Study on O_2 Concentration and Temperature Measurement with 760nm Diode Laser in Ununiform Distributed Condition

Miyeon Yoo, Sewon Kim, and Changyeop Lee

***Abstract*—It is important to measure the internal temperature or temperature distribution precisely in combustion system to increase energy efficiency and reduce the pollutants. Especially in case of large combustion systems such as power plant boiler and reheating furnace of steel making process, it is very difficult to measure those physical properties in detail. Measurement and analysis by tunable diode laser absorption spectroscopy can be attractive method to overcome the difficulty. In this paper, TDLAS methods are used to measure the oxygen concentration and temperature distribution in various experimental conditions. Especially, this paper suggest a possible approach to measuring an ununiform distributed condition.**

***Index Terms*—Tunable diode laser absorption spectroscopy, temperature distribution, gas concentration, oxygen.**

I. Introduction

For a large combustion system, it is important to measure the internal temperature or temperature distribution precisely. Temperature is one of the indispensable physical value to operate and maintain the combustion system efficiently and design a new combustion system as well.

In order to maintain high combustion efficiency of the powerplant boiler and to last its stable operation, oxygen concentration value is also needed. And it can be transformed to the air-fuel ratio that is a crucial variables to operate a boiler. However, almost the whole current equipment in plant has a limitation in measurement, and its reliability has become an issue to be resolved. One of the typical concentration measurement methods is using the zirconia sensor. It is a method to measure the oxygen concentration. This method is only conducted pointwise measurement locally inside the combustion system. Then the measurement value may somewhat differ from the average oxygen concentration distributed actually. Besides, the reliability becomes lower if some particulate matters are attached to the measuring instrument. And another disadvantage is durability. Due to the limitation of longevity, the calibration cycle of the sensor will get shorter gradually and it is directly connected with maintenance problem.

The thermocouple or pyrometer is also one of the typical temperature measurement apparatus, but they can measure only the wall or adjacent area of the huge combustion system. Because they can measure only some limited areas and have low precision, their probability or reliability may become an issue. So it is very important to develop a technique can measure heterogeneous area or harsh combustion environment.

To complement the limitations or demerits described above, researches are dealing with TDLAS (Tunable Diode Laser Absorption Spectroscopy) method recently, and it shows great performance in some experimental study and demonstration test.

TDLAS method can be used to measure the temperature, concentration, or speed of a gas with diode laser. Absorption spectroscopy measuring system with tunable diode laser can realize non-contacting and real-time measurement and semi-permanent longevity. Moreover it can measure several gases simultaneously [1]-[5]. And it is a line integral method that can measure the practical value or distribution of gas concentration or temperature. It means TDLAS method has high reliability compare with point-wise measuring methods, because it performs an analysis procedure on the average temperature of the line that the laser light has passed along. In addition, the measurement range can be chosen freely, and the precision is high, too.

This study aims to make clear the characteristics of concentration and temperature analysis when use 760 nm diode laser with TDLAS method and to predict the temperature distribution of an ununiform distributed condition.

II. Fundamental Principle

A. Beer-Lambert Law

Beer-Lambert law is the most common fundamental principle of direct absorption spectroscopy. It is described briefly as following Fig. 1.

When an uniform distribution of a gas is existed in the limited space, Beer-Lambert law can be expressed with an ratio between incident laser intensity (I_0) and transmitted laser intensity (I) as Equation (1).

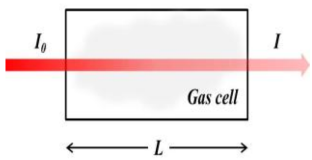

Fig. 1. Schematic of direct absorption spectroscopy measurement.

$$\ln\left(\frac{I}{I_0}\right) = P\int_0^L X_{abs}(x) S_i[T(x)]\phi_v dx \equiv a_v \tag{1}$$

Manuscript received January 16, 2015; revised April 10, 2015.

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DOI: 10.7763/IJMMM.2015.V3.191

where P[atm] is the pressure, L[cm] is the path length, X_{abs} is the local mole fraction of an absorbing species, S[cm^{-2}atm^{-1}] is the linestrength of a transition and ϕ is the lineshape function of a particular transition, respectively. Lineshape function ϕ is normalized as 1.

The intergrated absorbance A can be obtained as following equation (2).

$$A = \int_{-\infty}^{\infty} a_v dv = P\int_0^L X_{abs}(x)S_i[T(x)]dx \tag{2}$$

Usually, Absorbance of absorption spectroscopy is simply defined like as equation (3).

$$A_i = PX_{abs}S_i(T) \tag{3}$$

B. Concentration and Temperature

As mentioned above, the integrated absorbance is proportional to the partial pressure. Therefore, the concentration of the gas species can get simply.

$$X = \frac{X}{P \cdot S(T) \cdot L} \tag{4}$$

Gas temperature can be measured using the ratio of the two absorbance area derived as equation (5).

$$R = \frac{A_1}{A_2} \approx \frac{S_1(T)}{S_2(T)} \exp\left[-\frac{hc}{k}\left(E_1^{"} - E_2^{"}\right)\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \tag{5}$$

where h[J·s] is the Planck's constant, c[cm/s] is the speed of light, k[J/K] is the Boltzmann's constant.

Equation (5) can be summarized on terms of temperature.

$$T = \frac{\left(\frac{hc}{k}\right)\left(E_2^{"} - E_1^{"}\right)}{\ln\left(\frac{A_1}{A_2}\right) + \ln\left(\frac{S_2(T_0)}{S_1(T_0)}\right) + \left(\frac{hc}{k}\right)\left(\frac{E_2^{"} - E_1^{"}}{T_0}\right)} \tag{6}$$

where T_0[K] is the reference temperature (usually 296K), v_0 [cm^{-1}] is the line center frequency and E"[cm^{-1}] the lower state energy of the transition [6].

C. Temperature Binning

Temperauter binning method is used to measure a temperature distribution of an ununiform temperature field. The information of the temperature distribution in a gas space can be obtained by this method using a single laser only.

Temperture binning method is derived as equation (7) that is a discretized from of equation (1).

$$\tilde{A} = \frac{A}{P} = \sum_{j=1}^{n}\left[S(T_j)X_{abs,j}L_j\right] \tag{7}$$

The whole measurement path with non-uniform properties is decomposed into n sections, and each section is assumed nearly uniform temperature space of T_j, mole fraction of $X_{abs,j}$ and path length of L_j. For the selected m absorption transitions, the following linear equation (8) can be set from equation (2).

$$\begin{bmatrix} S_1(T_1) & S_1(T_2) & \cdots & S_1(T_n) \\ S_2(T_1) & S_2(T_2) & \cdots & S_2(T_n) \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ S_m(T_1) & S_m(T_2) & \cdots & S_m(T_n) \end{bmatrix} \cdot \begin{bmatrix} (X_{abs}L)_1 \\ (X_{abs}L)_2 \\ \vdots \\ (X_{abs}L)_n \end{bmatrix} = \begin{bmatrix} \tilde{A}_1 \\ \tilde{A}_2 \\ \vdots \\ \vdots \\ \tilde{A}_m \end{bmatrix} \tag{8}$$

III. Experimental Setup and Condition

Experiments have been performed with 760 nm wavelength of DFB diodelaser and power is 20 mW. Laser wavelength was controlled by laser controller and function generator. Controlled laser beam was sent to transmitting part through a single mode fiber. At the end of the fiber, collimator lens was mounted to make a parallel beam. Multimode fiber collimator was used to take and deliver light signal passed through the target gas space to a detector.

First of all, to check the characteristics of penetrated signal on oxygen concentration and temperature, experiments have been conducted in various temperature and concentration conditions, the concentration range was from 2.7% to 6.49% and the temperature range was from 319K to 803K.

The experiment to measure temperature distribution in a line has been conducted using electrical furnaces with set different temperatures. Fig. 2 is a schematic diagram of experimental condition on temperature division measurement. The experiments for temperature sectional measurement in a line were performed in conditions which are 21% of the oxygen concentration and 1 atm of the pressure. The four wavelengths were selected of 760.07 nm, 760.09 nm, 760.21 nm and 760.26 nm.

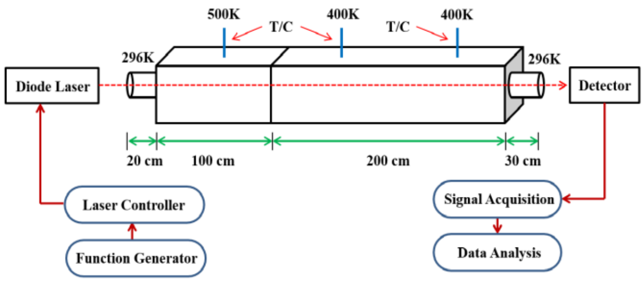
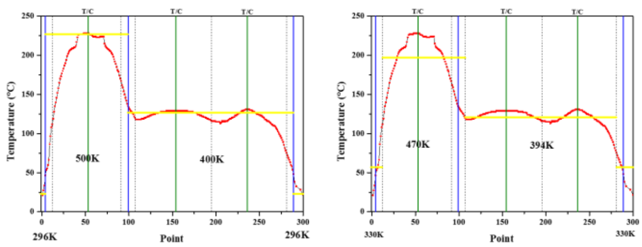


Fig. 2. Schematic diagram for the measurement of temperature distribution.



(a) Case 1 (296, 400, 500K) (b) Case 2 (330, 394, 470K)

Fig. 3. Assumptive temperature profiles by step type.

Fig. 3 shows the temperature assumption conditions by step type compared with real temperature distribution. The temperature distribution was simplified by step functional distribution. The temperature values of case 1 were 296K, 400K and 500K, those are the temperatures in the center position of each electric furnace. In case 2, three temperatures, 330K, 394K and 470K were selected and those are the average temperatures of each divided section.

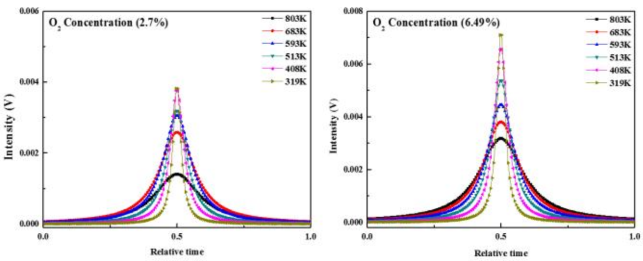
IV. Result

A. Concentration and Temperature

In Fig. 4, the higher O_2 concentration leaded the bigger absorbance area. And when the temperature increases, the area of the absorbance was found to decrease.

Fig. 5 shows peak intensity differences between 2.70% O_2 concentration condition and 6.49% O_2 concentration condition according to the temperature. In this graph, the intensity changing tendency is figured out easily. Peak intensity becomes higher when temperature decreases and gas concentration increases.

It shows general optical characteristics in gas field. If there are many gas molecules can absorb a specific ray, intensity signal become stronger. And as temperature becomes higher, the molecule motions are promoted and it leads higher broadening effect that is a major cause to lower intensity signal in specific wavelength.



(a) O_2 concentration : 2.7% (b) O_2 concentration : 6.49%

Fig. 4. Effect of temperature on absorbance spectra at various O_2 conditions.

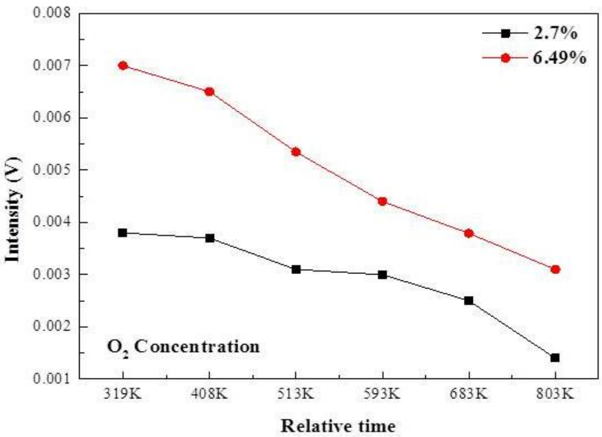


Fig. 5. Comparison of peak intensity.

Fig. 6 shows the measured absorption signal when the temperature was 600K. The obtained signal was analyzed and compared with the measurement data of electro-chemical type gas analyzer. The concentration of oxygen was measured about 2.119% by optical method while the measurement value was 2.110% in EC type gas analyzer. Measurement precision was similar in both manner while the execution time of optical method was under one tenth as compared with that of EC type gas analyzing.

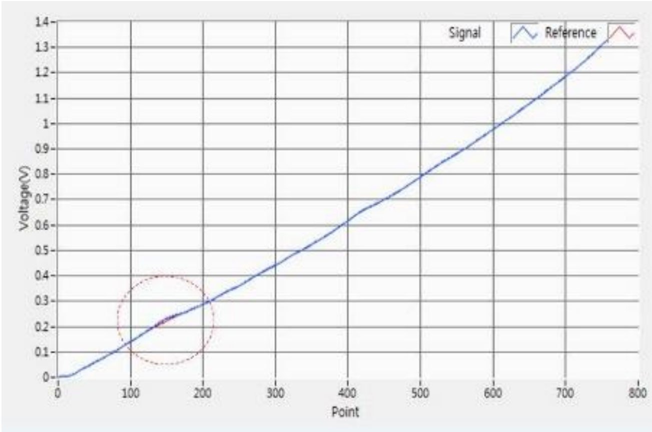
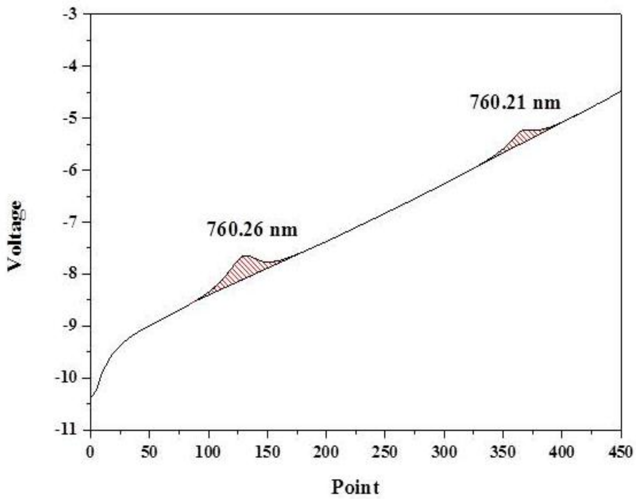
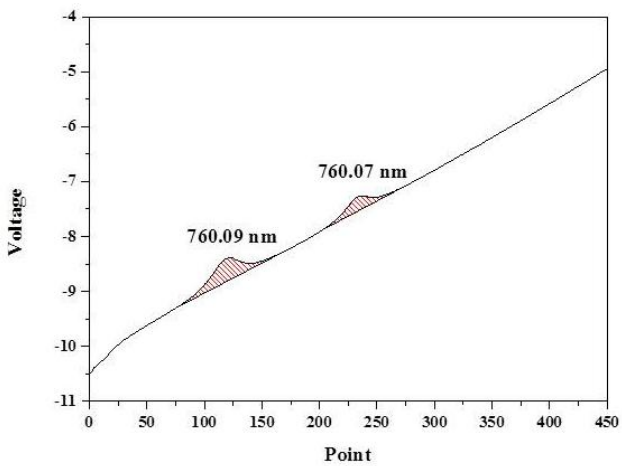


Fig. 6. Measured absorption signal (760 nm).

B. Temperature Binning



(a) Absorptions in 760.21&760.26 nm



(b) Absorptions in 760.07&760.09 nm

Fig. 7. Absorption signals about 760 nm wavelength.

Fig. 7 shows the measured absorption signals about 760 nm wavelength. The oxygen concentration was 21% (general atmosphere condition) and maximum temperature was 500K. All absorption signals in Fig. 7 were gained from a single diode laser just by controlling the current input to the diode laser using the characteristics of wavelength tunable laser.

TABLE I: DIFFERENCE BETWEEN REF. DISTANCE AND CAL. DISTANCE

(A) CASE 1

	Ref. Dist.(cm)	Cal. Dist.(cm)	Error(%)
L_1(296K)	50	72.25	44
L_2(400K)	200	171.43	14
L_3(500K)	100	105.81	5.8

(a) Case 2

	Ref. Dist.(cm)	Cal. Dist.(cm)	Error(%)
L_1(330K)	66	72.80	10
L_2(394K)	184	171.72	6.6
L_3(470K)	100	105.47	5.4

Table I shows the results by analyzing the absorption signal using the equation (7) and (8). The temperatures were assumed in this calculation and the unknown factors are distance in each assumed temperature. The temperature profiles were assumed by two cases as shown in Fig. 3.

In result, calculated distance of each temperature region by analyzing the absorption signals shows similar tendency with reference distance qualitatively, although the quantitative values have sizable errors.

However the errors in case 2 are small as compared with case 1. In case 1, sectional temperatures were assumed by maximum value in each section, while the sectional average temperature values were used in case 2. So it is very important to reduce the error that the step functional temperature profile should be decided exactly in order to represent the actual temperature profile in assumption stage.

V. CONCLUSIONS

This study have been conducted to improve the measurement capacity of TDLAS method in various conditions.

The O_2 concentration has been measured precisely where the temperature range was 319~803K and the concentration range was 2.70~6.49%. And the error rate was 0.4% at 600K and 2.110% condition.

Next, an experiment has been performed to predict the sectional temperature distribution in the ununiform distributed condition. The actual temperature distribution was simplified by step functional profile in order to compare the difference between the setting temperature and the measured temperature. It is possible to reduce the error of the measurement if the conditions for temperature division are set in more subdivision with reasonable assumption. This method can be applied to measure the temperature distribution in a large combustion system such as powerplant boiler and steel manufacturing furnace.

ACKNOWLEDGMENT

This work was supported by the Power Generation & Electricity Delivery Core Technology Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (No. 20131020102330).

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