Study on the Concentration Measurement of the Pollution Gases from Coal-Fired Power Station

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Abstract. CO₂ is a main kind of pollution gases discharged from coal-fired power station. The relationship between gas concentration and pressure, temperature is deduced base on the law of Beer-Lambert and the theory of gas line-shape. The tunable diode laser spectral technology is used to analyze the changing regularity of the peak, half-peak width of the absorption curve with pressure and temperature.

1. Introduction
In our country the energy structure mainly depends on coal burning, especially in electric power industry. With the development of the economy, the total amount of coal combustion is increasing year by year. Statistically coal occupied 70 % in the primary energy consumption in our country. A great quantity of CO₂ from coal combustion is discharged to atmosphere, which brings on serious air pollution. CO₂ has the decalescence and adiabatic function. The increment of it can result in invisible “glass cover”, which makes the heat from sun radiation to the earth can’t disperse into the outer space, so the earth surface gets hot and forms greenhouse effect [1]. Traditional air pollution monitoring methods mainly base on wet chemical process technology and experimental analysis after absorption sampling. In recent years, many single-point measurement instruments appear, such as ultraluminescent method SO₂ monitor, chemiluminescent method NOₓ monitor and non-dispersal infrared method CO₂. Comparing with these methods, absorption spectral technology has more prospects. Spectroscopic is an ideal environment monitoring technology because of its large monitoring scope, multi-components and highly selective detection and real-time analysis. The widespread spectroscopic techniques in trace gas detection include ultraviolet/visible wave band differential optical absorption spectroscopy technology (DOAS), differential absorption laser radar (DIAL), Fourier transformation infrared spectroscopy (FTIR), and tunable diode laser absorption spectroscopy (TDLAS) and so on [2,3]. In this paper, TDLAS technique is discussed in detail.

The basic principles include the law of Beer-Lambert, Fourier transform, nonlinear-optical frequency transform, the technique of laser modulation and so on. Here the method of harmonic detection is put forward and CO₂ absorption curve changing with different pressure and temperature is mainly analyzed [4].

2. Measurement theory
The interaction between electromagnetic radiation and atom or molecule is the basis of spectral detecting the pollutant components and characteristic. According to the absorption characteristic of the trace gas in ultraviolet, visible and infrared spectral band, the gas concentration can be educed [5,6]. A
bunch of light whose intensity is $I_0$ passes through absorption cell, based on the law of Beer-Lambert, its output intensity is:

$$I(\lambda) = I_0(\lambda) \exp(-A(\lambda))$$

(1)

where $A(\lambda)$ is the absorptivity and can be described by equation:

$$A(\lambda) = \sigma(\lambda)NL = \alpha(\lambda)L$$

(2)

where $I_0(\lambda)$ is the emission light intensity, $I(\lambda)$ is the output light intensity through the measured gas, $L$ is the length of light path, $N$ is the concentration of the absorbent, $\sigma(\lambda)$ is the absorption coefficient which is irrelevant to the measurement instruments.

When the signal is weak, $I(\lambda)$ can be shown as follows:

$$I(\lambda) = I_0(\lambda) \exp(-A(\lambda)) \approx I_0(\lambda)(1 - A(\lambda))$$

(3)

$\sigma(\lambda)$ is a fixed value under constant pressure and constant temperature. $L$ is also a fixed value in experiment. So

$$1 - I(\lambda)/I_0(\lambda) = kN$$

(4)

where $k$ is relevant to pressure and temperature.

But this measurement method has high demand to the environment, $k(P,T)$ will change with different pressure and temperature and need many modify. So another method is obtained. Here $S$ is defined as the area enclosed by the absorption curve,

$$S = \int \left[1 - \frac{I(\omega)}{I_0(\omega)}\right] d\omega = \int \alpha(\omega)L d\omega$$

(5)

According to atomic physics, $\sigma_{ik} = S_0 g(\omega, P, T)$, where $S_0$ is a constant being irrelevant to temperature and pressure, $\omega_c$ is the laser central frequency of located at absorption curve, $g(\omega_c, P, T)$ is the normalized line-shape function, namely $\int g(\omega_c, P, T) = 1$. When the penetration light intensity $I(\lambda)$ is weak, $N_i$ is irrelevant to $I$, that is,

$$\int \alpha_{ik}(\omega) d\omega = \int N_i \sigma(\omega) d\omega = N_i \int \sigma_{ik} d\omega = N_i \frac{h\omega_c}{c}$$

(6)

So

$$S = \frac{LN_i h\omega_c B_{ik}}{c}$$

(7)

For the given energy level $i$, $k$, $B_k$ and $\omega_c$ are fixed values, so $S$ is direct proportional to $N_i$, namely the area enclosed by the absorption peak is proportional to the concentration.

$H$ is defined as the peak height of the absorption curve:

$$H = I_0/I - 1 \approx \alpha(\omega_c)L = Sg(\omega_c, P, T)NRT$$

(8)

where $R$ is the volume percentage of the measured gas. At high pressure, the line-shape is Lorentzian line-shape, that is $g(\omega_c) = \frac{1}{\pi \nu(\sigma_i + 2\sigma_b)N}$, so

$$H = S \frac{1}{\pi \nu(\sigma_i + 2\sigma_b)N} \approx \frac{SRL}{\pi \nu(\sigma_i + 2\sigma_b)} \propto R$$

(9)

when the temperature is unchanged, line height $H$ is independent of particle concentration $N$, so $H$ has no relation with $P$, only depending on gas percentage $R$.

In addition, $\nu = \frac{8kT}{\pi \mu}$, so $H$ is proportional to $\sqrt{T}$.

$\delta\omega$ is defined as half-peak width:

$$\delta\omega = \gamma^{el} + \gamma^{int} = \pi \nu(\sigma_i + 2\sigma_b)N \propto N$$

(10)

Moreover when the pressure is lower, the line-shape isn’t Lorentzian line-shape, but Gaussian line-shape may be dominant.
3. Experimental installation and results
In experiment, the laser source is 1580nm VCSEL laser made by THORLABS Corporation. The kit equipments include current controller LDC200 and temperature controller TED200. The temperature is controlled at 30°C, the injected current is 2.3mA and the output power of the laser is 0.5mW. Figure 1 illustrates system block diagram.

F05 digital synthetic filter gives a 50kHz sine wave superimposed on a sawtooth wave whose frequency is 28Hz, amplitude is 400mV. The two superimposed waves modulate the laser by current controller, the output light pass through the sample cell 30cm in length, then being received by the detector. The phase-locked amplifier obtains the signal and carries on second derivation calculus. At last Origin soft is used to perform linear fit to these experimental data.

Figure 1. Block diagram of experiment system.

Figure 2 illustrates the absorption cross-section of CO2 in the wavelength 1.57 – 1.59 μm from HITRAN database. The absorption curve detected by the phase-locked amplifier under room temperature and standard barometric pressure is shown in Figure 3.

3.1. The study of concentration of CO2 changing with pressure
Pumping air out of the double sample cell, then pure CO2 is pumped into the cell and the cell is kept at standard pressure. Data acquisition is carried on by the acquisition system and computer. Sequentially one of the cells is vacuumed for several times to perform the measurement in different pressure: 100%,
50%, 25%, 12.5%, 6.25%, 3.125% and 1.5625%. The different absorption curve is illustrated in Figure 4.

![Figure 4. The absorption curve of CO₂ in different pressure.](image)

It can be known from measurement principle that the half-peak width becomes smaller with the diminished pressure. The phase-locked amplifier picks up the second harmonic. In figure 4, the second derivative curves become more cragged. But the absorption curves after 25% of one barometric pressure don’t comply with this variation regularity that because the Lorentzian line-shape isn’t dominant under low barometric pressure.

The absorption curves of different concentration of CO₂ at one barometric pressure are displayed in Figure 5. The peak height is proportional to the gas percentage in the air. We construct Figure 6 to illustrate the relation between the concentration and the peak height. It is a perfect straight line.

![Figure 5. The absorption curves of different concentration.](image)

![Figure 6. Concentration-peak fit curve.](image)

3.2. The study of concentration of CO₂ changing with temperature.

Voltage controller is used to control the temperature changing of the cell. The half-peak width is proportional to \( \sqrt{T} \) at fixed pressure and temperature. When the changing of \( T \) is small, the half-peak width has no obvious changing. Here we only give the correlation absorption curves which have 30°C apart. The half-peak width narrowing with the lower temperature can be seen clearly in Figure 7.
4. Conclusion
In this paper, the changing of CO$_2$ absorption curve with pressure, temperature is analyzed mainly based on the TDLAS technology. According to the relationship between the concentration and the peak height, half-peak width, the CO$_2$ concentration can be obtained. The noise from the lens before laser and the terminal face of cell influence the detection precision. In addition, we put attenuation pad before the sample cell to detect the saturated absorption in experiment. This phenomenon can be reduced by decreasing the light intensity. In a word, the combination of the absorption spectral technology and wave modulation technology improve the detection sensitivity, which can be applied widely in atmospheric optics, environmental detection, metallurgical and chemical industry and so on.

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