Accuracy of a Tunable Diode Laser Sensor in Large Scale Furnaces: Initial Test Results

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Abstract

The MetroLaser LTS-100 Laser Temperature Sensor is an instrument which employs Tunable Diode Laser Absorption Spectroscopy (TDLAS) to non-intrusively measure gas temperatures and water concentrations at temperatures up to 4000°F. Potential industrial applications for the sensor include process monitoring and control, as well as combustion diagnostics. Previous testing has demonstrated the feasibility of using the LTS-100 for measurements in large industrial settings.

To investigate the accuracy of the sensor at a large physical scale, LTS-100 measurement tests were performed on two levels of a full-scale ethylene cracking furnace simulator. Nearly simultaneous to each set of LTS-100 measurements, suction pyrometer traverses were performed to independently establish the temperature profile along the LTS-100 beam path. The time-averaged LTS-100 temperature readings were found to be an average of 32°F higher than the path-averaged suction pyrometer data on the lower level of the furnace. Water vapor concentrations were found to be 3.9% and 4.3% lower than theoretical values on the lower and upper levels of the furnace, respectively.

The experimental temperature data acquired during the test program were used in an initial assessment of a numerical model of the LTS-100. This model will be used as the basis for additional investigations into the performance of the LTS-100 in non-uniform temperature environments.

1. Introduction

Sensors employing Tunable Diode Laser Absorption Spectroscopy (TDLAS) techniques are attracting increasing interest for use in industrial environments, as evidenced by recent demonstrations in a coal-fired power plant (Ref 1) and steel, aluminum and electric arc furnaces (Ref 2). A particularly attractive feature of TDLAS-based sensors is the ability to make non-intrusive measurement of high temperature gas properties. By taking advantage of low-cost and reliable telecommunications laser components, the sensors are becoming increasingly well-suited for the industrial marketplace.

The MetroLaser LTS-100 Laser Temperature Sensor is a TDLAS-based sensor which is capable of measuring combustion gas temperatures and water vapor concentrations. The

sensor has previously been demonstrated in a coal-fired power plant (Ref 3) and an oil-fired glass plant (Ref 4).

The LTS-100 employs a two-line TDLAS technique which was designed with the assumption of uniform temperature distribution along the beam path. In general, the temperature measured using this technique along a non-uniform temperature profile can be shown to differ from the path-averaged temperature. The inequality is due to the non-linearity of the two linestrength curves as a function of temperature. The non-linearity results in a distortion of the ratio of path-integrated linestrengths from the path averaged temperature linestrength ratio. A theoretical study of this phenomenon is presented in Ref 5.

It is of interest to potential users of the LTS-100 to understand the accuracy of the system in a typical industrial setting where temperature non-uniformities exist. Toward this end, LTS-100 measurements were performed on an ethylene cracking furnace simulator at the John Zink Company, LLC Research and Development Test Center in Tulsa, OK. Nearly simultaneous to the LTS-100 measurements, comparative temperature measurements were made with a suction pyrometer to determine the temperature along the beam path. LTS-100 and pyrometer measurements were made at two elevations on the furnace.

This paper describes this test program and the resulting initial assessment of the LTS-100 measurement accuracy in a large-scale environment. Initial validation of a numerical model of the system is also presented.

2. TDLAS Theory

Absorption spectroscopy involves the measurement of the attenuation of a beam of light as it passes through a medium. The MetroLaser LTS-100 employs Tunable Diode Laser Absorption Spectroscopy to obtain fully resolved H_2O absorption lineshapes from which temperature and H_2O mole fraction can be computed. The technique operates as follows.

2.1 Spectral Absorbance

A beam of light of wavelength λ passing through an absorbing medium will be attenuated according to the Beer-Lambert relationship,

$$I(\lambda) = I_o(\lambda) \exp(-\alpha_\lambda), \tag{1}$$

in which $I(\lambda)$ is the beam intensity at wavelength λ after propagation through the absorbing medium, $I_o(\lambda)$ is the incident intensity of the beam, and a_λ is the spectral absorbance. The spectral absorbance of a given chemical species is dependent on species concentration, temperature, and pressure. For a single absorption line, i, this can be expressed by

$$\alpha_{\lambda,i} = P X L S_i(T) \phi_i(\lambda - \lambda_0) \tag{2}$$

where P is the static pressure (atm), X is the mole fraction or relative concentration of the probed species (H_2O, in this case), L is the absorption path length (cm), S_i is the

temperature-dependent linestrength specific to line i (cm^{-2}/atm), and $\phi_i(\lambda-\lambda_0)$ is the lineshape function (cm), which accounts for spectral broadening of the absorption line.

The linestrength for a particular absorption line changes with temperature according to the Boltzmann populations of the energy states (Ref. 6)

$$S_i(T) = S_{i,0} \frac{Q_0}{Q(T)} \exp\left[-\frac{hcE_i''}{k}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \times \left[\frac{1 - \exp(-hcE_i''/kT)}{1 - \exp(-hcE_i''/kT_0)}\right] \quad (3)$$

where $S_{i,0}$ is the linestrength at a reference temperature T_0, usually taken to be 73°F. The linestrength and the lower state energy, E_i'', are spectroscopic constants that are specific to the absorption line. $Q(T)$ is the total internal energy partition function, specific to the molecule, and Q_0 is it's value at T_0. The last multiplier, in brackets, accounts for stimulated emission, and is negligible at wavelengths less than 2.5 μm and temperatures below 4000°F.

Spectral absorbance along the beam path for a single absorption line, i, is found by integrating (2)

$$\alpha_{\lambda,i} = \int_o^L PXS_i(T(x))\theta(\lambda - \lambda_0)dx \quad (4)$$

where x is the position along the beam path and the linestrength is written as a function of temperature and beam path position. Total absorption along the beam path across all wavelengths for a single absorption line is:

$$\int_0^\infty \alpha_{\lambda,i}d\lambda = \int_0^\infty \int_o^L PXS_i(T(x))\theta(\lambda - \lambda_0)dxd\lambda \quad (5)$$

Assuming that the lineshape function does not vary significantly with x, (5) can be expressed as:

$$\int_0^\infty \alpha_{\lambda,i}d\lambda = \int_o^L PXS_i(T(x))dx \quad (6)$$

The ratio of total absorption for two absorption lines is:

$$R = \frac{\int_{-\infty}^\infty \alpha_{\lambda,1}d\lambda}{\int_{-\infty}^\infty \alpha_{\lambda,2}d\lambda} \quad (7)$$

Substituting (6) into (7):

$$R = \frac{\int_o^L PXS_1(T(x))dx}{\int_o^L PXS_2(T(x))dx} \qquad (8)$$

Assuming pressure and H_2O concentration are constant along the beam path, (8) can be written as:

$$R = \frac{\int_o^L S_1(T(x))dx}{\int_o^L S_2(T(x))dx} \qquad (9)$$

2.2 Calibration

When the temperature is constant along the beam path, (9) reduces to:

$$R = \frac{S_1(T)}{S_2(T)} \qquad (10)$$

Gas temperature can then be expressed as a function of the measured absorption ratio:

$$T = f(R) \qquad (11)$$

Equation (11) could be obtained theoretically by inserting equation (3) twice into equation (9). However, the measured relationship is somewhat different, since this simplified analysis does not take into account other, weaker, lines that are present. Therefore, the LTS-100 was calibrated using a flat flame burner with a constant temperature distribution along the beam path to experimentally obtain (11) (Ref 3). This equation is then used during real-time operation of the LTS-100 for calculation of temperature based on the measured absorption ratio.

3. Experimental Testing

3.1 Test Configuration

Testing was performed on a full-scale ethylene cracking furnace simulator at the John Zink Research and Development Test Center in Tulsa, OK. The simulator is a refractory-lined furnace with a height of 57' above ground and is designed to be representative of an ethylene cracking furnace (Figure 1). The exterior height of the furnace is 45'-9". The exterior cross section dimensions are 11.5' x 8.5' with a wall thickness of 1'. Air flow through the furnace is by natural draft and is governed by dampers on the burners.

Water flows through vertical pipes along the length of the furnace and across the exhaust duct of the furnace. The water flow simulates the thermal heat transfer of the process fluid in an industrial furnace application.

A tripod-mounted lens and detector assembly was mounted on the west side of the furnace (Figure 2a). A collimating lens and two-axis laser scanner were mounted in an enclosure which was mounted on a tripod on the east side of the furnace (Figure 2b). The tripods are shown positioned on the level 2 of the furnace in Figure 1.
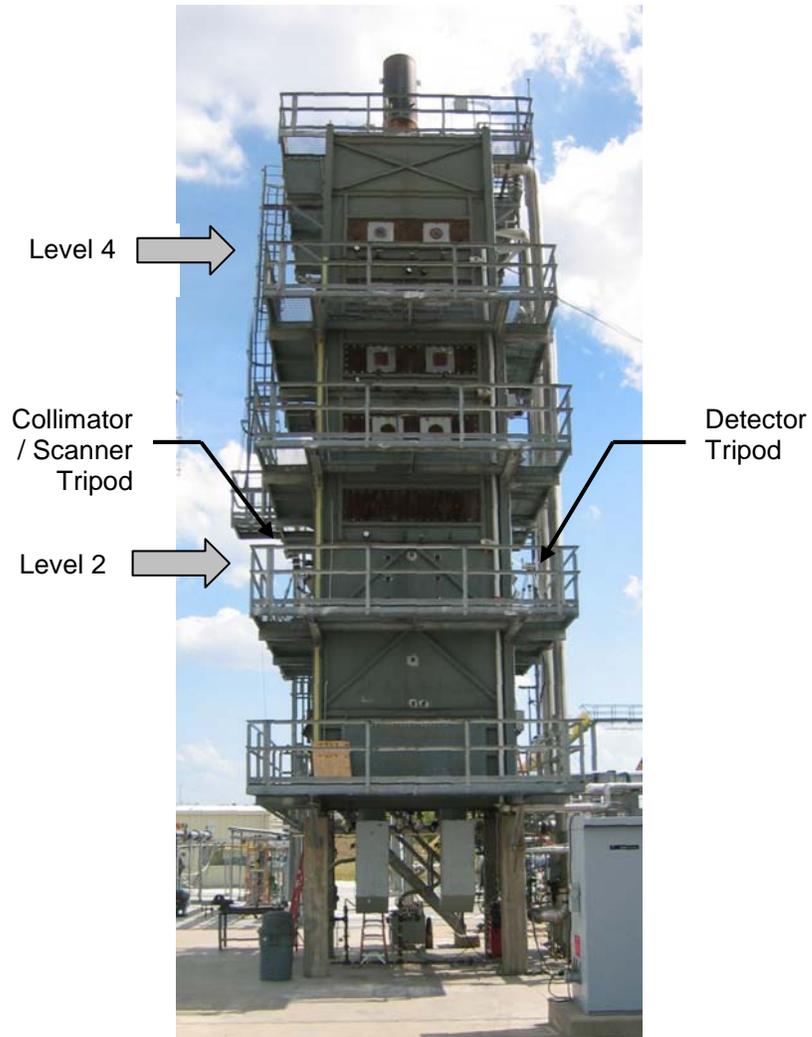
Figure 1.   Ethylene cracking furnace simulator with locations of optical components shown on level 2.

a) Detector Optics   *b) Collimator and Scanner Enclosure*
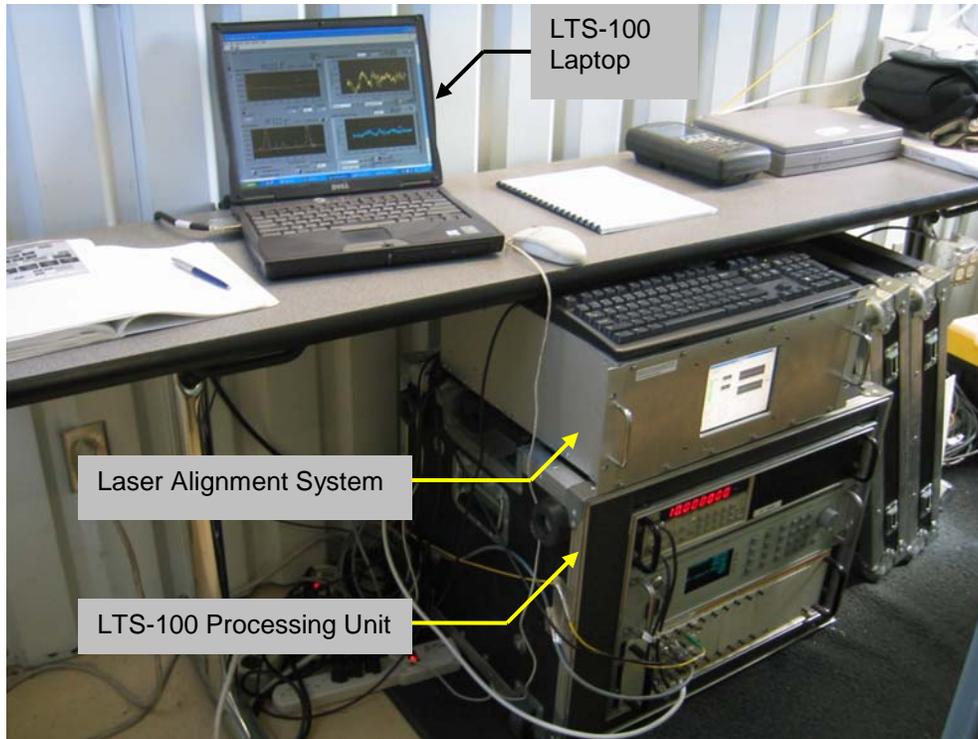*Figure 2. LTS-100 optical components.*

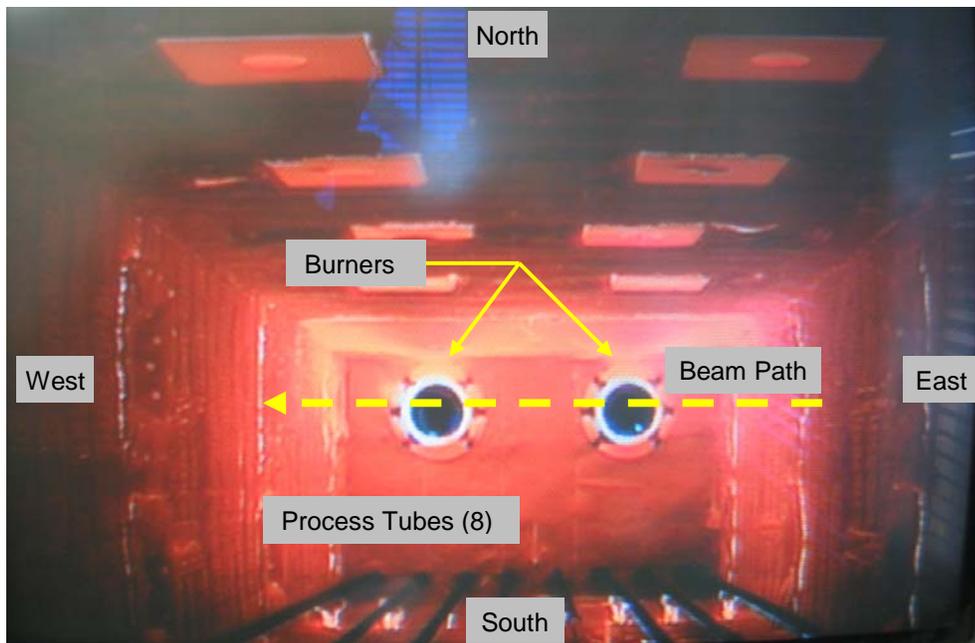*Figure 3. System hardware located in control room.*

Figure 4. Top view of furnace interior.

A Laser Alignment System (LAS), developed by BML, was used for rapid alignment of the beam across the furnace. The LTS-100 processing unit and laptop and the LAS controller were located in the furnace control room (Figure 3).

The LTS-100 beam passed over the floor mounted burners. A top view of the furnace illustrates the positioning of the beam relative to the burners and process tubes (Figure 4).

Two custom port mounting panels were designed for this test program. Each panel featured two parallel 2" ID ports separated by a distance of 6 inches. The initial motivation for this design was to permit simultaneous measurements at nearly identical positions with both the LTS-100 and a suction pyrometer. This test method was abandoned however due to space constraints on the platforms surrounding the furnace. For the present test program, LTS-100 measurements were typically followed within minutes by the pyrometer traverse, enabling the LTS-100 and pyrometer measurements to be made nearly simultaneously. The LTS-100 beam pathlength between the windows was 13.2 feet.

Theoretical water vapor concentration values were calculated based on fuel flow, excess furnace oxygen, ambient water vapor levels and assuming equilibrium combustion conditions

3.2 Testing on Level 2
LTS-100 data was acquired on level 2 between 12:49 PM and 12:54 PM on 8/12/05. Temperature and H_2O concentration measured by the LTS-100 are shown in Figure 5. The fuel flow was 100% methane, also termed Tulsa Natural Gas (TNG), and excess O_2 was 8.74%. Ambient humidity was 91%. The theoretical H_2O concentration in the furnace for these conditions is 16.0%. The fuel flow rate was 10,075 SCFH and the heat release rate was 9.15 MMBtu/hr.

The suction pyrometer featured a multimeter for displaying instantaneous temperature readings. Due to the varying instantaneous temperatures shown on the multimeter, it was not possible to measure the exact time-averaged temperature. Instead, the minimum and maximum temperature values, recorded automatically by a peak function on the meter, were measured over a two-minute interval at the ten stations along the nominal beam path. These values are presented in Figure 6.

The estimated time-averaged temperature at each station, found by taking the average of the minimum and maximum temperature, is also plotted in Figure 6. The time-averaged temperature plot illustrates that, with a range of 245°F, the temperature distribution across the furnace is far from uniform. Since the distribution of pyrometer measurements at each station as a function of time is not known and since the pyrometer measurements were not made simultaneously, the time-averaged profile presented here is an approximation. The average of all minimum and maximum temperatures across the path is also included in Figure 6.
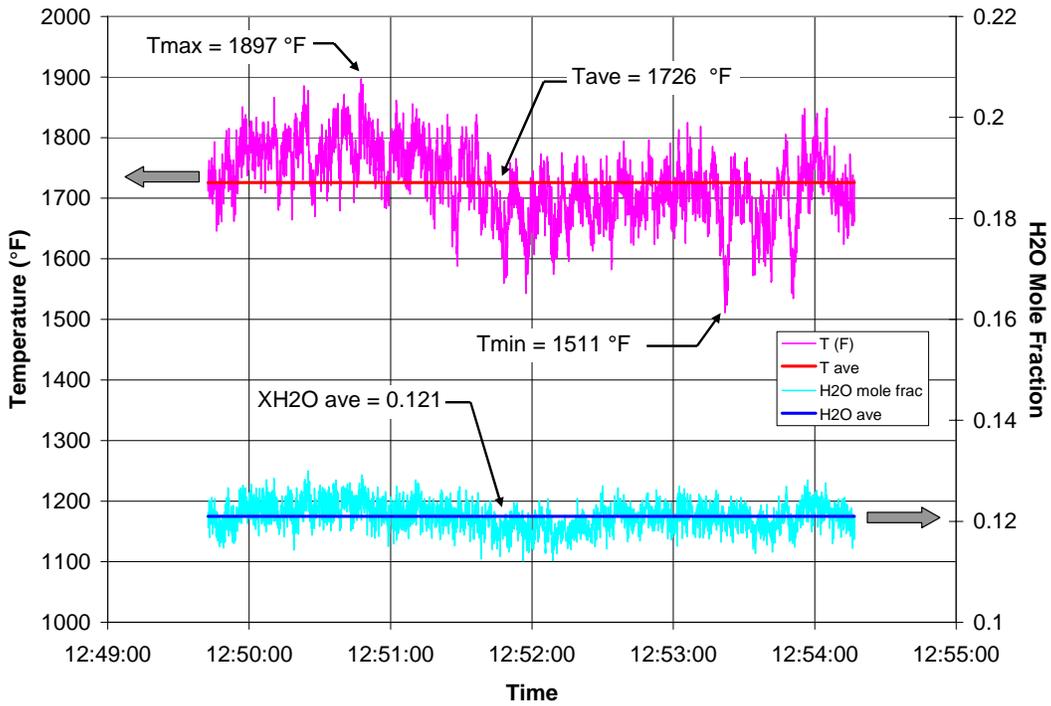
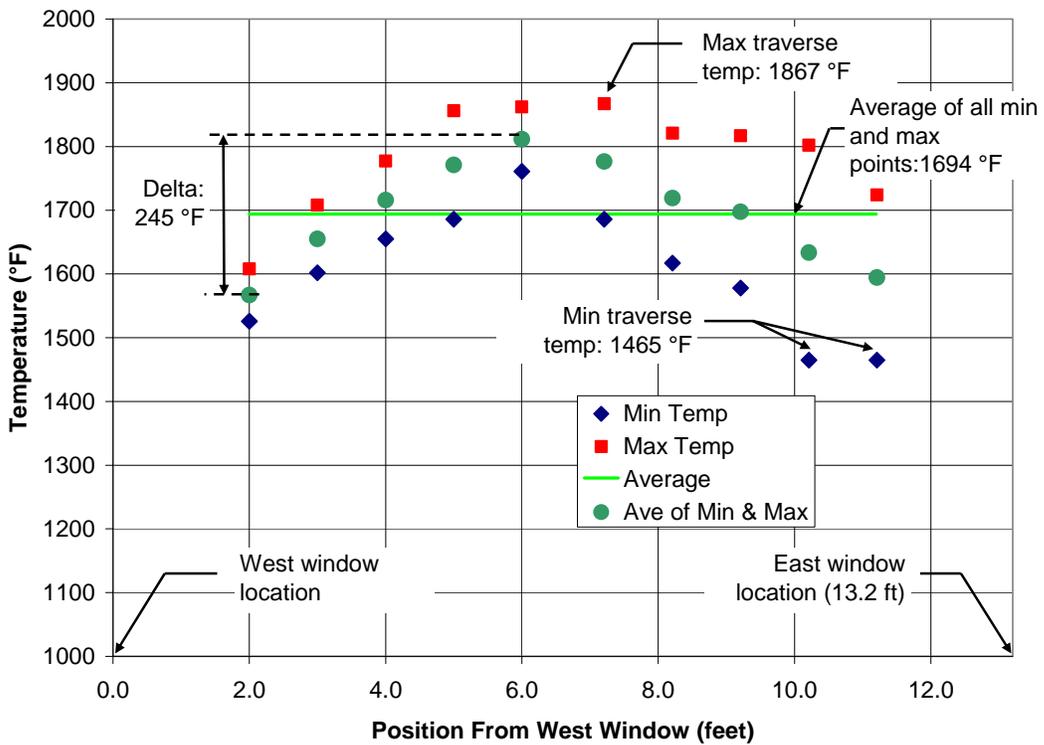*Figure 5. Temperature and H₂O concentration measurements on level 2.*

Figure 6. Suction pyrometer data at level 2.

3.3 Testing on Level 4

After the tests on level 2 were performed, the LTS-100 optical components and the pyrometer were moved to level 4. LTS-100 data acquired between 5:35 PM and 5:44 PM on 8/12/05 are shown in Figure 7. The fuel flow was 100% TNG and excess O_2 was 8.85%. Ambient humidity was 91%. The theoretical H_2O for these conditions is 16.7%. The fuel flow rate was 10,090 SCFH and the heat release rate was 9.19 MMBtu/hr.

Level 4 pyrometer traverse data, acquired immediately after the LTS-100 measurements are shown in Figure 8. The multimeter used for pyrometer temperature display did not return data in engineering units for points between 8.2 and 11.2 feet from the west window, inclusive. This occurred since these values appear to have been below the lower threshold of operation of the multimeter which is approximately 1300°F for the Type B thermocouple used in the pyrometer. Raw voltage readings from the pyrometer for these points correspond to below-ambient temperatures, suggesting that temperatures computed from voltage readings at each of these points should be rejected.

3.4 Results

A comparison of the LTS-100 and suction pyrometer data for levels 2 and 4 is shown in Table 1. A comparison of measured and theoretical H_2O concentrations is presented in Table 2.

Table 1. Comparison of LTS-100 and suction pyrometer measurements.

	Temperature (deg F)					
	Level 2			Level 4		
	LTS-100	Pyrometer	Delta (LTS-100 - Pyrometer)	LTS-100	Pyrometer	Delta (LTS-100 - Pyrometer)
Max	1897	1867	30	1741	1499	242
Average	1726	1694	32	1520	1401	119
Min	1511	1465	46	1195	1281	-86

Table 2. Measured and theoretical H_2O concentrations.

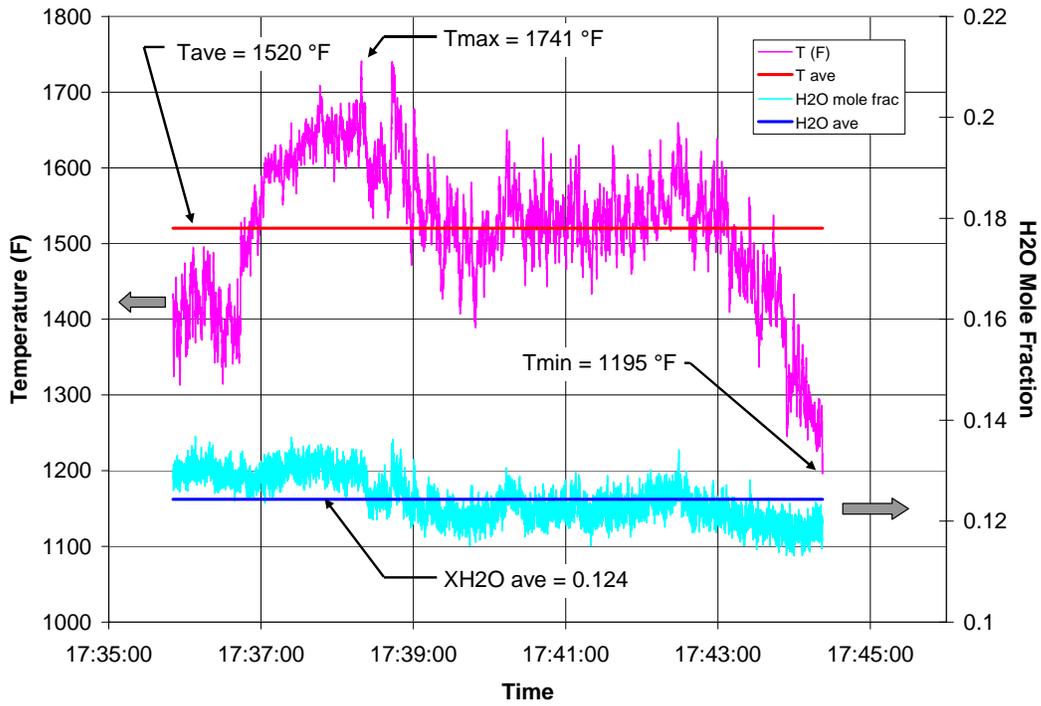|	Level 2	Level 4
LTS-100	12.10%	12.40%
Theoretical	16.00%	16.70%
Delta (LTS-100 - Theoretical)	-3.90%	-4.30%

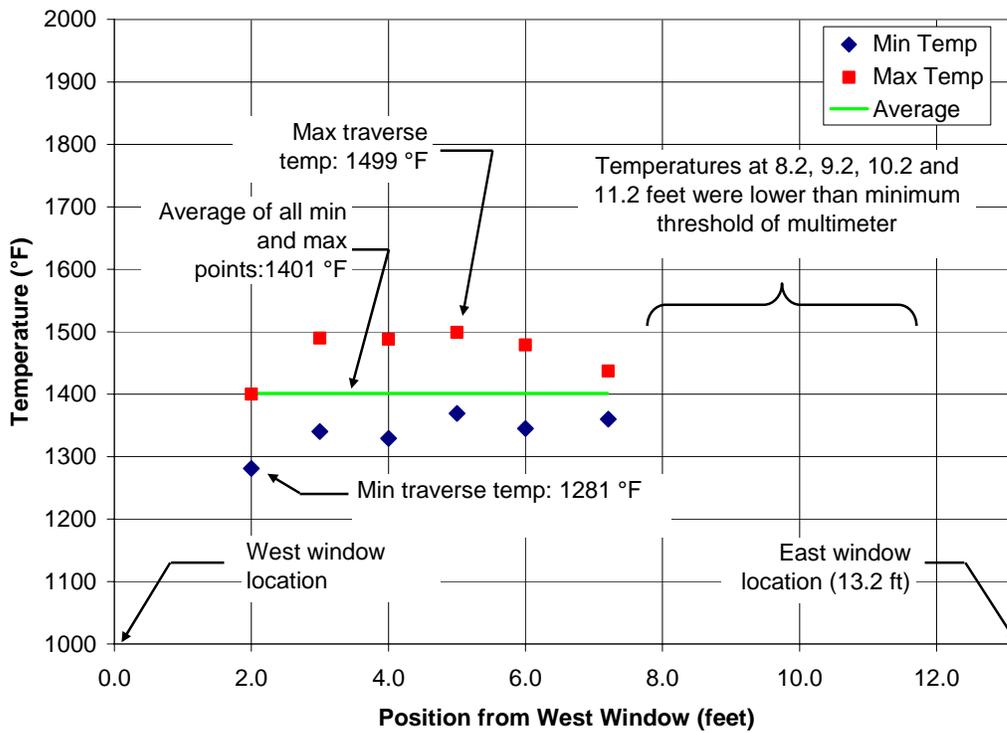*Figure 7. Temperature and H₂O concentration measurements on level 4.*

Figure 8. Suction pyrometer data on level 4.

3.5 Discussion
Prior to discussing the agreement between the LTS-100 and pyrometer data, a comparison of the response times of the pyrometer and LTS-100 is necessary to explain the data acquired by both instruments.

During normal operation, the LTS-100 obtains a snapshot of furnace conditions over a period of 50 microseconds and a snapshot is acquired at a rate of approximately 13 Hz. The pyrometer response time has not been quantified, but is estimated to be considerably longer than the LTS-100 due to: i) the approximately 5 Hz sampling rate of the multimeter on the pyrometer; ii) damping effect of the flow of furnace gas flow entering the pyrometer; and, iii) the response time of the thermocouple.

Temperature Data Acquired at Level 2
Maximum, average and minimum data for the LTS-100 are greater than the pyrometer data by 30, 32 and 46°F, respectively. Each of these data points is discussed here.

Good agreement between the average of the minimum and maximum pyrometer measurements and the time-averaged LTS-100 data is explained as follows.   The temperature measured by the LTS-100 is based on the ratio of the path-integrated linestrengths for two absorption features. In general, if there are temperature variations along the beam path, it can be shown that the path average temperature will not exactly match the LTS-100 temperature. However, the simulation below predicts that for the temperature distribution measured by the pyrometer, the LTS-100 should read only -2°F lower than the average temperature. Additional simulations, beyond the scope of this paper, indicate that for path averaged temperature distributions between 1200 and 2800°F with span-wise temperature differences of up to 250°F, the LTS-100 will theoretically measure within ± 5°F of the path averaged temperature (Ref. 5).

Agreement between the maximum values measured by the LTS-100 (1897°F) and the pyrometer (1867°F) is good but requires some interpretation. As shown in Figure 6, the peak maximum temperature measured by the pyrometer along the beam path was at a location 7.2 feet from the west window and other maximum values dropped off towards the walls. Since the LTS-100 returns a value close to the path-average, the peak LTS-100 measurement would be expected to be the average of the peak pyrometer values (1784°F). The explanation for the higher peak temperature measured by the LTS-100 is that turbulence in the flow may have caused the high temperature gas at the center of the furnace to momentarily be distributed along the entire beam path. While the LTS-100 would be able to detect such an event, the pyrometer might not capture such a transient due to a slower response time. A similar explanation is offered for the agreement between the minimum LTS-100 (1511°F) and pyrometer (1465°F) measurements.

Temperature Data Acquired at Level 4
LTS-100 measurements on level 4 (Figure 7) show that at this elevation in the furnace, there appeared to be large, slow, fluctuations in furnace temperature during the nine minute period over which data was acquired. The drop in temperature to 1195°F is consistent with temperatures apparently below approximately 1300°F east of the 7.2 ft position, as evidenced by the lack of pyrometer data in this region.

A valid comparison between LTS-100 and pyrometer data recorded at level 4 is not possible for the following reasons:

- significantly less than one full cycle of low-frequency oscillation in temperature was recorded by the LTS-100, therefore, a valid steady state average was not obtained;
- pyrometer measurements were not made at points beyond 7.2 feet from the western window; as a result, an accurate path-averaged temperature cannot be calculated; and,
- the two-minute time period for pyrometer measurements at each station along the beam path is considerably shorter than the time period of the low-frequency temperature oscillation; therefore, the pyrometer data may not reflect the true minimum and maximum temperatures at each station along the beam path.

W*ater Vapor Concentrations*
The LTS-100 consistently measured H_2O concentrations below predicted levels. It is thought that this difference may be due to additional air entering the furnace through the burner air inlet that was not accounted for in the predictions and is thereby diluting the measured H_2O concentrations.

Although the LTS-100 temperature data recorded on level 4 varies greatly, variations in H_2O measurements are relatively small. The fact that the average measured water vapor concentrations on levels 2 and 4 match closely is in agreement with the constant H_2O levels which would be expected above and well downstream of the flame zone in the furnace.

4. Validation of TDLAS Model
A numerical model employing absorption data from the HITRAN (Ref. 6) spectroscopic database was developed by MetroLaser to investigate the effect of temperature non-uniformities on LTS-100 temperature measurements. Although the LTS-100 employs an experimentally determined calibration relationship rather than that predicted from HITRAN data, the HITRAN-based model provides a means to study trends with different temperature distributions. The general behavior of the model and the experiments should be the same since the dominant absorption lines are the ones used in the model.

For the simulation results presented below, the H_2O concentration was assumed to be constant along the beam path and the path length was set to the 13.2 foot path length of the test furnace used during the test program.

4.1 Modeling Experimental Temperature Profile

The time-averaged temperature profile of pyrometer data from level 2 is plotted in Figure 9. A Gaussian distribution was heuristically fit to the average temperature profile and is also plotted in Figure 9.
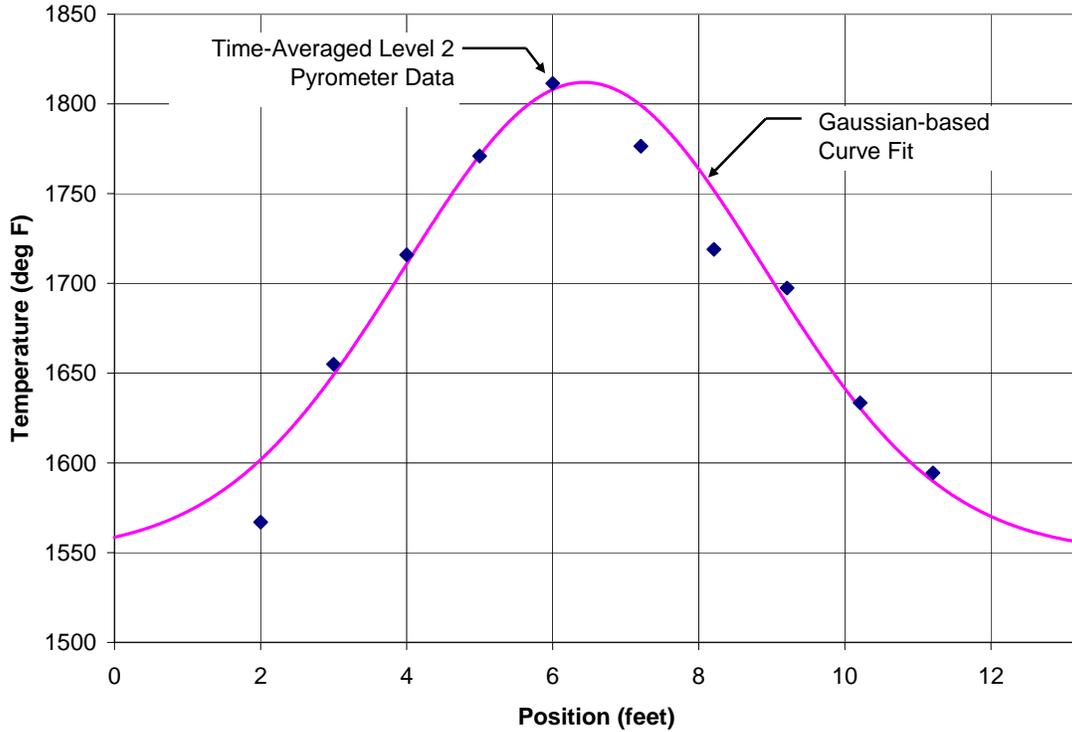

Figure 9. Time-averaged pyrometer data from level 2 and gaussian-based curve fit.

4.2 Results

Using the fitted temperature profile in the simulation, the computed path average temperature is 1672°F and the simulated TDLAS-based temperature is two degrees lower at 1670°F. These values are compared in Table 2 with data measured on level 2.

Table 2. Comparison of measured and simulated results for level 2 data.

	Average	TDLAS	TDLAS-Average
Simulated	1672	1670	-2
Measured	1694	1726	32
Measured-Simulated	22	56	

4.3 Discussion

The difference between the measured LTS-100 data and the simulated TDLAS measurement on level 2, 56°F, is attributed to the fact that the LTS-100 uses a measured calibration relationship whereas the simulation is based on spectroscopic data from the

HITRAN database. The 22°F difference between the simulated and measured averages is due primarily to the quality of the curve fit to the temperature data.

It is significant to note in Table 2, that in both the simulated and measured case, the TDLAS temperatures agree with the respective average data with only a small amount of error (-2°F simulated and +32°F, measured). This agreement supports the validity of the TDLAS model in capturing the trends of the experimental behavior of the LTS-100 in a non-uniform temperature distribution. This conclusion will allow the TDLAS numerical model to be used with confidence in estimating the performance of the LTS-100 under a wide range of non-uniform temperature conditions.

5. Summary

5.1 Experimental Testing
- On level 2 of the furnace, the temperature measured by the LTS-100 was only 32°F higher than the path averaged temperature measured by suction pyrometers, with the range of average temperatures across the path spanning 245°F.

- Measured water vapor concentrations at both levels 2 and 4 were within 0.4% of each other but approximately 4% less than theoretical values.

- Large, low frequency variations in LTS-100 temperature data at level 4, accompanied by short measurement periods and the limited temperature range of the pyrometer probe preclude a valid comparison between LTS-100 and pyrometer data at this location.

5.2 TDLAS Model Validation
- Good agreement occurred between the difference in the path averaged temperature and TDLAS-based measurements in both simulated and experimental cases.

6. Conclusions

This work provides experimental evidence that the temperature measured by the MetroLaser LTS-100 in a large scale, non-uniform temperature combustion environment approximates the path averaged temperature. Further, MetroLaser's numerical TDLAS model for prediction of measured temperature in a non-uniform temperature environment has been found to be in good agreement with the experimentally observed behavior of the LTS-100.

7. Future Work

Future work involves attempting to improve the understanding of TDLAS technology in general and the LTS-100, in particular. Two key areas of future work are:

- additional testing work and comparisons of LTS-100 with pyrometer and extractive probe measurements in various industrial settings; and,
- additional theoretical study of TDLAS measurement in non-uniform temperature and H_2O fields.

8. Acknowledgements

Jerry Buhler, Leon Longacre and the staff of the John Zink R&D Test Center are thanked for their assistance with this project. The efforts of Garrett Spaulding, who operated the ethylene cracking simulator furnace, are recognized for contributing greatly to the success of the test program.

9. References

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