Measurements of Temperature and H_2O Mole Fraction in a Glass Furnace using Diode Laser Absorption

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***Abstract*—Temperature and H_2O mole fraction have been measured non-intrusively in a float glass furnace using a newly developed tunable diode laser sensor system: the MetroLaser LTS-100. The technique utilizes a single near-infrared laser to measure H_2O absorption lines that are inactive at room temperature, therefore the measurement does not suffer from interference from ambient H_2O, resulting in an instrument that can be placed a safe distance from the furnace being measured. Results are presented of measurements at a rate of 5 Hz during four hours of operation, revealing details of the firing and exhausting cycles of the furnace. The measured temperatures had a precision of 11 K rms and an estimated accuracy of 50 K. These results represent a capability that is not available with conventional sensors, and may lead to improved methods of furnace operation and control.**

I. INTRODUCTION

Tunable diode laser absorption sensors are finding an increasing number of applications in industrial settings. Inexpensive near-infrared lasers and fiber optic components are especially well suited to industrial environments because they offer the potential to make non-intrusive temperature and species measurements in a rugged package. Because they have been developed for the large telecommunications market, these components generally require very little maintenance, and tend to have very long lifetimes. Recent industrial applications include coal-fired power plants [1-3], a full scale ethylene cracking furnace simulator [4], a steel furnace [5], and a waste incinerator [6]. To date, however, there has been very little work done in applying diode laser absorption sensors to the glass industry.

Float glass plants produce glass panels for windows, mirrors and a wide variety of other purposes. They require constant monitoring to ensure consistency of product. Small variations in operating conditions can cause defects in the product that render it worthless. A continuous real-time sensor for temperature and species could be of great help in providing the needed consistency by allowing furnace operators to monitor combustion gas conditions.

Current techniques for monitoring the consistency of furnace operation involve thermocouples embedded into refractory walls, optical pyrometers for viewing refractory surfaces inside the furnace, and gas sampling with non-dispersive or Fourier transform infrared analysis. However, none of these techniques provides real-time temperature and species measurements in the combustion gases, which could perhaps be used for feedback and control for maximum stability and efficiency of the furnace. A prototype sensor developed by MetroLaser, the LTS-100, is demonstrated here that offers this capability.

At the invitation of a major glass producer, we performed experiments using the LTS-100 to measure temperature, H_2O mole fraction, and overall attenuation in a glass furnace. The goals were (1) to investigate how the instrument would perform in this industrial environment, (2) to evaluate the suitability of the technique for long-path measurements, and (3) to provide the host company with valuable data that is not obtainable using industry standard measurement techniques.

II. EXPERIMENTAL SETUP

The application chosen here was a float glass plant that uses a cross-fired furnace with regenerative heat recovery. Fig. 1 shows a diagram of the furnace, which consists of a tank containing molten glass into which the raw materials are fed, and two regenerator chambers, one on each side of the molten glass chamber. The furnace operates in a cycle, reversing direction approximately every 20 minutes. Air flows up into one of the regenerators, gets preheated, and combines with a fuel spray to produce flames directed over the surface of the molten glass. Hot gases exit through the regenerator on the other side. The exhaust gases heat a brickwork matrix in the regenerator that serves as a thermal reservoir, supplying heat to the incoming combustion air when the cycle reverses. Cycling the flow maintains high temperatures in the brickwork matrix, bringing the incoming air to a temperature of about 1590 K before combustion.

A. Beam Launch and Catch

The layout for all experiments conducted is depicted in Fig. 1, in which the furnace is shown firing from right to left, and the raw materials, which include sand, saltcake,

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limestone, soda ash, etc., are fed in at the bottom. As shown in Fig. 1, a fiber collimator was placed at one end of the left-side furnace regenerator and a detector was placed at the other end. The total optical path through this part of the furnace was 18.3 m. The LTS-100 processing unit was placed near the detector end to allow the raw signal to be viewed while aligning the laser. A near-infrared laser was coupled to a 75-m single-mode telecom fiber to deliver light to the collimator at the other side. The collimator was located 4.1 m from the furnace entrance port, which was a 12-cm x 18-cm rectangular opening. Fig. 2 shows the detector and LTS-100 processing unit on the receiving end of the furnace. The detector was placed 2.3 m from the furnace exit port, which can be seen glowing at the upper right in the photograph.

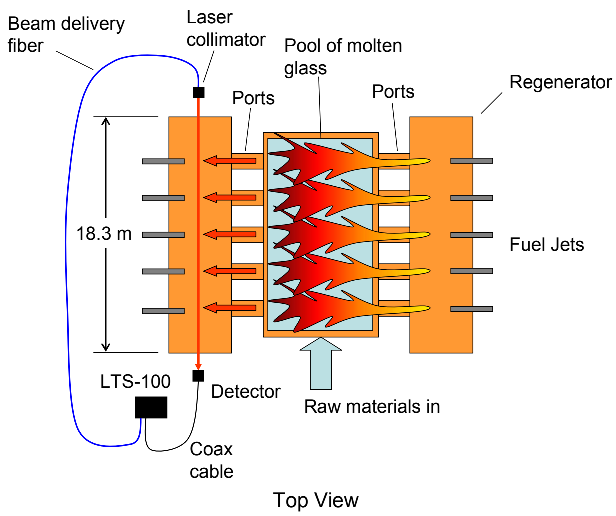

Fig. 1. Layout of the experiment to conduct diode laser measurements in a cross-fired float glass furnace.

Fig. 2. Detector mounted on a tripod at right, receiving signals from a laser beam passing out of the regenerator section of a float glass furnace. The LTS-100 processing unit can be seen on the left.

B. Alignment

To align the beam through the furnace, a visible laser with a wavelength of 655 nm was used in place of the near-infrared beam by coupling it to the beam delivery fiber. The plan was to direct the visible beam through the combustion zone while observing the spot on the opposite wall, and steer it through the exit port. However, this approach did not work because the light intensity inside the furnace was too great. Several types of optical filters were tried for blocking the furnace emission while trying to view the laser spot, but no spot was observed using any of them. The filters tried were a number 9 welding mask, and number 5 welding mask, and a 655-nm narrowband dielectric filter. Each of these filters blocked enough of the furnace emission to enable looking into the furnace. However, even when using the 655-nm interference filter, there was too much flame emission within the bandpass of the filter, overwhelming the eye's ability to detect the 655-nm laser spot on the furnace wall. Thus, another alignment method had to be found.

Alignment of the beam through the furnace was successfully accomplished using a gun sight type of alignment system. Fortunately, the optical density was low enough that when looking through the furnace entrance port one could see the exit port on the other side. This made it possible to point the collimator toward the exit port using the gun sight alignment system. Then the visible beam was found coming out of the exit port, and the detector was placed accordingly to catch it. Once the alignment was accomplished with the visible laser, the delivery fiber was re-connected to the near-infrared laser and the LTS-100 could be used for measuring average temperature and H_2O concentration along the 18.3-m path through the furnace.

III. Results and Discussion

A. Measured Lineshapes

The long path through the furnace provided strong differential absorption signals as the laser was scanned across two prominent H_2O lines, yielding high signal-to-noise ratios (SNRs). Fig. 3 shows experimental absorbances plotted against laser scan time for both parts of the cycle: (a) firing, and (b) exhausting. Absorbance is defined as the natural log of the transmittance, I/I_0, where I is the measured intensity at the detector, and I_0 is the baseline intensity, which is what the intensity would be in the absence of the two prominent H_2O lines. The baseline is obtained by curve fitting a portion of the absorption scan that excludes the two prominent lines. Temperature is obtained from the ratio of areas under the two lines, and H_2O concentration is obtained from the peak height of the second line. The details of the technique are to appear in [7].

The two prominent lines can be seen in Fig. 3, the first at about 6 µs into the scan, and the second at about 32 µs, although they are much stronger for the exhausting case, (b), than for the firing case, (a). This is because there is more H_2O present in the exhausting case. During firing, ambient air is being drawn from outside the furnace and is heated to about 1590 K by the brickwork matrix in the regenerator. The measurement is being made at a location just upstream of where it mixes with a spray of fuel oil droplets and combusts. In Fig. 3, five individual scans are plotted to show reproducibility for both the firing and exhausting cases. The scans in each case were taken about one second apart, each depicted as a different color. It can be seen in Fig. 3 that these five scans essentially overlie one another in both the firing and exhausting cases, indicating a very low noise level in the measurement. Note that the entire scan occurs within 40 μs. An advantage of this technique is that each measurement is essentially instantaneous, enabling accurate measurements in a highly turbulent environment.

The SNR of the measured lineshape can be calculated from the maximum absorbance signal and the noise level of absorbance, which is about 5×10^{-4}. From Fig. 3, the maximum absorbance is about 0.2 for the firing case and about 1.0 for the exhausting case, resulting in a SNR of 400 and 2000 for the firing and exhausting cases, respectively. These high SNR values are significantly greater than what can be expected from existing temperature and species measurement techniques, and may someday lead to unprecedented levels of process control.

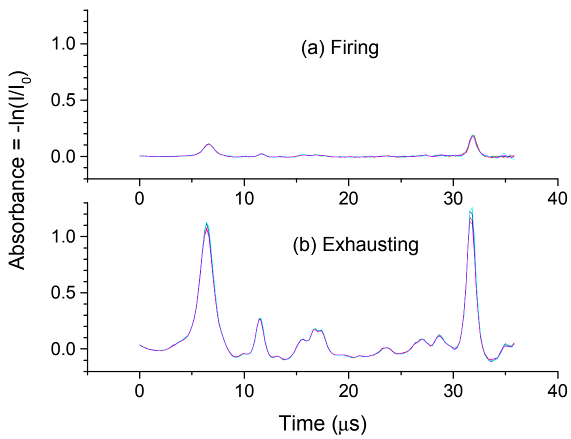

Fig. 3. Measured lineshapes of the H_2O spectrum near 1483 nm in a glass furnace during firing and exhausting cycles. The indivudual curves are separate scans at the same conditions.

B. *Temperature and H_2O Concentration Measurements*

The high SNR's resulted in data of exceptional quality that is probably not obtainable using other existing temperature and H_2O sensors. Fig. 4 shows plots of temperature and H_2O concentration as a function of measurement time during four hours of furnace operation. Two sets of data were acquired, each lasting about two hours, with a 15-minute break in between. For the first set, each data point was written to file as soon as it was processed, resulting in a data rate that varied from about 30 Hz at the start to about 10 Hz after two hours. The slowing of the data rate with time resulted because of a non-optimized memory allocation in the signal processing program. A newer version of the program will not have this limitation. In the second set, a running average of 10 data points was written to file at a fixed rate of 5 Hz. The first data shown in Fig. 4 was digitally filtered afterward with a 5 Hz bandwidth so that it could be compared to the second set. At this bandwidth, the rms precision in the temperature data was found to be 11 K, and the accuracy was calculated to be about 50 K, based on the uncertainty in the flame temperature used as a calibration source [7].

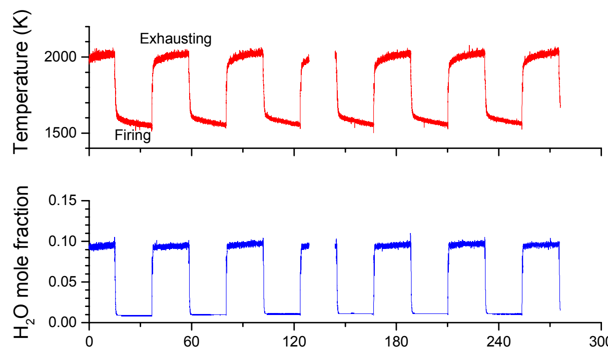

Fig. 4. Time histories of temperature and H_2O mole fraction in a glass furnace, measured by a diode laser sensor.

The level of noise in the raw transmittance signal (not shown) was considerably more than that in the resulting temperature and H_2O data. This reflects the fact that the temperature and H_2O are obtained from the resonant absorbance of the molecule. The absolute transmittance of the beam is fluctuating due to beamsteering from the turbulence. However, the resonant absorbance is a relative measurement obtained from the absorbance at line center minus the baseline absorbance. Thus, the fluctuating baseline is subtracted out and the resonant absorbance can be measured much more accurately than the absolute absorbance, or transmittance.

The operating characteristics of the furnace can be seen in the data of Fig. 4. During firing, the temperature and H_2O concentration are seen to be about 1590 K and 1 %, respectively. These values represent the condition of the air drawn into the furnace just upstream of the combustion zone. The H_2O concentration of 1 % is essentially that of the ambient air, and the temperature of 1590 K is due to preheating by the brickwork matrix that serves as a thermal reservoir. During exhausting, both the temperature and H_2O concentration are significantly higher, about 2030 K and 10 %, respectively. This is to be expected, since combustion gases are passing by the measurement location for this case. The measured values of both temperature and H_2O concentration throughout the cycle are consistent with the design specifications of the furnace, according to the plant engineers.

Details in the heating and cooling rates of the furnace are evident in the temperature traces of Fig. 4. As the exhausting part of the cycle begins, the temperature rapidly jumps to about 1950 K. Then it slowly rises, reaching its maximum of about 2030 K at the end of the half cycle. Prior to the application of this sensor, these characteristics were not known, since it is not possible to measure these temperatures using existing sensors. A similar time dependence can be seen in the cooling rates during the low temperature parts of the cycle, during firing, where all of these half cycles are observed to be slanted downward in Fig. 4. The cooling slope during this part of the half cycle would depend upon the mass of brickwork that heats the air in the regenerator. A potential use of this sensor would be to monitor the performance of this brickwork matrix as a thermal reservoir.

Fig. 5 shows some of the data from Fig. 4 near a transition from low to high temperature with the time axis expanded. In this example, details of the process can be discerned in the temperature and H_2O traces, both of which show an inflection point occurring at about 211 minutes. The initial rise before the inflection is caused by the flow reversal bringing hot gases from above the melt across the beam path. As new incoming air continues to flow, the temperature dips slightly, followed by another sharp rise as the fuel injection begins and ignition occurs. The ability of this sensor to resolve such transients in real time could help plant engineers to monitor furnace performance and identify problem areas, possibly leading to improvements in performance through more accurate timing of cycle events.

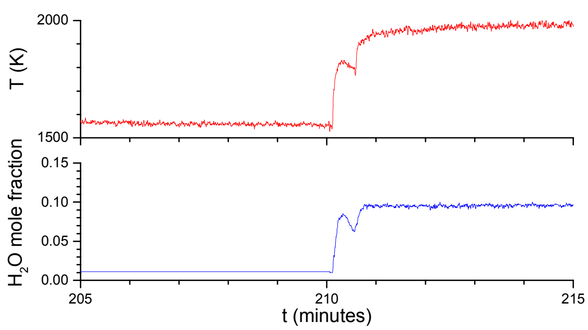

Fig. 5. Diode laser measurements in a glass furnace regenerator during a transition from firing to exhausting.

IV. Conclusions

A diode laser sensor has been applied to the measurement of temperature and H_2O concentration in the combustion gases inside a float glass furnace, yielding the first ever measurements of these quantities in such a furnace. Scanned wavelength absorption measurements through a 18.3-m path through the furnace resulted in low measurement noise, with an observed precision in temperature measurements of 11 K rms, and an accuracy of about 50 K. Real time measurements were obtained that revealed details about the operating characteristics of the furnace, including the capturing of transient processes that could perhaps be used for timing of cycle events in a feedback and control loop to optimize efficiency and minimize defects.

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