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Chapter 4

Industrial Applications of Tunable Diode Laser Absorption Spectroscopy

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Abstract

Tunable diode laser absorption spectroscopy (TDLAS) utilizes the absorption phenomena to measure the temperature and species concentration. The main features of the TDLAS technique are its fast response and high sensitivity. Extensive research has been performed on the utilization of diode laser absorption spectroscopy for the system monitoring and its control. The TDLAS technique gives self-calibrations to reduce the noise such as particles and dusts because the laser wavelength is rapidly modulated at kHz rates. In addition, two dimensional (2D) temperature and concentration distributions can be obtained by combining computed tomography (CT) with TDLAS. The TDLAS applications have been extensively studied with great progress. This chapter largely focuses on the engineering fields, especially the practical industrial applications.

Keywords: tunable diode laser absorption spectroscopy, computed tomography, temperature measurement, industrial applications, challenge

1. Introduction

Absorption spectroscopy using the diode lasers has been employed to measure the temperatures and concentrations for at least 40 years [1, 2]. Tunable diode laser absorption spectroscopy (TDLAS) utilizes the absorption phenomena to measure the temperature and concentration. The strength of permeated light is related to the absorber concentration according to Lambert-Beer's law. The temperature and atomic or molecular concentration are determined by the line shape functions and the Boltzmann equation. Based on TDLAS, different molecules such as O_2, CH_4, H_2O, CO, CO_2, NH_3, HCl, HF, and so on can be detected in situ and

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continuously with high selectivity and sensitivity. When employing the sensitive detection techniques, the detection limit can be improved to ppm or ppb. TDLAS can also be employed for velocity measurement using the Doppler effect of light, which can be applicable in the range of near or over the velocity of sound. Due to its reasonable cost and ruggedness, it has been used for mass flow monitoring. With the increasing maturity and broader availability of laser light sources and peripheral electro-optical components, TDLAS has been applied in numerous industrial applications.

1.1. Theory

TDLAS utilizes the absorption phenomena to measure the temperature and species concentration. When the light permeates an absorption medium and an energy transfer process as shown in **Figure 1**, the atomic or molecular concentration is in proportion to the strength of transmitted light according to Lambert Beer's law. Atomic or molecular concentration is related to the amount of light absorbed, as follows [3–5]:

$$I_\lambda / I_{\lambda 0} = \exp\{-A_\lambda\}$$
$$= \exp\left\{-\sum_i \left(n_i L \sum_j S_{i,j}(T) G_{V i,j} \right)\right\} \tag{1}$$

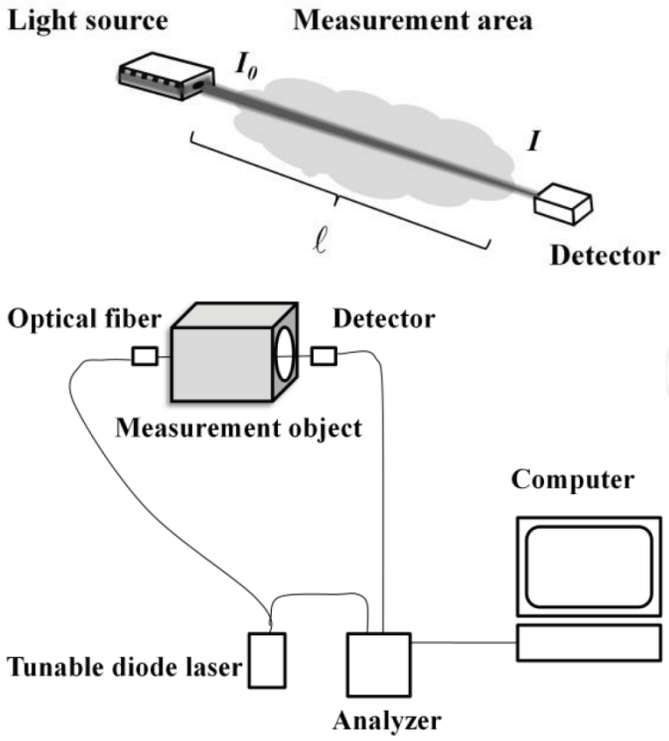


Figure 1. Light transmission through an absorption medium and energy transfer process. (a) Light transmission through an absorption medium and (b) energy transfer process of TDLAS.

here, $I_{\lambda 0}$ is the input light intensity, I_{λ} is the transmitted light intensity at wavelength λ, A_{λ} is the absorbance, n_i is the number density of species i, L is the path length, $S_{i,j}$ is the temperature-dependent absorption line strength of the absorption line j, and $G_{vi,j}$ is the line broadening function. There are three types of line broadenings including natural broadening, Doppler broadening, and collision broadening. The natural broadening usually is small and shows the inconsiderable contribution to the actual spectra observed in practical applications. The Doppler and collision broadenings are the dominant broadenings in practical applications with the line shape functions. The combination of the Doppler and collision broadenings is described by the Voigt function in elsewhere in detail [6]. Thus, by measuring the attenuation of light that permeates an absorption medium containing atoms or molecules, their temperature and concentration can be obtained. The population fraction at each molecular energy level is dependent on the temperature according to the Boltzmann equation [5], which shows the temperature dependence of the absorption line intensity given by $S_{i,j}$ in Eq. (1) to evaluate the temperature.

The theoretical H_2O absorption spectra at different temperatures can be checked using the HITRAN database [4], as shown in **Figure 2**. For example, two H_2O absorption wavelength

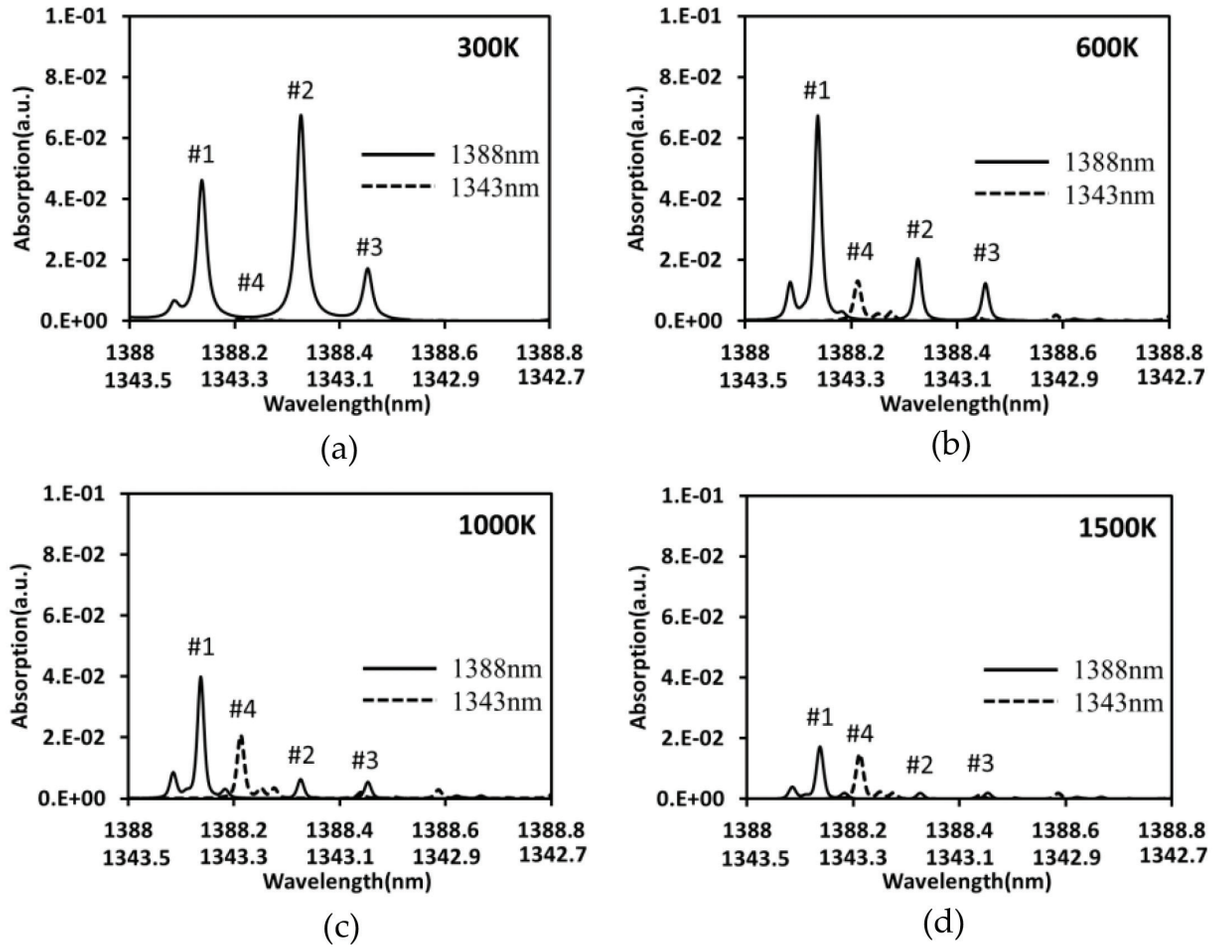


Figure 2. Theoretical H_2O absorption spectra at different temperatures. (a) 300 K, 0.1 MPa, (b) 600 K, 0.1 MPa, (c) 1000 K, 0.1 MPa. (d) 1500 K, 0.1 MPa [4, 10].

regions of 1388–1388.6 nm and 1342.9–1343.5 nm are employed to cover the temperature range of up to 2000 K. These two H_2O wavelength regions are mixed to form the synthetic H_2O absorption spectra. The temperature and H_2O concentration are measured using four absorption lines located at 1388.135 nm (#1), 1388.326 nm (#2), 1388.454 nm (#3), and 1343.298 nm (#4). **Figure 3** shows the temperature dependence of theoretical H_2O absorption spectra of these four absorption lines. The temperature error can be reduced when using several absorption lines with different temperature dependences. The temperature can also be measured using other species such as CO_2, O_2, and so on.

TDLAS is a line of sight measurement technique, which is based on the total amount of absorption along the laser path. As is well known, the computer tomography (CT) technique is widely applied to the medical fields. The CT technique reconstructs the two-dimensional (2D) information by a set of absorption signals. This technique has been gradually applied to TDLAS. A set of laser paths goes through a measurement area and their absorption signals are used to reconstruct the 2D image of a measured area as shown in **Figure 4**. The integrated absorbance in the path p is defined as follows:

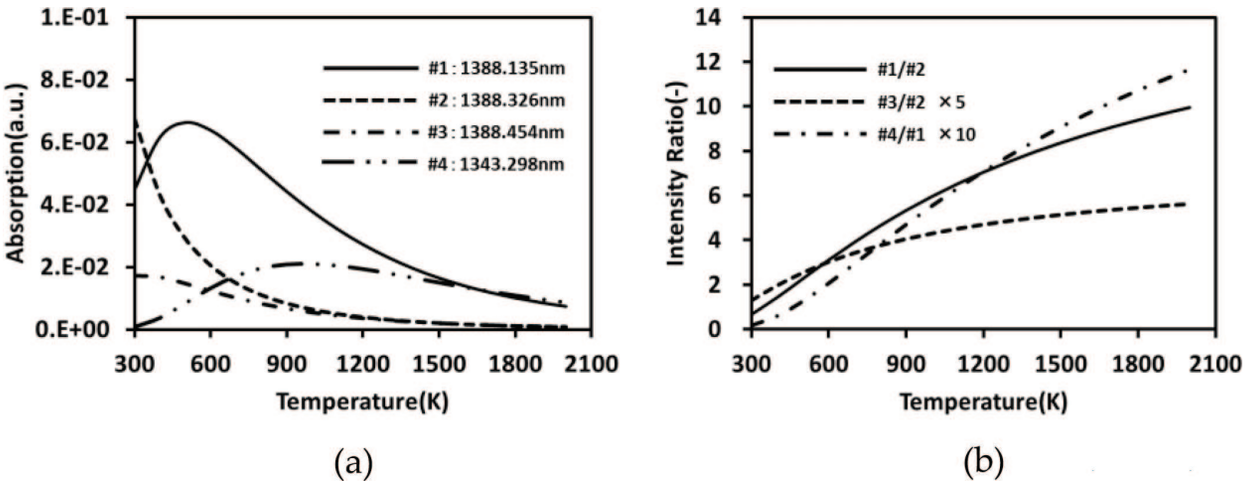


Figure 3. Temperature dependence of theoretical H_2O absorption spectra. (a) Temperature dependence of four absorption lines and (b) temperature dependence of intensity ratio of two lines [4, 10].

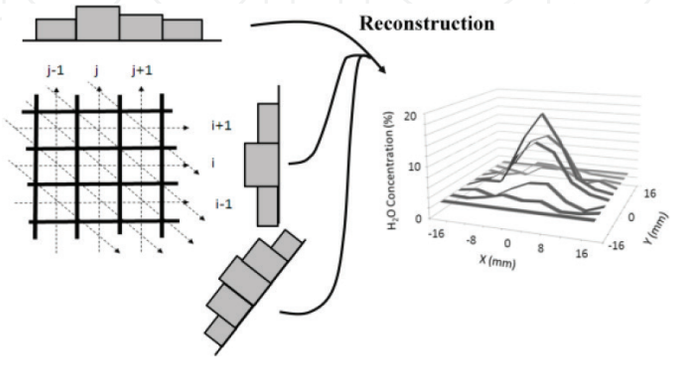


Figure 4. 2D image reconstruction by a set of absorption signals using CT.

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$$A_{\lambda,p} = \sum_{q} n_q L_{p,q} \alpha_{\lambda,q} \tag{2}$$

here, $A_{\lambda,p}$ is integrated absorbance of some wavelength λ in a path, $\alpha_{\lambda,q}$ is absorption coefficient of some wavelength λ inside a grid q on the path and is dependent on temperature and density of species. $L_{p,q}$ is path length inside the grid q. The integrated absorbance is dependent on both temperature and concentration. Therefore, the temperature distribution has to be calculated by more than two different absorbance values. Using a set of Eq. (2), 2D distributions of temperature and concentration are reconstructed by CT. One merit of the TDLAS technology is its fast response. Theoretically, the 2D reconstruction can be done at a rate higher than kilohertz. The temperature and species concentration at each analysis grid are determined using a multifunction minimization method to reduce the spectral fitting error, as shown in **Figure 5**. The measurement errors are induced by a lot of factors, such as number of beams, view angles, CT-algorism, uncertainty of spectral database, and so on [7–15].

The absorption spectra are synthesized with the molecular databases including the HITRAN database [4], which are used to evaluate the absorption characteristics. It is worth to inform that not all the absorption lines are always included in the databases. It is necessary to check and confirm the validity of the simulation results. It is important to reduce the noises as much as possible for the detection of the trace absorption signals. The method of obtaining low-noise signals is theoretically simple with several key factors. These noise effects depend largely on lasers and optics. Careful consideration is necessary to select these components.

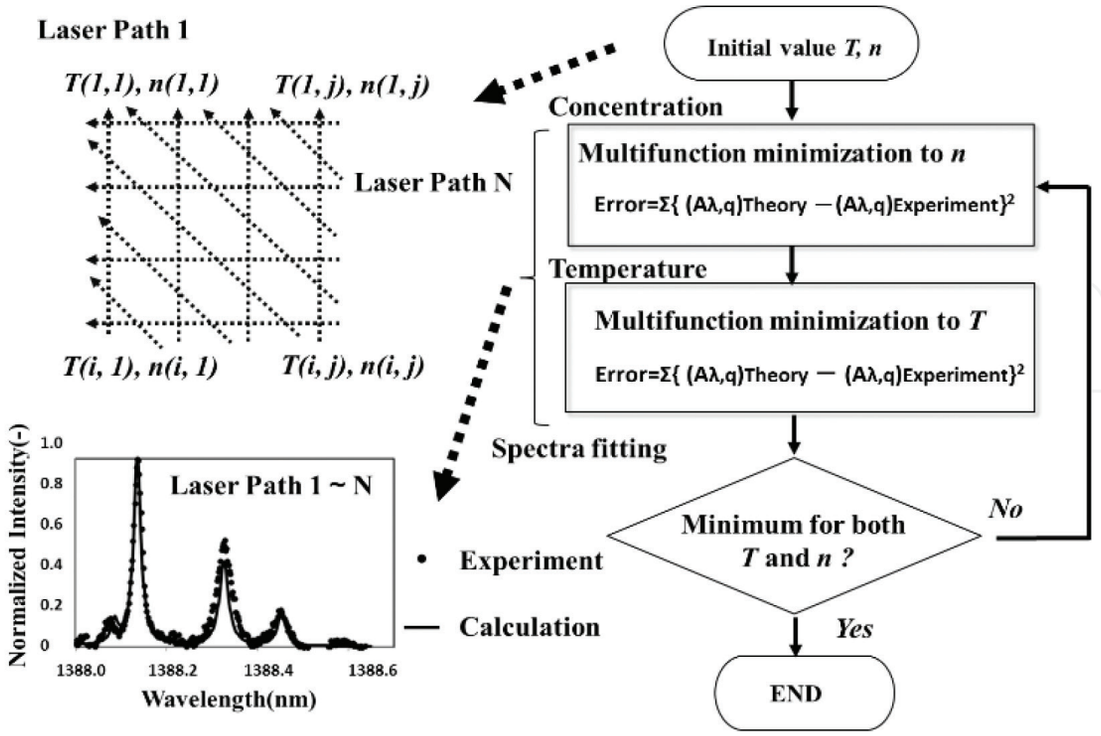


Figure 5. CT algorithm [10].

1.2. Geometric arrangement and measurement species

Figure 6 shows the typical geometric arrangement of TDLAS. The tunable diode lasers are utilized as a light source which transmits through the measurement area. The transmitted light is measured by a photodiode. The laser light with the modulated wavelength is usually employed to enhance the detectability of absorption signals. Distributed feedback (DFB) lasers are most frequently used for the various applications, as well as distributed Bragg reflector (DBR) lasers, vertical cavity surface emitting lasers (VCSELs), and external cavity diode lasers (ECDLs). On the other hand, photodiodes are its common detectors. The wedged windows are commonly used to reduce the etalon effects of the laser access, as shown in **Figure 6(b)**. TDLAS has been used to clarify the basic phenomena in industrial processes, the monitoring and advanced controlling of industrial systems. The selection of laser wavelength and the reduction of noises are the most important factors for TDLAS. In the practical industrial applications, the important step is the theoretical predictions of TDLAS spectra to select the laser wavelength.

In the practical industrial applications, various different species exist in a measurement area and the spectral overlaps appear between each species. The absorption spectra are often theoretically calculated with precision. Therefore, it is important to select the lines showing no or

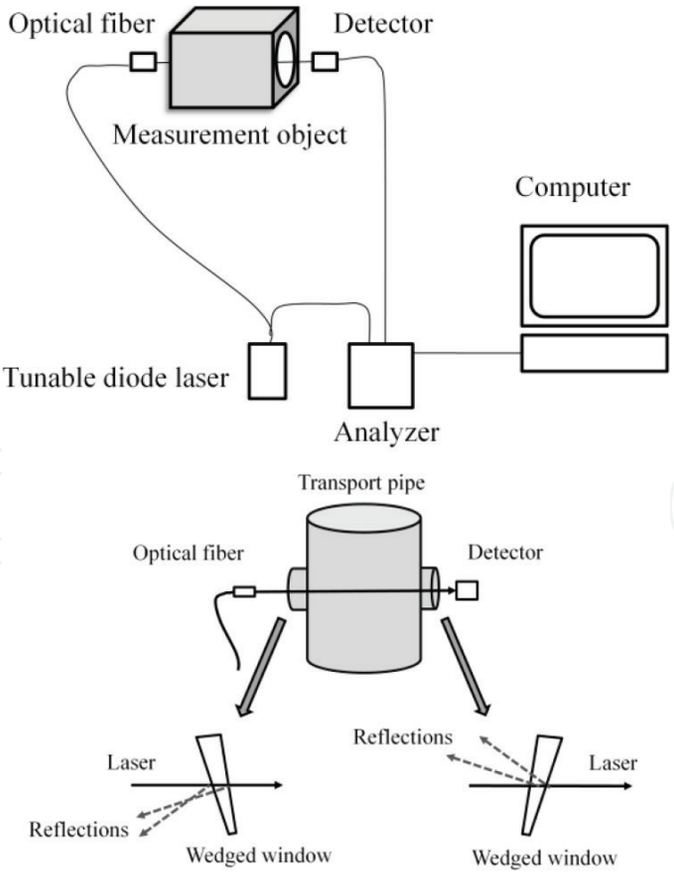


Figure 6. Typical geometric arrangement of TDLAS. (a) Typical geometric arrangement. (b) Wedged windows used in the laser pass.

less interference with other molecules. The theoretical and experimentally screening of quantitative measurement species in measurement conditions (especially high temperature and high pressure) is very necessary and important before applying TDLAS to the practical fields [16–21]. Because the main devices, such as tunable diode lasers and photodiodes, are much less expensive than those of other laser diagnostics, such as Nd:YAG lasers and CCD cameras, the cost of a TDLAS unit is reasonable when compared with those of other laser diagnostics. This is one of the biggest motivations to apply TDLAS for practical industrial applications. TDLAS is mainly used for gas measurements.

2. Applications

With the development of technology and devices, TDLAS has been employed in various industrial applications, including combustion and flow analyses, trace species measurements, environmental monitoring, process monitoring and its control, plasma processing, and so on [3, 5]. There are two approaches for TDLAS applications. One is based on the extractive sampling systems. The measured gases are sampled and introduced into a measurement cell. A multipath cell is often used to enhance the detectability of TDLAS. The laser beam is reflected using a set of mirrors to make a long path length in the measurement cell. The other is the in situ measurements of temperature, species concentrations, pressure, and velocities. The laser beam is introduced into the measurement area directly. In these applications, the fiber optics are usually used to maintain the ease and robustness of its utilization. TDLAS has been applied to clarify the basic phenomena in industrial processes and the monitoring and advanced controlling of the industrial systems. In order to control the industrial systems, the process parameters should be measured without the interference on the processes. TDLAS with high sensitivity and fast response features enables the monitoring of system control parameters in the practical industrial applications.

2.1. Car engine applications

An increasing concern with the environmental issues from car engines, such as air pollution, global warming, and petroleum depletion, has been paid much more attention to study the phenomena and solutions in various ways. TDLAS has been used for engine measurements in various ways including intake air, exhaust, and engine cylinder measurements [22]. TDLAS has a lot of merits in engine applications due to its fast response and high sensitivity.

Figure 7 shows a TDLAS application for the engine exhaust gas and intake air measurements [22]. In each combustion cycle, the response time is l ms to measure the temperature and the gas concentrations of CO, CO_2, H_2O, and CH_4. **Figure 7(a)** shows the measurement positions in the engine and the schematic diagram of sensor unit. A sensor was directly attached to a flange part of the piping. An optical fiber was used to guide the laser beam to the sensor unit. The transmitted laser beam was detected by a photodiode after it passed through the measurement gas flow. The parallel mirrors were set in this sensor to reflect the laser beam

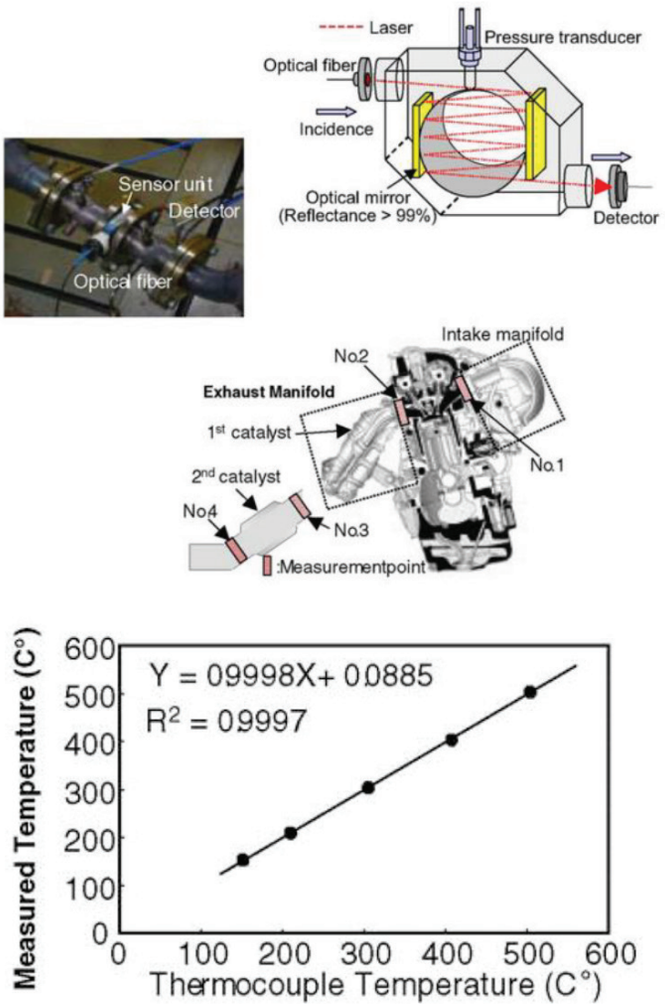


Figure 7. Application of TDLAS to engine exhausts and intake air measurements. (a) Measurement positions and schematic of sensor unit. (b)Temperature measurement result [22].

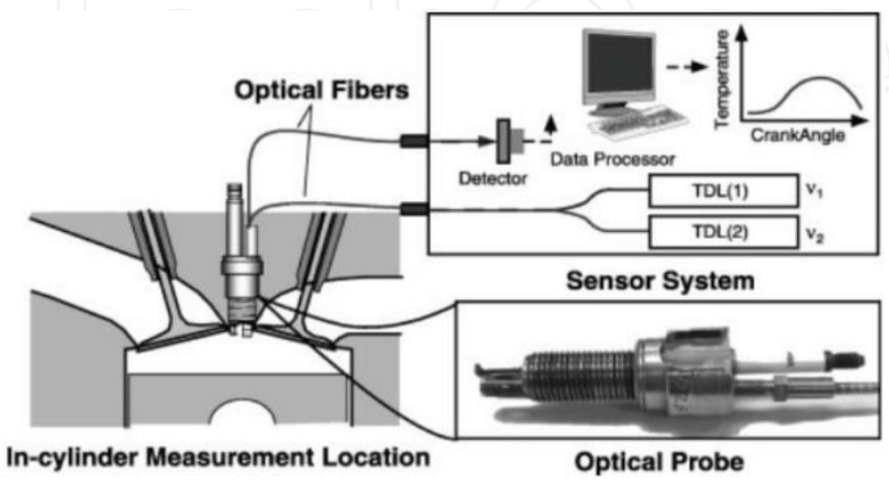


Figure 8. TDLAS sensor unit embedded in a spark plug [26].

10 times, which covers almost all areas in the piping. In order to measure several different gas concentrations simultaneously, the laser light from each laser diode was combined into a single optical fiber by the time-division-multiplexing. **Figure 7(b)** shows the temperature measurement results, which illustrated a strong correlation between the temperature measured by the TDLAS technique and the thermocouple with the measurement error of 10°C or less. TDLAS also obtained the transient phenomenon for the temperature and gas concentrations. NO_x is the important exhaust species in engine combustions. NO_x has also been measured using TDLAS in engine exhausts. NO, NO_2, and N_2O show the strong absorption band in the MIR wavelength region. A quantum cascade laser was mainly applied in these applications [23]. A room-temperature, high-sensitivity quantum cascade laser sensor for SO_2 and SO_3 measurements in the aircraft test combustor exhaust was also developed and demonstrated at ppmv levels [24].

TDLAS has also been employed to the temperature and concentration measurements in the engine cylinder [25]. TDLAS shows some drawbacks in high-pressure fields due to the pressure broadening effects. Therefore, it is essential to develop some relevant countermeasures to compensate these effects. The broadened H_2O absorption spectra during combustion were reduced by using a tunable external-cavity diode laser (ECDL) with the scanned wavelength range from 1374 to 1472 nm. The engine was operated in homogeneous-charge compression ignition (HCCI) mode. The temperature and H_2O concentration were measured every 85 s from each laser scan. It is demonstrated that the measured temperature and H_2O mole fraction rose from 800 K and 0.3% to 1350 K and 2.7% during the 35 crank-angle degrees(CAD) of a single compression stroke.

Figure 8 illustrates a schematic diagram of the temperature and concentration measurement in the engine using TDLAS [26]. The measurement device was embedded in a spark plug. A 6 mm-laser path next to the spark plug enables the temperature and H_2O concentration measurements near the spark plug. DFB lasers at 1345 and 1388 nm were used with a 2f wave-

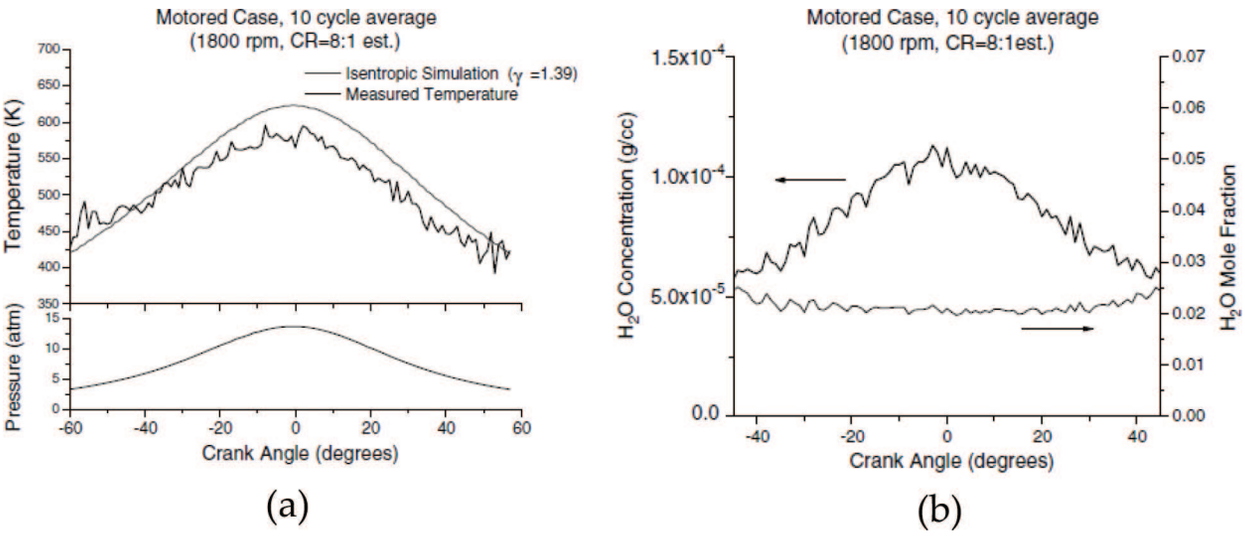


Figure 9. Gas temperature and H_2O concentration measurement in a motoring, single-cylinder engine. (a) Measured temperature. (b) Measured H_2O concentration [26].

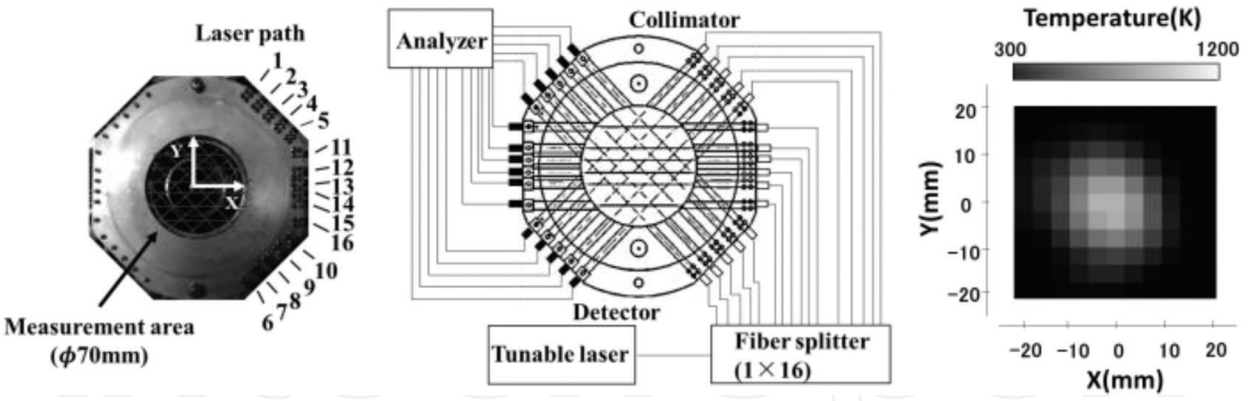


Figure 10. CT measurement cell and temperature measurement result [10].

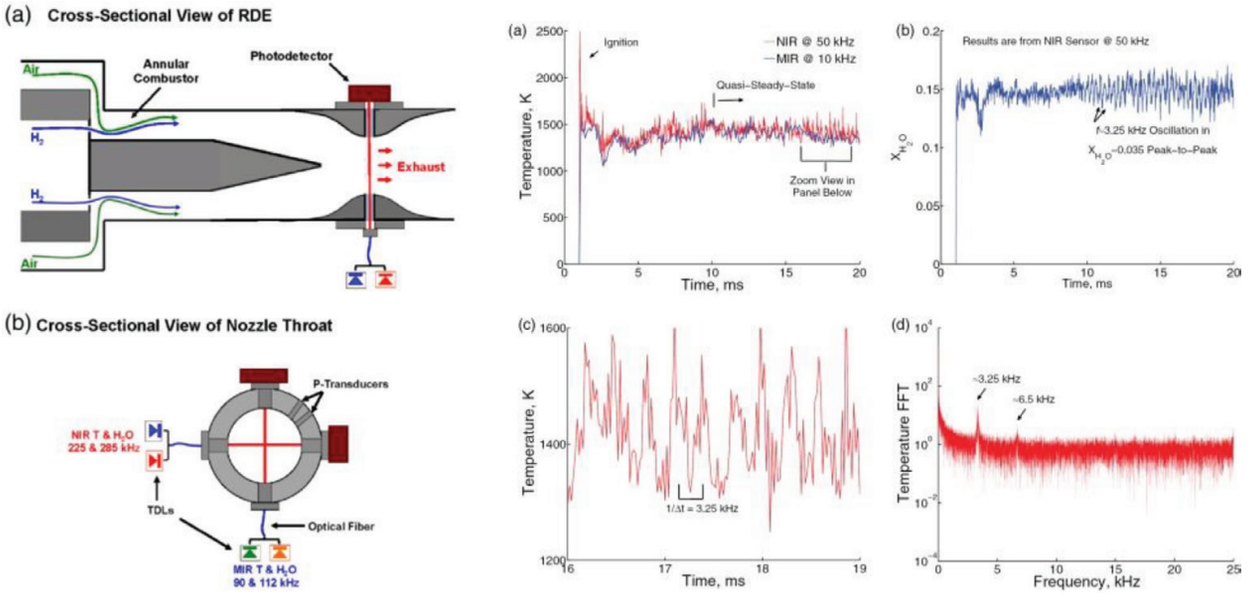


Figure 11. High-bandwidth scanned-wavelength-modulation spectroscopy sensors for temperature and H_2O in a rotating detonation engine. (a) Experimental setup; and (b) temperature and H_2O mole fraction measurement results [28].

length modulation technique. The temperature was determined according to the absorption ratio of two transitions. The H_2O concentration was determined from one of the absorption intensities using this inferred temperature. The temperature and H_2O concentration can be detected over the ranges of temperature and pressure from 500 to 1050 K and 0.11 to 5 MPa at 7.5 kHz in the internal combustion engines. The measurement results of temperature and H_2O concentration in a motoring, single-cylinder engine is shown in **Figure 9**.

The TDLAS technology combined with CT technology has also been applied in a multi-cylinder automotive engine [27]. The fast and continuous imaging of a 2D measurement section can be acquired using this combined method. However, it is rather hard to be attained by laser induced fluorescence (LIF). The size of the laser access ports for TDLAS application is small. In this case, it is not necessary to make large access windows into the combustion chambers for TDLAS, whereas it is often necessary in LIF applications. The optical fibers and collimators can be embedded in the optical access ports in the engine cylinder. This method has been demonstrated to detect the rapid changes of the fuel concentration distribution at a resolution of 2°of the crank angle.

The transient phenomena, such as start-ups and load changes in engines, have also been gradually clarified in various conditions. In order to develop the non-contact and fast response 2D temperature and concentration distribution measurement method, the theoretical and experimental research has been studied according to the absorption spectra of water vapor at 1343 and 1388 nm combined with CT (CT-TDLAS) [10]. The absorption spectra were measured to calculate the instant 2D temperature simultaneously using 16 path measurement cell shown in **Figure 10**. The 2D temperature measurement results of CT method were compared with that of the thermocouple measurements to evaluate the quantitative measurements of temperature. The linear relation between the measured temperatures by CT-TDLAS and thermocouple was confirmed between the temperature range 500 and 800 K. The high temperature field application has also been discussed to demonstrate its applicability for various types of combustors.

2.2. Jet engine applications

TDLAS has been applied to the jet engine measurements in various ways, which include rotating detonation engine (RDE) [28], scramjet engine [29, 30], and gas-turbine engine [31, 32] measurements. According to the measurement results of TDLAS with fast response and high sensitivity features, the dynamic flame behavior in a jet-engine combustor can be solved which is caused by many physical processes such as fuel-air mixing, fuel atomization and vaporization, and so on.

Figure 11(a) shows an application of TDLAS to RDE exhaust gas [28]. The TDLAS measurement was conducted to solve the detonation frequency of RDE at various global equivalence ratios and mass flow rates and to evaluate the combustion efficiency. The measurement response time was 0.lms to measure the temperature and H_2O mole fraction in the detonation

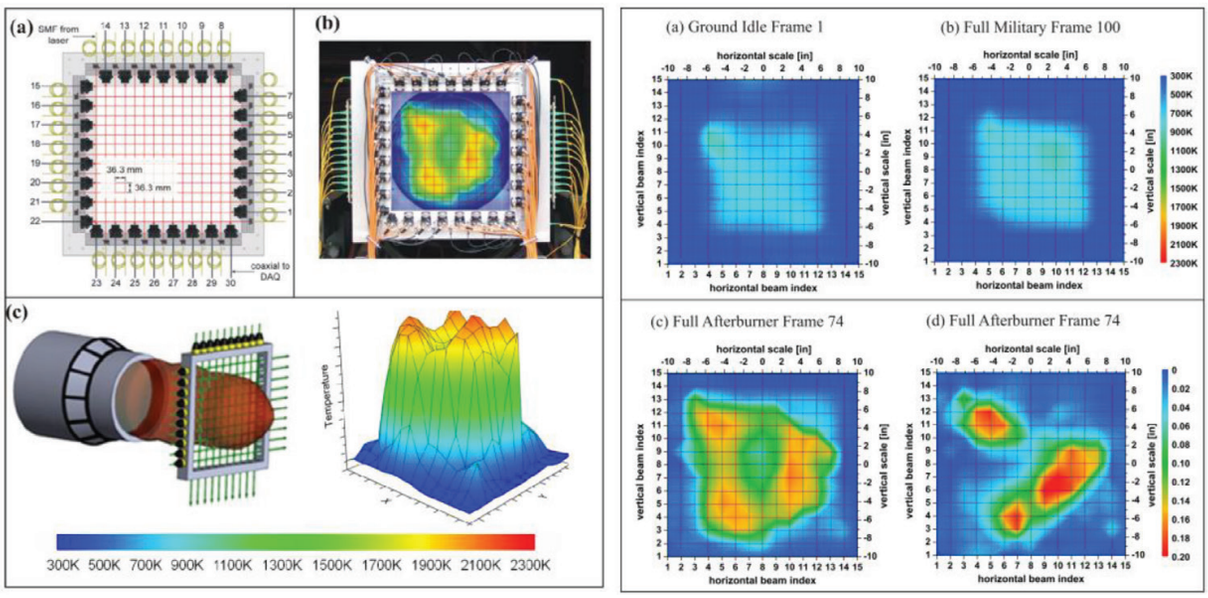


Figure 12. Application of hyperspectral tomography (HT) in a practical gas-turbine engine. (a) Schematic representation of the optical test section hardware including configuration of the probe beams. Panel, a photograph of the frame and the optical components overlaid by a sample reconstruction, schematic of the location of the measurements plane in the exhaust and a sample measurement of the 2D distribution of the temperature measured at this location. (b) A set of sample results obtained in the J85 engine [31].

cycle. A NIR sensor and A MIR sensor were directly attached to a throat part of the RDE nozzle via 6.35 mm diameter sapphire windows wedged at 2° to avoid etalon reflections. In the NIR sensor, two frequency-multiplexed tunable diode lasers near 1392 and 1469 nm were employed to measure the temperature and H_2O mole fraction in the RDE exhaust. In the MIR sensor, two frequency-multiplexed tunable diode lasers near 2551 and 2482 nm were employed to measure the temperature in the RDE exhaust. The laser beam was guided to the sensor unit by an optical fiber and detected by a photodiode after passing through the measurement gas flow. **Figure 11(b)** shows the temperature and H_2O mole fraction measurement results at engine start. The clear distinct oscillations in temperature and H_2O mole fraction that occur near 3.25 kHz corresponding to a detonation wave speed of nearly 1600 $m \cdot s^{-1}$ is recognized between the measurements by TDLAS and the Fourier analysis.

Figure 12 shows an application of hyperspectral tomography (HT) in a practical gas-turbine engine [31]. The HT technique is based on CT employing the multiple line-of-sight-averaged measurements with the absorption spectra of water vapor. 2D temperature and H_2O concentration at the exhaust plane of jet engine were measured using the HT technique. **Figure 12(a)** shows the schematic representation of the optical test section hardware. The measurement response time is up to 50 kHz to measure 2D temperature and H_2O concentration at 225 spatial grid points. In the HT sensor, a narrowband CW Fourier-domain mode-locked (FDML) laser source with a wavelength range from 1335 nm to 1373 nm was used to measure 2D temperature and H_2O concentration in the engine. As optical access ports, optical fibers and collimators are embedded in the exhaust plane of the engine. A measurement grid consisting of 30 dual-wavelength optical paths has been implemented in the exhaust plane (15 of them

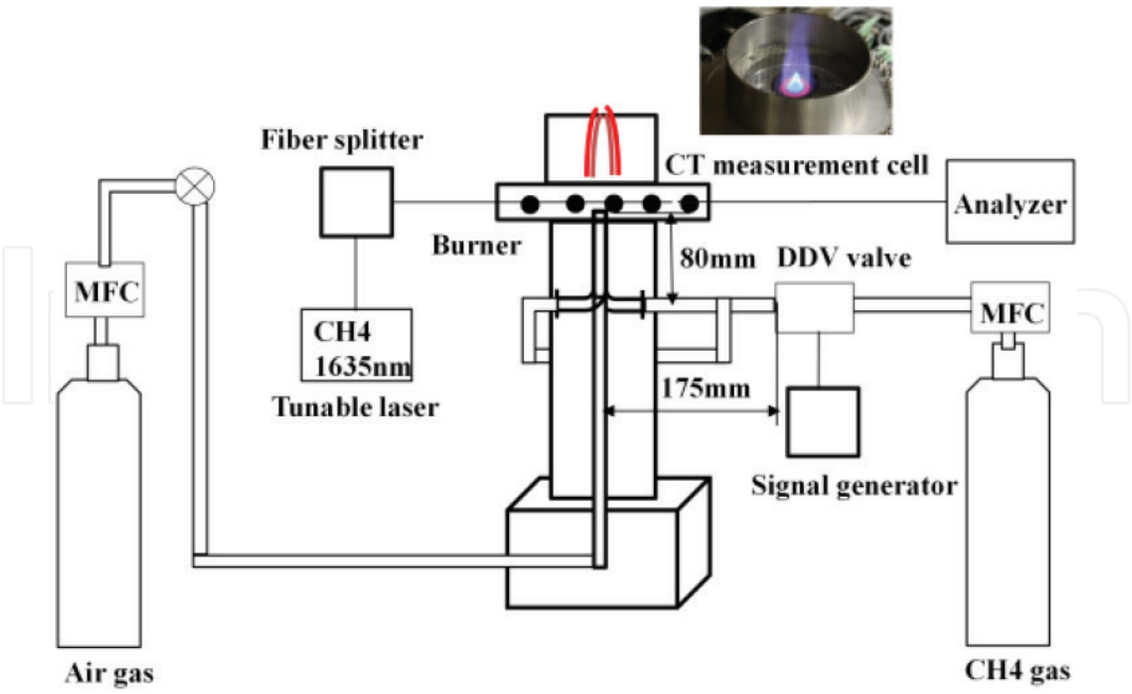


Figure 13. Experimental setup of time-resolved 2D temperature and CH_4 concentration in an oscillating CH_4-air Bunsen-type flame using CT-TDLAS [11].

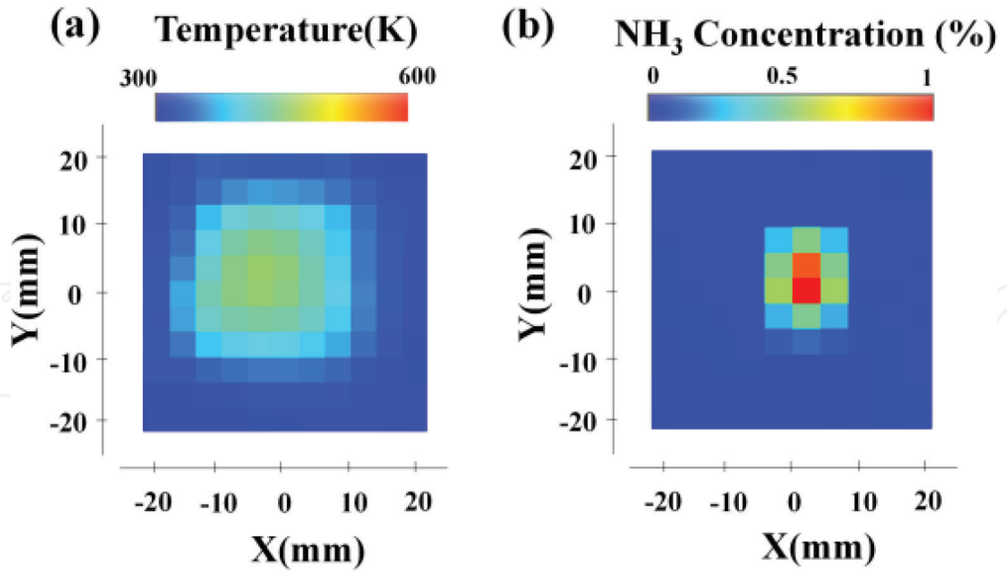


Figure 14. 2D temperature and NH_3 concentration measured by CT-TDLAS [11].

installed to probe the measurement plane horizontally and 15 vertically). The laser beam was detected by a photodiode after passing through the exhaust stream to record the transmitted laser intensity with a data acquisition system. The measured tomographic images are shown in **Figure 12(b)**. The reconstructions were obtained under representative conditions in the engine. Its applicability for actual gas-turbine jet engine has been demonstrated.

2.3. Burner and plant applications

From a laboratory scale burner to a large commercial-size burner, TDLAS has been applied to several different types of burners. Many laser diagnostics methods have drawbacks in the large-scale applications. TDLAS does not show a serious demerit and even shows a merit in these applications because its signal intensity increases according to the path length. These applications have extended to incinerator furnaces [33], coal-fired boiler burner [34, 35], coal gasifier [36], and so on.

The CT-TDLAS method has been applied to the oscillating flames to measure the time-resolved 2D temperature and concentration distributions [9, 11]. **Figure 13** shows the experimental setup of time-resolved 2D temperature and CH_4 concentration measurements using CT-TDLAS in an oscillating CH_4-Air Bunsen-type flame. In order to confirm the flame oscillation characteristics, the oscillating flame was also measured by a CCD camera. **Figure 14** shows the measurement results of 2D temperature and NH_3 distribution using CT-TDLAS. 2D temperature and gas concentration distributions were successfully reconstructed by this CT method. The accuracy of the reconstructed results depends on the accuracy of the absorption database and the number of laser path (spatial resolution). The spatial resolution becomes 3 or 4 mm depending on the measurement position when using the 16 path measurement cell. CT-TDLAS with a potential of kHz response time enables the real-time 2D temperature and species concentration measurements in various fields.

In order to reduce the emission of harmful substances from the burner and plant, such as O_2, CO, NO, and so on the reactions within the facilities must be stabilized. In turn, it requires the accurate and rapid measurement of composition change in the system conditions. The O_2 and CO concentrations were measured using TDLAS in a 300ton/day commercial incinerator furnace [33]. The wavelength conversion technique extended the available wavelength region to both longer and shorter wavelengths [34, 35], which was utilized to measure NO and mercury in a coal-fired boiler burner. The CO, CO_2, CH_4, and H_2O mole fractions in the synthesis gas products of the coal gasification were measured using TDLAS to observe the batch feeding of coal caused by the composition change with small temperature fluctuations in the reactor [36]. The results measured by TDLAS were in good agreement with that of the gas chromatography (GC) analysis. Simultaneously, it is faster than that of GC analysis. The real time feature of TDLAS is important to control the combustor for the combustion stabilization.

The simultaneous detection of CO, H_2O, and temperature using TDLAS is also reported in the combustor chamber of a coal power plant [37]. The NIR-diode-laser-based dual-species in situ spectrometer was successfully tested over two 60 h periods in a 600 MW full-scale lignite-fired power plant (absorption paths, 13 and 20 m). A fractional absorption resolution of better than 10^{-3} with a time resolution of 30s was achieved, despite the severe disturbances and high temperatures within the in situ measurement path. The measurement results of spectra and temperature are shown in **Figure 15**.

The water vapor spectra is shown in the right-hand plot of **Figure 15(a)**. The line *A* was used to determine the H_2O concentration derived in the presented spectrum. The H_2O concentration was 14.5% by volume. It can determine a minimum detectable absorption of 3.3×10^{-4} (1σ), which corresponds at that temperature to a resolution of 0.1% by volume H_2O. The line area ratio of H_2O lines *A*(13 0 13 ← 14 0 14, 211 ← 000), *B*(625 ← 634, 112 ← 000), and *C*(735 ← 634,

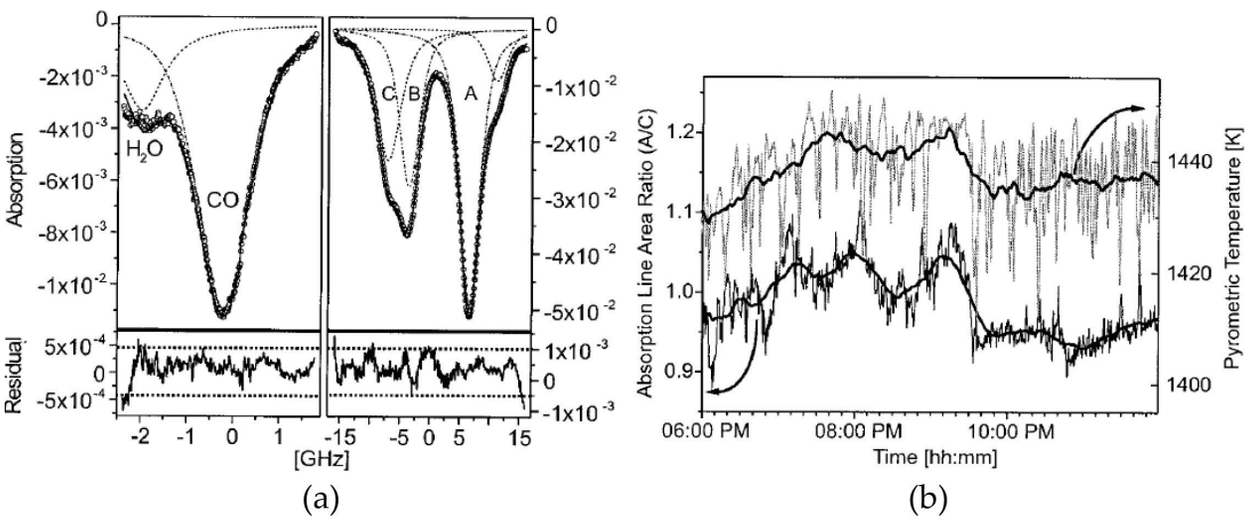


Figure 15. Measurement results of spectra and temperature. (a) Typical in situ line shapes of CO line at 1559.5 nm and H_2O at 813 nm. (b) Time series of the line area ratio of H_2O lines compared with temperature data from the radiative pyrometer [37].

211 ← 000) was used as a temperature indicator to compare the temperature data from the radiative pyrometer taken looking into the combustion chamber, as shown in **Figure 15(b)**.

2.4. Process monitoring applications

Due to the fast and non-contact features and reasonable cost of TDLAS technology, TDLAS is actively applied for the process monitoring. The process monitoring applications cover aluminum industry, steel making industry, semiconductor industry, chemical industry, food and pharmaceutical industry, and so on. Now the conventional devices are mainly employed for the process monitoring in these industries. Some of the applications described above also belong to this category of process monitoring applications.

There are several specific and useful atoms or molecules in each industry [38–41]. For example, HF is an important species for the aluminum making industry because the aluminum smelting process utilizes alumina(Al_2O_3) and cryolite(Na_3AlF_6) resulting in the HF emission [39]. O_2, CO, and CO_2 are the important species in many plants including the steel making industry [39] and most of the combustion related industries [32]. NO_x are also the important species for the emission control from these processes. It has been demonstrated in several applications of TDLAS for chemical vapor deposition (CVD) process monitoring [42, 43]. CH_4 and C_2H_2 have been monitored using a quantum cascade laser at 7.84 nm [42]. HCl has also been measured in a CVD process [43]. In the semiconductor industry, the impurities, such as H_2O, affect the plant performances. TDLAS has an excellent sensitivity for the H_2O measurement. H_2O mass flux monitoring and temperature in a freeze drying process have also been detected using TDLAS [44]. These results have been utilized to a non-contact product temperature determination. **Figure 16** shows the TDLAS product temperature calculation during a SMART Freeze Dryer run processing, which were compared with that of thermocouple data and Manometric Temperature Measurement (MTM) method.

The applicability of diode-laser absorption to the arcjet plume diagnostics has also been demonstrated [45]. The reconstruction of the absorption coefficient field of the arcjet's argon exhaust plume was employed to measure the spatial temperature and the atomic number density distribution of a 3 kW class arcjet. Various parameter measurements can be performed when changing the arcjet's mass-flow rates and the discharge currents. The measurement results show that the maximum temperature and atomic number density increase with the arcjet's mass-flow rate and the discharge current.

An optical NIR process sensor for the steel making furnace pollution control and energy efficiency is also proposed [46]. The response of peak height versus CO mole concentration was linear according to the experimental results. The standard deviation of the CO mole concentration was 0.8 pct CO. The gas temperature, CO and water concentrations were also simultaneously detected using a single laser in this study. **Figure 17** shows the dependence of the selected water peak height ratio on the temperature. The error analyzed here indicated that the optical technique can measure the gas temperature within a standard deviation of 30°C. This chapter cannot be fully comprehensive for all the industries and applications. The aim is to highlight several interesting and widespread applications of TDLAS in industry.

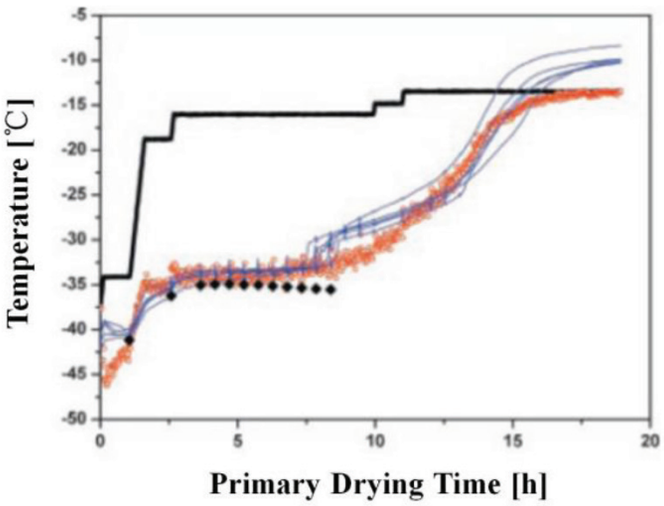


Figure 16. TDLAS product temperature calculation during a SMART freeze dryer run processing 5% (w/w) sucrose (3 mL fill volume/vial, 112 vials total load, 20 mL Wheaton). Symbols represent thick solid line = shelf inlet temperature, empty circles = $T_{p\text{-}TDLAS}$, thin solid lines = $T_{b\text{-}TC/center}$ (n = 5), filled diamonds = $T_{p\text{-}MTM}$ [44].

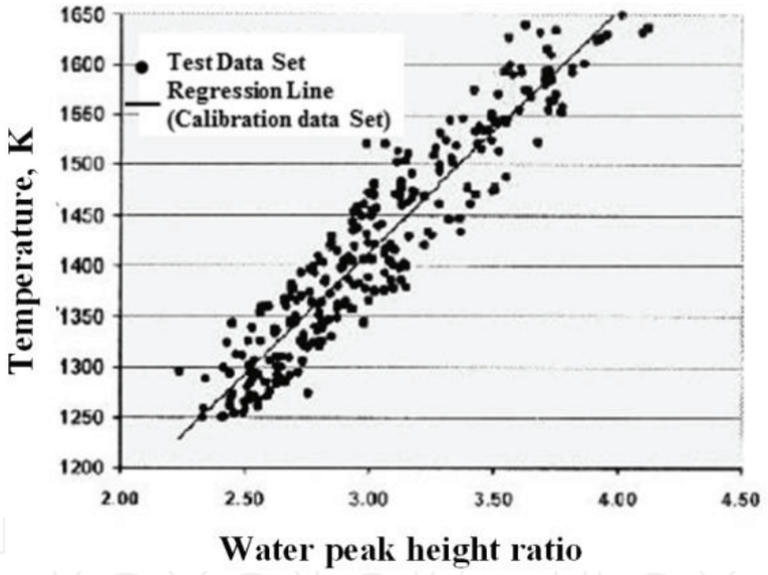


Figure 17. Comparison of the water peak height ratio with the thermocouple measurements [46].

3. Challenges

The applications of TDLAS have extended to the various industrial fields. Besides the applications mentioned earlier, TDLAS can be applied for the environmental monitoring, plant safety, and so on. It has been demonstrated that the carbon isotopes of CO_2 can be detected for the forest air monitoring using TDLAS. The highly reliable laser diodes with high power with a wide continuous single mode tuning range and low frequency drift are very necessary for TDLAS applications. Because of the small size of diode lasers, TDLAS can also be employed as a miniature sensor. It would not be an exaggeration to say that TDLAS at a NIR wavelength region has already had a high-quality finished form for the practical industrial applications.

On the other hand, there have been several challenges to advance the TDLAS applications in a MIR wavelength region. The fiber delivery system is the most notable and desired technology in this wavelength region. However, the silica-based fiber optics cannot be used in this wavelength region and there is no reliable and easy-to-use fiber delivery devise. The development of optical fiber delivery system will make TDLAS much more appealing to various industrial fields. The advancement of lasers and detectors in MIR region is also important to make the TDLAS system reliable and rugged. MIR lasers allow more sensitive detection, whereas the lasers with a broader tuning range make the multiple species detection with a single laser possible. It means that a future developed instrument of TDLAS might be able to selectively detect several different gases using a single laser, or to work as the universal, cost-effective spectrometers.

Other promising applications of TDLAS are 2D and 3D measurements using CT technology. TDLAS combined with CT shows a great potential for the fast and continuous imaging in a measurement area. 2D measurement has been proposed and applied for some industrial applications using CT-TDLAS, which should be further developed, especially 3D measurement. This technique is promising to clarify the basic phenomena in industrial processes and the monitoring and advanced controlling of the industrial systems. The development of fast CT algorisms and CT optical systems is inevitable together with an advanced measurement technology. The improved performance of TDLAS will also open up the new application fields. Simultaneously, the reduced costs of TDLAS system will substitute the conventional sensors by TDLAS-based sensors.

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