injection-current modulation. During fixed-WMS-$2f/1f$ experiments, the wavelength of each laser was centered at the linecenter of the absorption transition of interest, while during scanned-WMS-$2f/1f$ experiments the lasers were swept across their respective absorption transitions at 2 kHz to enable measurements of WMS-$2f/1f$ spectra. The light from each laser was combined and split onto two paths using a fiber multiplexer, thereby enabling a direct comparison between measurements acquired using the single-ended-sensor architecture and a conventional line-of-sight (LOS) architecture (see Figure 1).

Figure 1 illustrates the burner, optical components, and experimental setup used in the work discussed here. The single-ended sensor used a fiber bundle consisting of a single SMF-28 fiber for pitching the laser light and 6 multimode fibers for catching the backscattered laser light (see [4] for more details). The fiber bundle was integrated into a custom 1/8" NPT pipe fitting with internal threads on one end to accommodate a conventional FC/PC-to-SMA mating sleeve. On the opposite end, a retaining ring was used to secure a single lens (6 mm diameter, 15 mm focal length, AR-coated, plano-convex) against a shoulder tilted at 7° relative to the fiber axis (to avoid collecting backscatter off

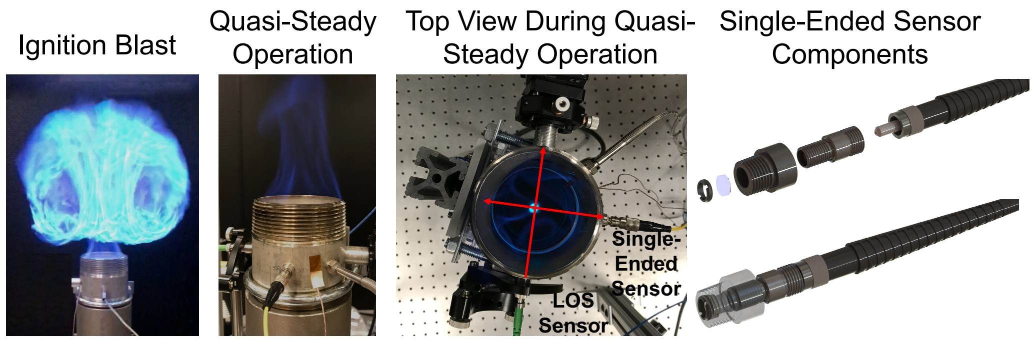

Fig. 1. Experimental setup used to acquire measurements of temperature and H_2O in a propane-air burner.

the flat lens face). The distance between the lens and fiber was adjusted to maximize the collection efficiency (as done in [4]) and fixed in place using a locknut.

The single-ended sensor was installed into a stainless-steel pipe (3" inner diameter) that was connected to a swirl-mixed propane-air burner. An optical collection efficiency of 2.5% was achieved for this 3" (single pass) working distance. Due to the simplicity of this design, no alignment adjustments are required, thereby enabling installation in a matter of seconds (equivalent to installing a pipe plug).

3. Results

Two experiments were conducted to demonstrate the versatility and robustness of the single-ended LAS sensor. 1) high-bandwidth fixed-WMS-$2f/1f$ measurements were acquired during an ignition blast, and 2) scanned-WMS-$2f/1f$ measurements were acquired at 2 kHz for 100 ms, once per minute over a period of 12 minutes with the burner operating at quasi-steady-state.

Figure 2 shows a temperature time history measured using fixed-WMS-$2f/1f$ with a 25 kHz measurement bandwidth during an ignition blast. The measurements acquired using both architectures (i.e., line-of-sight or single-ended) exhibit excellent agreement throughout the measurement duration (nominally within 10 K of each other), suggesting that the temperature field behind the blast wave is axisymmetric and that the single-ended sensor is accurate. Further, the two sensor architectures yielded comparable measurement precision: 1σ variation of 22 K (line-of-sight) and 26 K (single-ended) during the steady portion of the test (i.e., from 15 to 25 ms).

Figure 3 shows example scanned-WMS-$2f/1f$ signals and temperature and H_2O mole fraction results acquired over

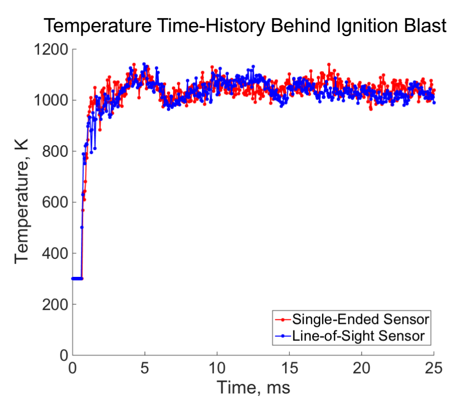

Fig. 2. Temperature time history acquired during an ignition blast using fixed-WMS-$2f/1f$ with the single-ended and conventional line-of-sight sensor architectures.

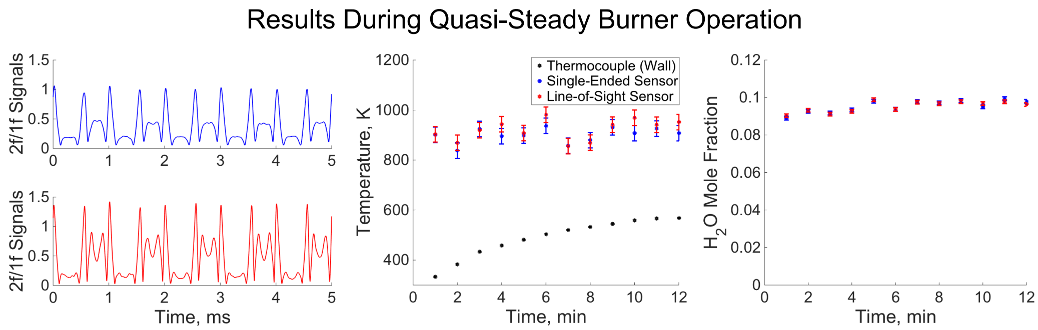

Fig. 3. Representative scanned-WMS-$2f/1f$ signals and measurements of temperature and H_2O mole fraction acquired using the single-ended sensor with the burner operating at quasi-steady-state.

a 12 minute period with the burner operating at quasi-steady-state. The WMS signals acquired using the single-ended architecture exhibit a signal-to-noise ratio of $\approx$1000 at linecenter. For the temperature and H_2O results shown, each data point represents an average over the 100 ms measurement duration and the error bars represent a 1σ precision. The temperature and H_2O mole fraction measured along both paths agree within precision of each other and exhibit a typical 1σ precision of 25 K and 0.1% by mole, respectively. During the 12-minute test, the outer wall temperature of the burner increased from 330 to 570 K, which suggests that the temperature of the lens (employed by the single-ended sensor) reached a temperature of at least 570 K. The optical power collected by the single-ended sensor and the signal-to-noise ratio of the WMS signals did not degrade during the entire 5-day measurement campaign which consisted of over 100 fired tests.

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