Regular

Water Vapor Detection System Based on Scanning Spectra

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Abstract: Scanning the absorption spectral line of water vapor through wavelength around 1368.597 nm is successfully used to measure the value of micro-moisture content. The synchronous superposition average of original signal algorithm based on labview is innovated and applied to detecting weak spectrum absorption signal instead of low pass filter. Two data processing methods are used to get the concentration of water vapor in ppm: one is a general formula method which has newly deduced a general formula to calculate the concentration of gas with temperature and beam intensity ratio when the pressure is equal to or greater than 1 atm; the other is engineering calibration method which is proved to have high resolution and accuracy with the fitted curve of beam intensity ratio and concentration in ppm when the temperature changes form 258 K to 305 K and the pressure ranges from 1 atm to 5 atm.

Keywords: Water-vapor detection, scanning spectra, detecting under high gas pressure, near-infrared absorption

1. Introduction

As is known to all, water, the earth's most widely distributed and reserved substance that exists in three forms as gas, liquid and solid, has been closely related to human activities. Moisture measurement, previously mainly used for meteorological observation, has now been inseparable from many fields such as industry [1], agriculture, and information technology [2]. Looking only at industry, it contains metallurgy, petroleum, chemical [3], electronics, electric power, textile, medicine, foodstuff, timber, papermaking, architecture, air conditioning, and even the nuclear and aerospace industries. In this century, water measurement technology has been developed rapidly by creating various types of hygrometer and humidity sensor for measuring water in the three forms. Moisture analysis can be classified into two major categories. One is physical analysis method including weightlessness method [4], distillation method [5], adsorption method [6], relative density method, dew point method [7], electro-analysis, spectrometry, gas chromatography [8], etc. The other is chemical analysis method consisting of gas escape tube evolution method, acid or alkali generation method, Karl Fischer method [9], etc. However, these methods have some shortages and limitations in practical application: on the one hand, tasting results always vary from water vapor measuring

devices to testing technology which is sensitively influenced not merely by real-time temperature and humidity but also by artificial error from operation; on the other hand, detecting period is very long to lead a potential risk of equipment and inefficient site tracing monitoring. Therefore, with its high efficiency, practicality, property of environmental protection, spectrometry has been widely applied and developed in the field of gas detection.

Difference method [10] and second harmonic method [11] are the current research focus on detecting water vapor concentration using spectrometry. Nevertheless, not only has difference method its limited measuring accuracy, but also second harmonic method needs complicated signal processing. In this paper, scanning the absorption spectral line of water vapor around 1369 nm to measure its concentration is used for the first time. A near infrared (NIR) distributed feedback laser diode (DFB-LD) [12, 13] is used as light source of which wavelength changes along with its injected current. The water vapor concentration can be calculated using the beginning and the transmitted laser intensities [14]. This scheme has quicker response, higher sensitivity and better accuracy than previous ones.

2. Measurement principle

Once transitions happen, spectral lines will appear owing to a gas molecule containing large amounts of rotation and vibration levels. Normally, transitions of these two kinds of levels occur at the same time, thus generating NIR spectra which are widely used in engineering applications [15].

The water vapor spectrum in the region of 1368.51 nm–1368.69 nm with its center of 1368.597 nm is analyzed to be the best absorption transition for sensitive measurement of concentration according to HITRAN database [16] when the temperature (T) is 296 K and the pressure (P) is 1 atm for the reasons as follows:

(1) The region of 1368.51 nm–1368.69 nm

includes only one transition so that there will be no chance for that transition to overlap with neighboring transitions when the pressure broadening [17] complicates absorption measurement and introduces time-varying absorption transition line widths.

(2) The transition, near 1368.6 nm, is selected as a particularly promising line due to the superior signal-to-noise ratio (SNR) in the later circuit.

(3) Compared with other wave band, tunable diode laser around 1330 nm has many strongpoints such as higher reliability, mature technology and less fiber loss in single mode of about 0.27 dB/km [18].

In direct absorption spectroscopy measurements, a collimated laser beam with an intensity of I_0 is shone through the sample gas, and the transmitted laser intensity I is measured with a detector, as shown in Fig. 1. When the laser frequency v (cm^{-1}) is resonant with the frequency of a transition for the absorbing species in the gas, the laser energy will be absorbed. The attenuation of the laser intensity along the path length of L can be described as follows:

$$(I / I_0) = \exp(-\alpha(v) \cdot P \cdot L) \qquad (1)$$

where P (atm) is the total pressure, L(cm) is the gas path length, $\alpha(v)$ (atm^{-1}·cm^{-1}) is the absorption coefficient. (I/I_0) (intensity ratio) can be measured along with the scanning spectra.
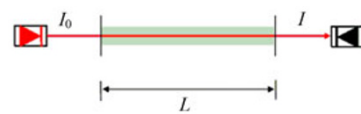

Fig. 1 Schematic of Beer-Lambert.

From the formulae mentioned in [19–23] ,we deduce the following general formula to calculate the concentration of gas with temperature and intensity ratio when P is equal to or greater than 1 atm for the first time:

$$C = \frac{\gamma_{\text{others}}(T)}{\gamma_{\text{others}}(T) - \gamma_{\text{self}}(T) + (1 - (I / I_0)_{v.\min})^{-1} \cdot \frac{L \cdot S(T)}{K \cdot \pi \cdot T \times 10.1325}} \times 10^6$$

$$(2)$$

where K, 1.3806505×10^{-23} (J/K), is Boltzmann

constant, T (Kelvin) is the gas temperature, $(I/I_0)_{v.\min}$ is the minimum of intensity ratio, C is the concentration of the detected gas in ppm (percent per million), $S(T)$ (cm·mol^{-1}) is the line strength of the transition at temperature T, $\gamma_{\text{self}}(T)$ [cm^{-1}·atm^{-1}] and $\gamma_{\text{others}}(T)$ (cm^{-1}·atm^{-1}) are the broadening coefficients due to the collisions between the absorbing molecules themselves and between the absorbing molecules and the perturbing molecules. $S(T)$, $\gamma_{\text{self}}(T)$ and $\gamma_{\text{others}}(T)$ can be found in HITRAN database. However, in addition, we can just calculate the water vapor concentration in air at present with (2) as only the broadening coefficient due to the collisions between the absorbing molecules and the air molecules ($\gamma_{\text{others}}(T)=\gamma_{\text{air}}(T)$) can be checked out according to the database.

3. Experimental facility

Figure 2 shows a schematic of the experimental arrangement for the quantitative measurement of water vapor concentration. The length of gas cell is 10 cm. A DFB-LD is used as primary laser source to investigate H_2O spectra near 1369 nm. The fiber-coupled output of the light source is split into two beams (0.9, 0.1). The 90% intensity is transmitted through the sample gas, caught and sent to an INGaAs PIN (positive-intrinsic-negative) photo detector. The rest 10% intensity is transmitted through fiber to a similar detector to provide an intensity reference. Both signals from two detectors are collected by data acquisition card (DAC) which is connected to a computer to do further processing. The output power of the 90% intensity varies with wavelength and must be normalized using the reference signal for quantitative absorption measurement in order to remove the laser intensity fluctuations.
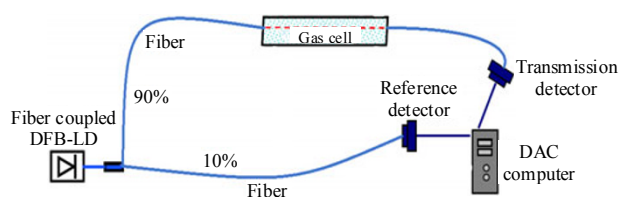

Fig. 2 Experimental configuration.

4. Concluding water vapor concentration by general formula

This test is conducted under 1 atm at the temperature of 287 K when the water vapor concentration of air in ppm is 20.67.

As shown in Fig. 3, the "I" area which is not absorbed by the water vapor and the "Ⅱ" area around 1368.59 nm whose absolute value is attenuated because of gas absorption are both included in one scanning period. In Figs. 4 and 5, curve C is transmitted intensity signal; curve D is reference signal; curve A, the normalized curve (beam intensity ratio, BIR for short), get filtered in matlab, thus obtaining curve B; curve E is normalized signal processed by synchronous superposition average algorithm in labview.
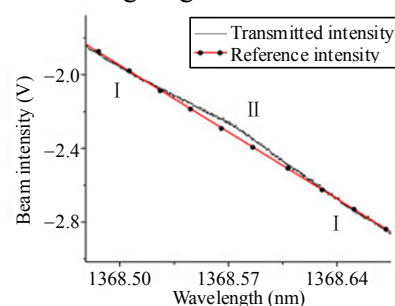

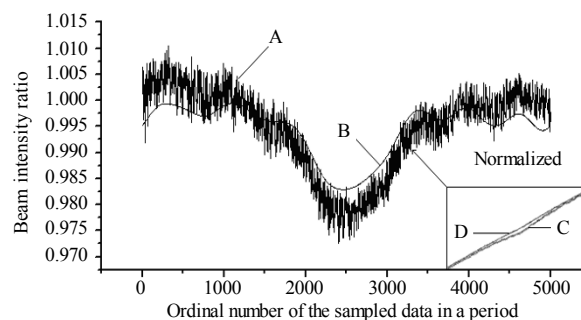Fig. 3 Spectral intensity along with wavelength.
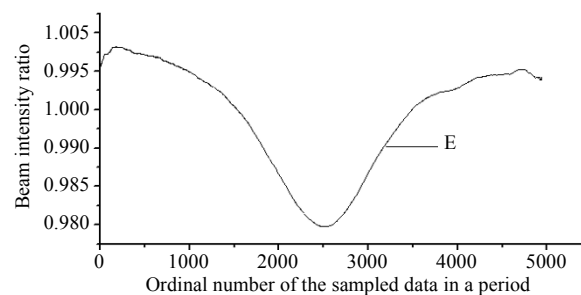

Fig. 4 Filtering the normalized signal.

Fig. 5 Normalized signal processed by synchronous superposition average algorithm.

Obviously, curve A needs further treatment for its large noise. However, curve B, processed by matlab low pass filter, is always found to have lower peak value than curve A, even the low-pass frequency and the type of filters (including Butterworth, Chebyshev, Elliptic, and Equiripple) have been replaced several times. Therefore, low pass filter is not a good choice for this test. In order to solve this problem, we designed a synchronous superposition average algorithm which theoretically took the average value of multiple stacking signals collected several times under the same circumstance. This method can offset all kinds of random noise and filter out disturbed noises effectively (for example, the positive and negative noises at a certain wavelength point share the same proportion of 50% for random character when the stacking fold tends to be infinite, once being superimposed and averaged, they will be completely cancelled out. At the same time, the useful signals accumulate constantly, which can lead to a good signal to noise ratio. However, restricted by collection rate and hardware performance, the work efficiency reduces as the superposition number increases. Therefore, we need to determine the superposition number according to the demand of system precision. We set the stacking number around 200 times after repeated experiments and the corresponding result was shown as curve E which has the same line shape that exactly matched curve A. Taking the peak value of curve E of 0.97898 into (2) and calculating the concentration in ppm, we found the outcome in line with the real value detected by dew point hygrometer.

According to the theory of this algorithm, the error is only concerned with superposition number. In order to get relatively more accurate standard value, we took 24 hours to set the number as 1209600, thus getting the peak value of curve E of 0.97895. Therefore, by comparing 0.97898 with 0.97895, 200 times superposition number was

acceptable in this experiment.

5. Concluding water vapor concentration by calibration method

The transmitted intensity (I) will have little change in contrast to I_0 if the mixed gas has extremely low water vapor concentration, thus making little change in DAC distortion range and leading an inaccurate peak value of the BIR. In order to handle this problem, we should improve SNR of the BIR before the signal is caught by DAC (shown in Fig. 6). Consequently, the final peak value (W_{min} for short) of signal processing is not the original BIR anymore because of basic operation induced by a series of analog devices. Instead of figuring out the peak value of BIR from W_{min} and calculating the concentration with (2), we designed a new method of calibration as it was difficult to obtain the inverse calculation coefficient.
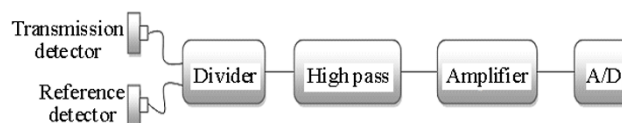

Fig. 6 Signal processing.

This test was conducted when the temperature changed form 258 K to 305 K and the pressure ranged from 1 atm to 5 atm. The final peak values, in turn, were recorded in Table 1 when changing the water vapor concentration, temperature and pressure in the gas cell. The objective concentrations in ppm were written down according to specula-surface condensation dew point instrument at the same time, thus providing data to fit a function curve $f(W_{min})$ (shown in Fig. 7) reflecting the rule that objective concentration in ppm varied from W_{min}. During this experiment, we found that if the concentration was determined, W_{min} would remain invariant even the pressure and temperature kept changing when the pressure was greater than or equal to 1 atm and the temperature ranged from 258 K to 305 K. However, just to be complete, calibration should be updated

since the pressure would not affect W_{min} unless the pressure is below 1 atm.

Table 1 Recorded and calculated data.

| Group	W_{min}	$f(W_{min})$	Objective concentration	Difference（%）
1	−2.41008	14.892	19.01634	−21.6884
2	−2.40335	45.00875	50.4610	−10.8049
3	−2.40086	56.1515	61.5549	−8.77818
4	−2.38591	123.0528	125.985	−2.32746
5	−2.38234	139.0285	140.1574	−0.80545
6	−2.36072	235.778	220.299	7.02636
7	−2.35569	258.2872	251.954	2.513653
8	−2.34773	293.9083	300.313	−2.13269
9	−2.31726	430.2615	430.684	−0.0981
10	−2.27513	618.7933	600.246	3.089941
11	−2.18046	1042.442	1042.33	0.010697
12	−2.11209	1348.397	1345.56	0.21086
13	−2.00013	1849.418	1865.27	−0.84984
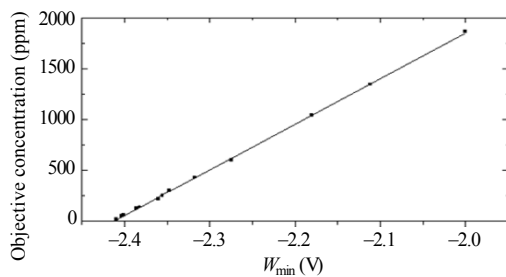
Fig. 7 Acquired data points and fitted curve.

In Fig. 7, W_{min} is abscissa, objective concentration in ppm is vertical coordinate, the filled dots come from Table 1, and the fitted curve is linear expressed as (3):

$$f(W_{min}) = 4475 \cdot W_{min} + 1.083 \times 10^4 . \qquad (3)$$

Once the function of $f(W_{min})$ is confirmed, the real concentration in ppm can be calculated by taking W_{min} into (3).

Table 1 makes a thorough exposition on the difference between the objective concentration and the concentration in ppm operated with (3). The relative error increases when the concentration gets decreased for the follow reasons:

(1) The concentration is too low for specula-surface condensation dew point instrument to perform as well as expected.

(2) It is difficult to process low SNR signal caused by quite low water vapor concentration.

In calibration method, 11 ppm concentration can be picked out (groups 2 and 3 in Table 1) and the measurement error basically stays within a stable level of 10 ppm.

6. Conclusions

The water vapor detection system based on scanning spectra has properties of high efficiency, practicality, sensitivity and low cost. It can be realized by two kinds of means: general formula method and calibration method. Each method has its own advantages and disadvantages: general formula method, easy manipulated, does not suit for the circumstances blow the pressure of 1 atm and mixed gases apart from air; calibration method, complex for large amounts of scale data, has higher sensitivity. Finally, by means of synchronous superposition average of original signal algorithm, both of these two schemes successfully explored and validated the possibility of high precision measurement of water vapor concentration through scanning spectra around 1369 nm.

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medium, provided the original author(s) and source are credited.

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