Progress in the Development of a TDLAS Sensor for Industrial Applications

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Abstract
A tunable diode laser-based temperature sensor is being developed by Bergmans Mechatronics LLC and MetroLaser Inc for non-intrusive measurement of combustion gas temperatures in large-scale settings. Upgrades to the system to tailor the instrument for industrial applications are presented. Recent testing in a coal-fired power plant over a period of 37 hours has shown that the system is capable of resolving small changes in internal boiler conditions. Discrepancies between measured and expected temperatures levels in the power plant are discussed.

1. Introduction

Measurement of furnace gas temperatures continues to be of interest to operators of large scale industrial combustion systems. In the coal-fired power generation industry, potential applications for such measurements include fireball centering, increased precision of turbine inlet steam temperature control and optimization of direct ammonia injection NO_x reduction systems. To support this demand within the power industry and in other industries involving large-scale, high temperature combustion processes, the Bergmans Mechatronics LTS-100 Laser Temperature Sensor is being developed for non-intrusive measurement of temperature of up to 4000 °F.

The LTS-100 employs a two-line Tunable Diode Laser Absorption Spectroscopy (TDLAS) technique. The technique makes use of two closely-spaced temperature-dependent absorption features of water near 1500 nm in the electromagnetic spectrum. Small-scale flat-flame burner testing generates a calibration curve relating measured absorption to gas temperature. The calibration curve is then used as the basis for determining large-scale gas temperature based on measured absorption.

Industrial-scale testing of the first system prototype in a power plant and a glass plant has previously been described (Refs. 1-2) and the results of an initial investigation into the accuracy of the sensor in a large-scale configuration have also been presented (Ref. 3). These efforts have demonstrated the feasibility of temperature measurement with the LTS-100 in large-scale, industrial combustion systems.

Upgrades to the system have resulted in a more advanced, second prototype instrument. These upgrades have been implemented with the goal of increasing the suitability of the system for industrial use. The upgrades include:

- an improved automatic laser beam alignment system;
- ruggedized boiler-wall mounted enclosures for optical components; and,
- an integrated Processing Unit.

This paper provides an overview of the current system and provides a description of recent full-scale, testing of the current prototype in a coal-fired power plant.

2. Theory of Operation

During operation of the LTS-100, the laser beam is projected through the combustion gases while the laser output is scanned over a range of wavelengths near 1500 nm. The laser light is received by a photodiode detector on the opposite side of the combustion gases. The detector output is processed to produce a spectrum of the absorption over the range of scanned wavelengths. The ratio of the areas under two prominent absorption features in the absorption spectrum is calculated and a calibration curve relating absorption to temperature is used to determine the combustion gas temperature.

The calibration curve is generated during testing in a laboratory environment. These tests involve passing the laser over a flat flame burner to produce a calibration absorption spectra while recording the gas temperature measured by a thin wire thermocouple (TC) placed at the same height above the burner as the laser. The ratio of the area under two prominent absorption peaks in the scan and the TC measurements are acquired for a range of fuel flowrates and the resulting collection of absorption ratios and TC data is used to produce a calibration curve.

Example calibration absorption spectra for TC readings between 1712 and 2788 °F are shown in Figure 1. In this plot, the time axis is related to the laser wavelength since the change in laser output wavelength is approximately linear with time. The TC values presented in the figure and those used to generate the calibration curve are corrected for losses due to radiation. Further details of the calibration process and the LTS-100 TDLAS techniques are presented in Ref. 1.

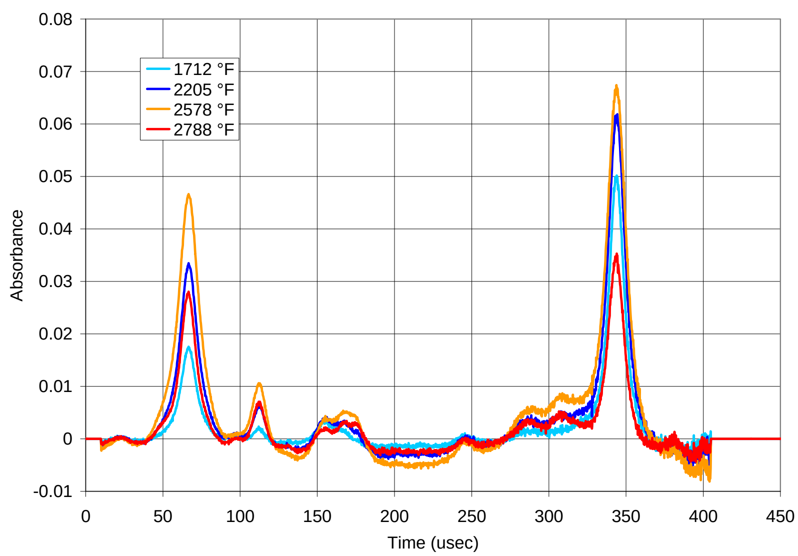

Figure 1. Typical Absorption Spectra Acquired During Calibration Testing

3. Power Plant Testing

System Description

The system was set up in late August and early September 2007 at a 485 MW coal fired, cyclone burner, generating unit at a power plant in the mid-western United States. The laser was projected across the boiler near the top of the boiler. This location is near the region referred to as the furnace exit plane and is located upstream of the superheater section. The beam passed parallel to the front and back walls of the boiler at a location approximately midway between these walls. The path length across the boiler was 48 feet.

A schematic layout of the system is shown in Figure 2. Laser light is transmitted from the Processing Unit to the launch optics enclosure via a fiber optic cable. The laser light passes through the boiler gasses and is received at the detector enclosure. Detector signals are transmitted back to the Processing Unit via coax cable. Not shown in Figure 2 are the power cable to provide power from the Processing Unit to the detector enclosure; and, a power and control cable to power the launch optics enclosure and control the laser scanner mirrors which are part of the Laser Alignment System, described below.

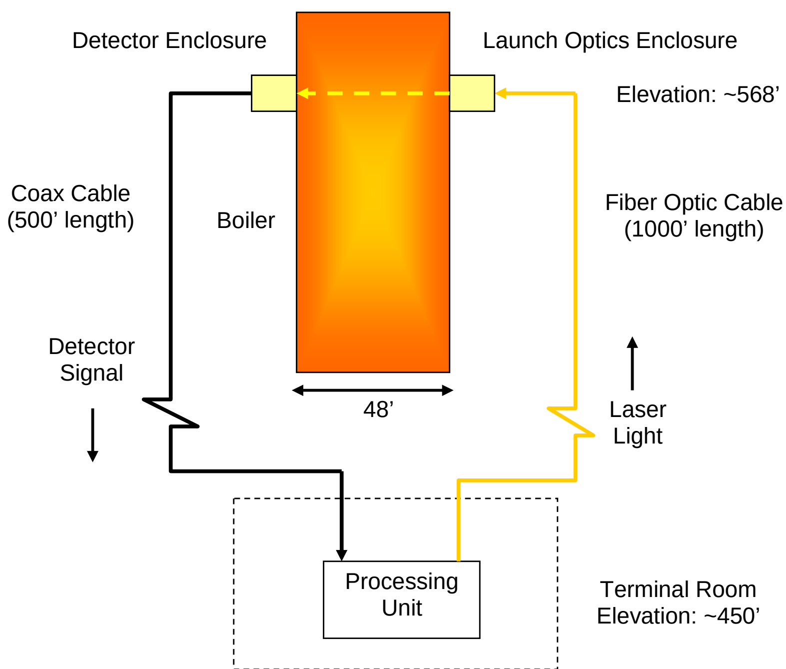

Figure 2. Schematic of LTS-100 Installation at Power Plant

The Processing Unit (Figure 3) contains the rackmount PC used for control and data processing tasks; the laser diode source; the laser controller; and, the control electronics for the Laser Alignment System. The Processing Unit was located in the climate controlled Terminal Room below the Control Room of the plant.

Figure 3. LTS-100 Processing Unit in Power Plant Terminal Room

Enclosures containing the launch and detector optics were mounted on 3” flanges attached to ports on either side of the boiler. The detector optics enclosure is shown in Figure 4. The exterior of the launch optics enclosure is identical. Vortex coolers fed by compressed air cool the enclosures. A simplified latching mechanism enables installation and removal by a single person using only three hand-turned nuts.

Figure 4. Detector Optics Enclosure Mounted on Power Plant Boiler

Laser Alignment System

A two-axis laser scanner (Figure 5) is mounted in the launch optics enclosure. Light from a collimating lens within the enclosure is reflected off the two electrically controlled mirrors and projected into the boiler. The beam can be controlled over a range of +/- 14° in pan and tilt with an angular resolution of 0.007° in either axis
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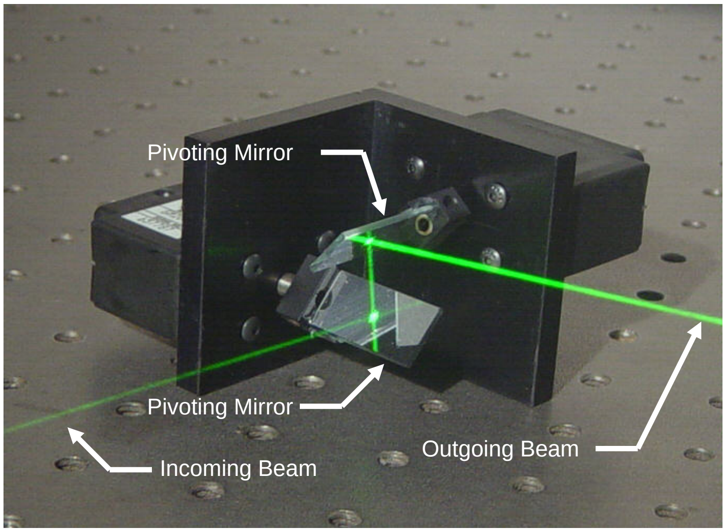


Figure 5. Two Axis Laser Scanner With Visible Laser Illustrating Beam Path

The beam pan and tilt angles can be controlled in either Manual Mode or Automatic Alignment Mode. In Manual Mode, the beam direction is adjusted by the user via the software Graphical User Interface. The user can toggle the system between Manual Mode and Automatic Alignment Mode.

When Automatic Alignment Mode is selected, the alignment process begins in the Raster Scan sub-mode. In this sub-mode, the beam is swept through a user-defined range of pan and tilt angles until the detector signal strength exceeds a specified threshold voltage level. Crossing this threshold is an indication that some part of the laser beam has illuminated the detector. A more refined search for the detector is performed by then engaging the Optimization sub-mode. In this sub-mode, the system makes continuous small changes to the pan and tilt angle with the goal of maximizing the signal strength at the detector. If the signal detector strength drops below a user-defined Re-Alignment Threshold, the Raster Scan sub-mode is re-engaged in an effort to re-acquire the detector.

During long term operation of the LTS-100, the system is typically operated in the Automatic Alignment Mode and Optimization sub-mode. This configuration allows the sensor to continuously maintain alignment of the beam across the boiler despite any small movements of the optical enclosures.

Results

The system operated continuously and autonomously over a period of 37 hours between 8 PM on 9/2/07 and 9 AM on 9/4/07. Figure 6 illustrates the power output, or load, of the generating unit and two temperature values: i) the change in temperature measured by the LTS-100 relative to the start of the test period; and, ii) the change in estimated boiler temperature relative to the start of the test period. The bandwidth of the LTS-100 temperature measurements was determined as the inverse of the wavelength scan time, which was 400 μs, divided by the number of scans averaged, which was 100, resulting in a measurement bandwidth for the instrument of 25 Hz. The LTS-100 data presented in Figure 6 is the result of further averaging the temperature measurements in groups of 300 to produce an effective measurement bandwidth of 0.083 Hz for the plot shown. As presented in this figure, during the test period, the generating unit was cycled twice between high (approximately 440 MW) and low (approximately 330 MW) load levels.

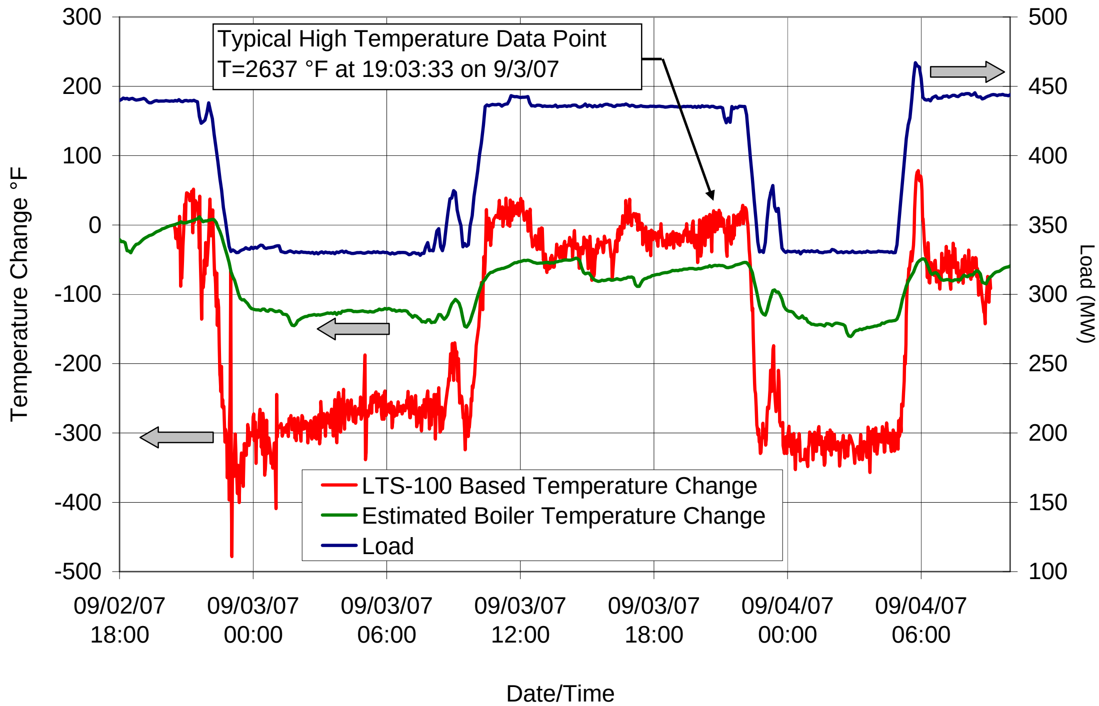


Figure 6. Measured and Estimated Temperature Changes and Plant Load

The temperature measured by the LTS-100 during this period varies over a 300 °F range between approximately 2600 °F during high load operation and 2300 °F during low load operation. By comparison, during this same period, the estimated boiler temperature, which is computed based on the inlet temperature to the economizer, is seen to vary over only approximately a 100 °F range.

The LTS-100 temperature reading of approximately 2600 °F at high load levels is considerably higher than the expected value of approximately 2200 °F under these conditions. This expected value is based on thermodynamic modeling, high velocity thermocouple measurements and passive IR spectrometers. An initial investigation into the discrepancy between the LTS-100 readings and expected temperatures is presented below.

Despite the differences between LTS-100 and expected data, it is significant to note that the LTS-100 is capable of resolving changes in internal boiler conditions during load changes. For example, following the downward drop in load at 10:45 PM on 9/3/07, there was a short upward spike in load. The LTS-100 data shows a corresponding steady drop in temperature and an upward spike in temperature during this period. Similarly, the LTS-100 recorded an upward temperature spike which matches the upward load spike during the morning of 9/4/07.

The Laser Alignment System was able to maintain alignment of the beam during the 37 hour period by making small adjustments to the commanded pan and tilt angles. Figure 7 shows the change in computed detector center position relative to the launch optics. The spikes in the pan and tilt angles correspond to periods when the system was in the Raster Scan sub-mode.

During the 37 hour test period, the system was in the Raster Scan sub-mode for approximately 11% of the time. This figure could be reduced by decreasing the Raster Scan search area or the Re-Alignment Threshold.

When the system is operating in Raster Scan sub-mode or during other events when a valid absorption spectrum cannot be acquired, the last valid absorption spectrum is used for Temperature calculations and no invalid temperature readings appear in the temperature data. As a result, a small portion of the temperature data presented above does not correspond to actual real-time measurements. In a future version of the software, when no absorption spectrum is acquired, no temperature reading will be output and a warning will be displayed to avoid the impression that valid data is being acquired.

It is interesting to note that there is a small but noticeable variation of 0.25° in Pan angle which appears to track the change in unit load. This variation in Pan angle is likely due expansion and contraction of the boiler walls caused by changes in heat transfer rates in the boiler. The benefit of the Laser Alignment System to system reliability is evident when one considers that the beam diameter at the detector during these tests is estimated at only 2” and that, relative to the launch optics, the size of the 3” diameter detector lens is equivalent to 0.3° of arc. Therefore, without continuous tracking of the detector by the Laser Alignment System, the beam could have moved nearly completely off the detector lens and no measurements would have been made for several hours during this test period.

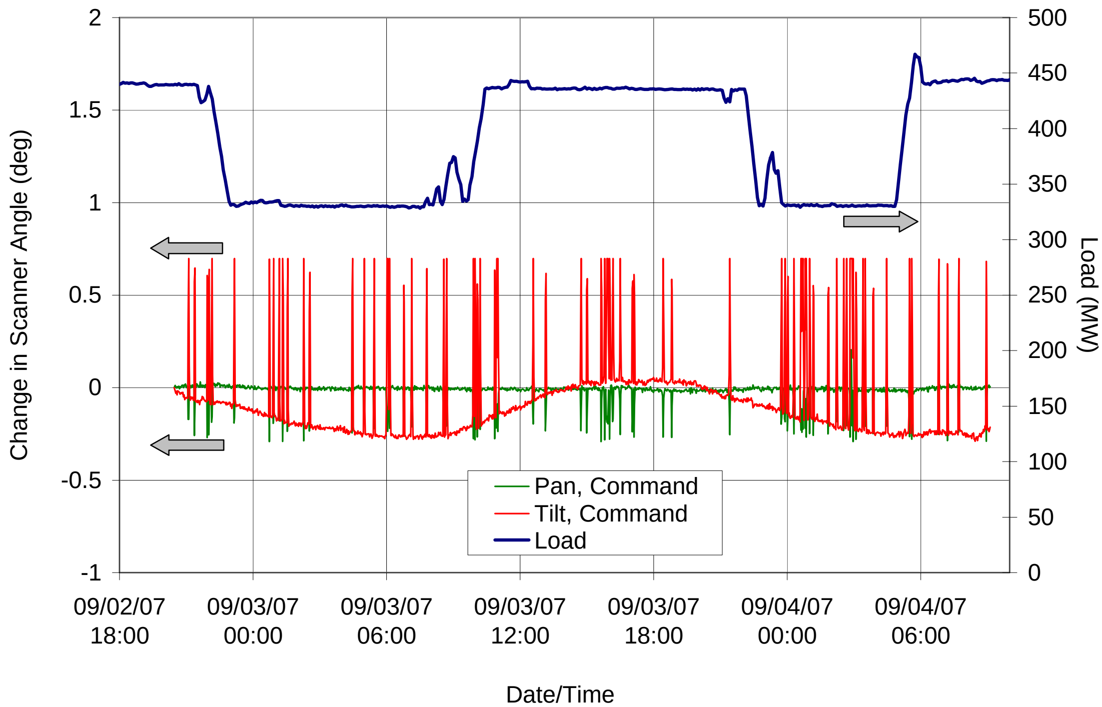
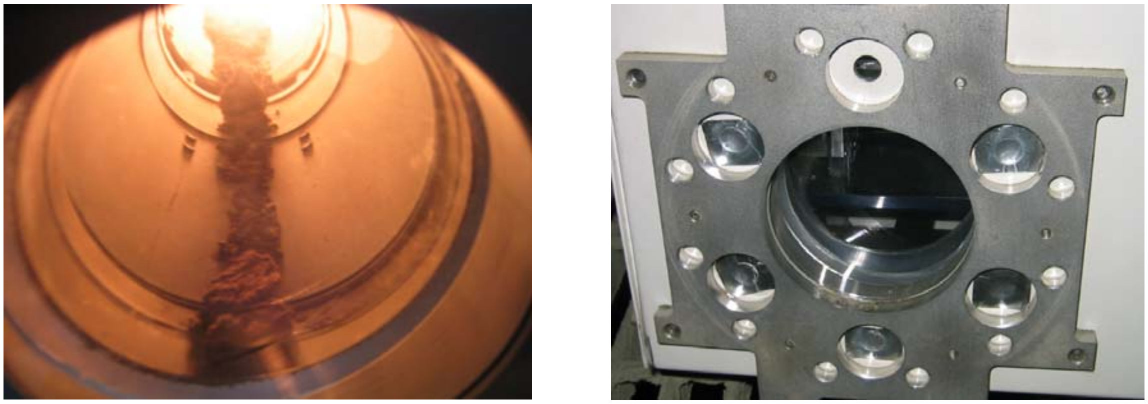


Figure 7. Change in Position of Detector Center Relative to Launch Optics

The optical enclosures functioned well before, during and after this test period. Only a small amount of slag build-up was evident in the instrumentation tubes after the enclosures had been mounted on the boiler for several days. Figure 8a shows a typical amount of slag build up in the detector port, viewed through the detector window. This slag is very loose and can be removed by partially removing the enclosure from the instrumentation port and allowing the sub-atmospheric pressure within the boiler to draw the particles into the boiler. No significant deposits formed on the optical windows. Figure 8b shows the launch optics window after being mounted for several days on the boiler.



a) Small Amount of Slag Accumulation in Instrumentation Port on Detector Side

b) Insignificant Deposits on Launch Optics Window

Figure 8. Negligible Buildup and Deposits on Optical Components Following Several Days on Boiler

4. Comparison of Expected and Measured Temperatures

Temperatures measured by the LTS-100 during the period when the plant was operating at high load were approximately 2600 °F while the expected level at this location and load is approximately 2200 °F. This section examines the possible cause of the discrepancy between expected and measured temperatures.

One known issue with the LTS-100 temperature measurements presented above is that the absorption data used to produce the original calibration curve was not corrected for ambient water concentration. The inclusion of this ambient absorption into the calibration data is estimated to cause an upward temperature bias of approximately 100 °F. Though this is not an insignificant source of error, it only accounts for a small portion of the current temperature discrepancy.

A possible explanation for part of the discrepancy may be provided by considering a comparison of the full-scale and calibration absorption spectra. A typical absorption spectrum while the unit was at high load during the evening of 9/3/07 is shown in Figure 9, which is an average of 100 scans, acquired over 10 seconds. At the time that this spectrum was produced, the LTS-100 measured a temperature of 2637 °F. This absorption spectrum was normalized by the magnitude of the Feature 1 peak and the regions near the Feature 1 and Feature 2 peaks are plotted in Figures 10 and 11, respectively.

Also included in Figures 10 and 11 are a set of selected corrected and normalized absorption spectra acquired during the calibration process. The calibration spectra presented here have been corrected for ambient absorption and have been normalized by the magnitude of the Feature 1 peak of each spectrum. The temperatures indicated for the calibration spectra are the readings of the thin-wire TC with a correction applied for losses due to radiation. It should be noted that TC radiation modeling errors cannot account for the elevated LTS-100 measurement since the largest radiation correction for the spectra presented here is only 75 °F.

When comparing the full scale and calibration spectra, it can be seen, particularly in the Feature 2 comparison plot, that the full scale spectrum seems to approximate a combination of both the 2578 °F and 2788 °F calibration spectra. This suggests that the conditions inside the boiler at this moment are similar to those present during the calibration when the thin-wire TC measured 2578 °F and 2788 °F.

Two possible explanations are considered for the unexpectedly high temperatures measured by the LTS-100. These are: 1) malfunction of the calibration TC, and 2) the effects of non-uniformity in the boiler.

Considerable care was taken to ensure that the thin-wire TC and the TC display unit were set up correctly. However, the discrepancies presented here are cause for an investigation into the possibility that erroneously high temperature readings were obtained with the thermocouple. Although we consider this explanation unlikely, additional investigations into the accuracy of the TC measurement system will be performed to explore this possibility.

A more likely explanation for the higher-than-expected measured temperatures is that in the power plant installation, the laser light may have been passing through flame fronts within the boiler. These flame fronts may contain localized regions which are near the adiabatic flame temperature of the coal (~4000 °F) and are heavily biasing the path-integrated absorbance spectrum towards a spectrum resembling a higher temperature environment.

Further investigations into the effects of non-uniform conditions along the beam-path, similar to the techniques presented in Ref. 4, will be performed to evaluate this possibility. Data contained in the absorption feature to the right of Feature 1 near 113 usec (Figure 10) and other absorption features in the present data may allow for the calculation of a second set of absorption ratio data and subsequently non-uniformity parameter data.

This non-uniformity parameter information may provide insights into the extent of non-uniformity along the beam-path and the likelihood of the proposed explanation that flame fronts are providing an upward bias to the LTS-100 temperature measurements.

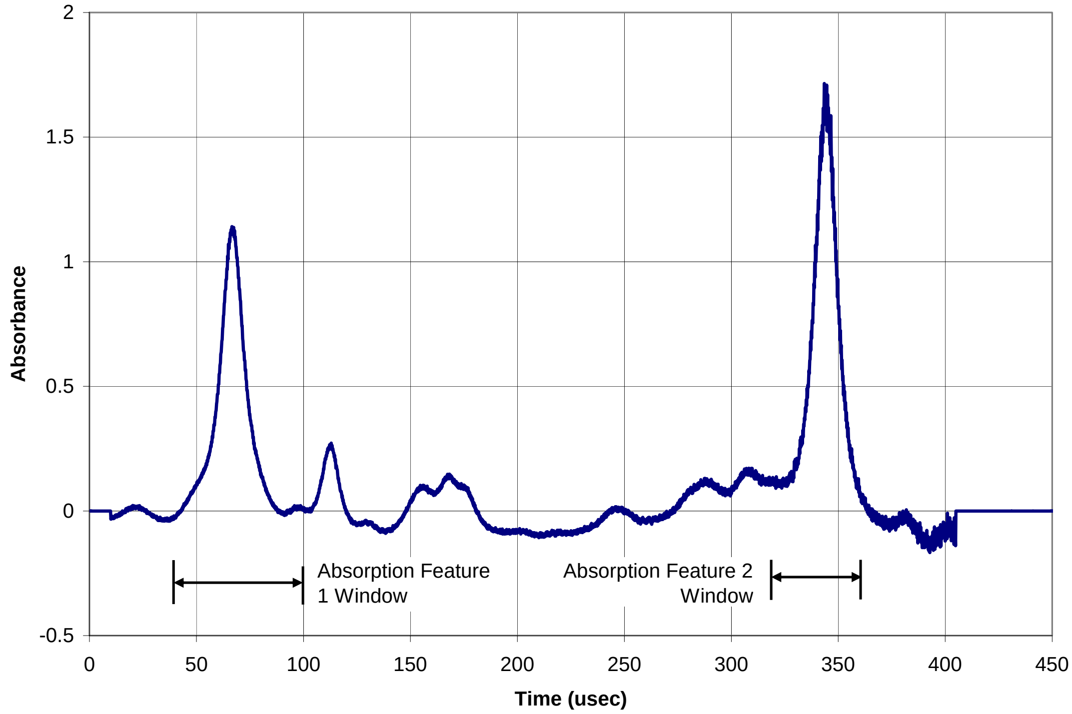


Figure 9. Full Scale High Temperature Spectrum Acquired at 19:03:33 9/3/07 (Measured Temperature = 2637 °F)

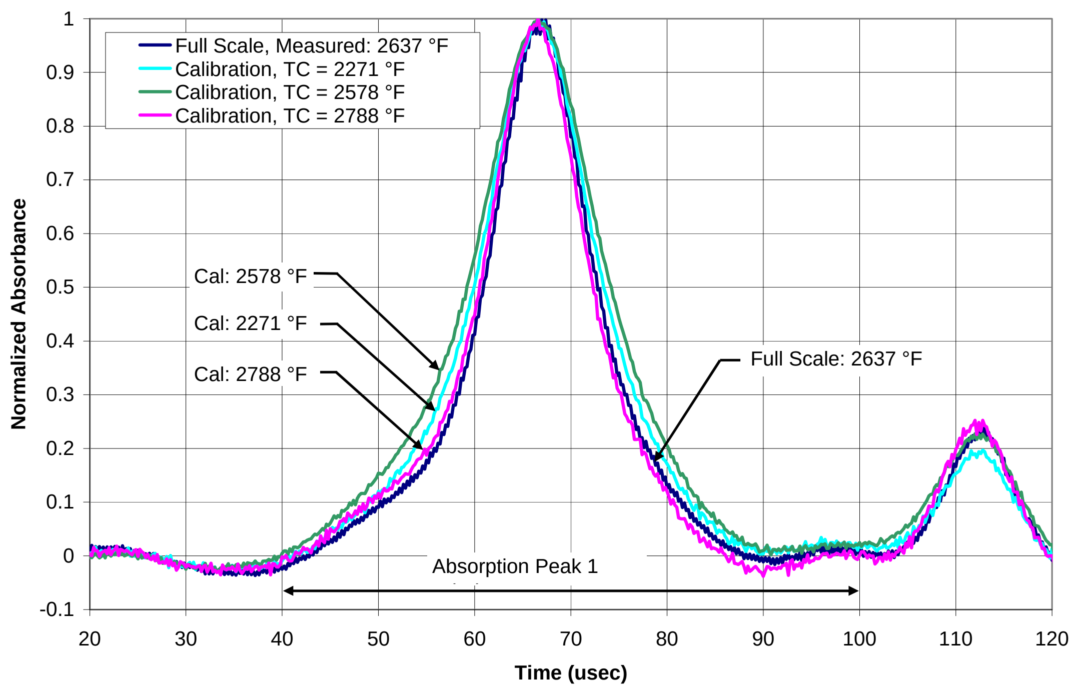


Figure 10. Normalized Full Scale and Calibration High Temperature Spectra (Feature 1 Peak)

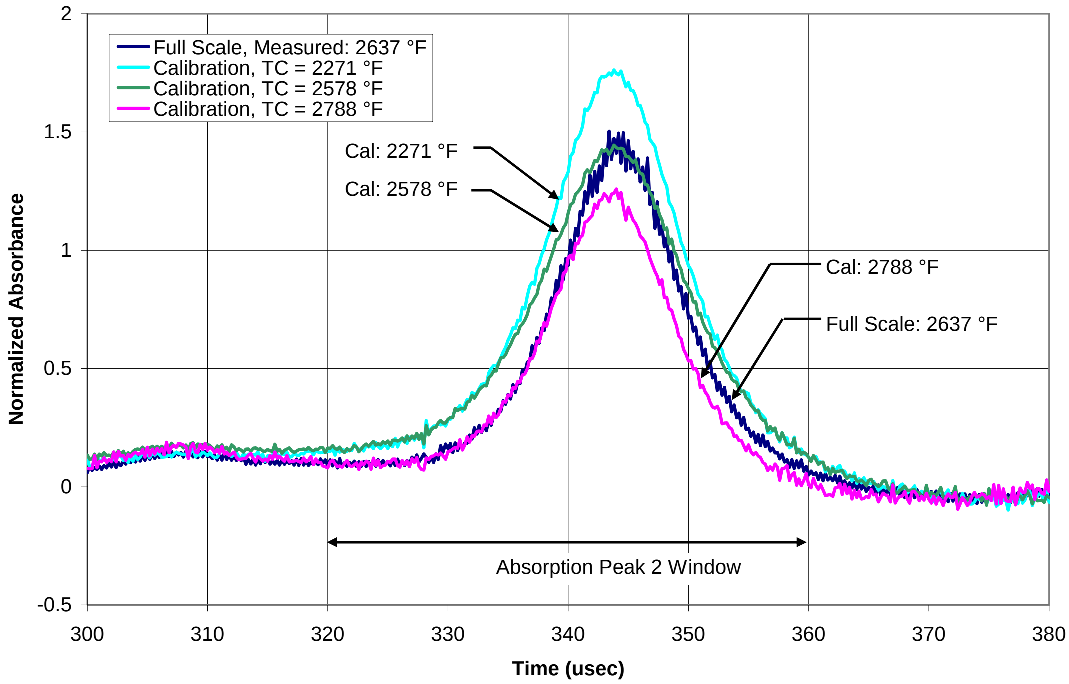


Figure 11. Normalized Full Scale and Calibration High Temperature Spectra (Feature 2 Peak)

Conclusions

This work has demonstrated that significant progress has occurred towards adapting the LTS-100 Laser Temperature Sensor to the needs of the industrial combustion community. Specific accomplishments towards this end include the development and demonstration of:

- ruggedized enclosures for optical components;
- an updated Laser Alignment System capable of maintaining beam alignment over a path length of 48 feet for a period of at least 37 hours;
- the capability to resolve both large and small changes in internal thermal conditions within a coal-fired power plant boiler.

The temperature readings made by the instrument were found to not be in full agreement with conventionally accepted values. This discrepancy will be the subject of future investigations.

References

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