Method of sensitivity improving in the non-dispersive infrared gas analysis system

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A method of interference correction for improving the sensitivity of non-dispersive infrared (NDIR) gas analysis system is demonstrated. Based on the proposed method, the interference due to water vapor and carbon dioxide in the NDIR NO analyzer is corrected. After interference correction, the absorbance signal at the NO filter channel is only controlled by the absorption of NO, and the sensitivity of the analyzer is improved greatly. In the field experiment for pollution source emission monitoring, the concentration trend of NO monitored by NDIR analyzer is in good agreement with the differential optical absorption spectroscopy NO analyzer. Small variations of NO concentration can also be resolved, and the measuring correlation coefficient of the two analyzers is 94.28%.

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Nitrogen oxides (NO + NO\textsubscript{2} or N\textsubscript{2}O\textsubscript{2}) are commonly emitted into the atmosphere from high-temperature combustion facilities during industrial production\cite{1,2}. When nitrogen oxides and volatile organic compounds (VOCs) are exposed to sunlight in the atmosphere, they undergo various chemical reactions, producing secondary products that are involved in photochemical smog. Some of the products are harmful to human health, including ozone, poly aromatic hydrocarbons (PAH), peroxides, and peroxyacetic nitric anhydrides (PAN)\cite{3}.

Non-dispersive infrared (NDIR) gas analyzers are ideal equipments for a continuous emission monitoring system (CEMS). They typically have high measuring sensitivity. However, the sensitivity of these gas analyzers depends on the relative humidity of the operating environment and the concentration of interfering gases such as carbon dioxide (CO\textsubscript{2}). Thus, a NDIR gas analyzer for measuring low concentrations of a target gas on the order of parts per million (ppm) should be effective in correcting such interference\cite{4−7}. In this letter, we report on a method of correction for interfering water vapor and CO\textsubscript{2} to improve the sensitivity of a NDIR NO analyzer. It aims to investigate the feasibility of high-sensitivity measurement of NO in the pollutant source.

Figure 1 shows the functional layout of the NDIR NO analyzer, including a power source, an infrared (IR) optical source, an optical filter wheel, a filter controller, a sample cell, a detector assembly, and a data processor. During operation, the optical signal generated by the IR light source passes through the optical filter wheel and the sample cell, and finally arrives at the detector assembly. The filter controller selects different optical filters in sequence to modulate the optical signal using different frequency bands of optical energy. Based on the absorption of optical signal by the sample gas at different frequencies, the analyzer can account for the absorbance interference and detect which types of gases are present in the sample.

The IR optical source is a glowing metal filament heated to a temperature of 1200 K, which generates an optical signal in the IR spectrum with a broad range of optical wavelengths from 1.5 to 10 µm. The optical filter wheel includes four filters which can filter the optical wavelengths at a certain frequency band (the reference filter is used to produce reference signal to adjust for drift, such as the voltage drift on IR light source, external vibration, etc.). Figure 2 presents the IR absorption spectra of NO, H\textsubscript{2}O, and CO\textsubscript{2}. The parameters of all filters are clearly shown in Table 1. The sample cell includes three spherical mirrors to increase the optical path length of the modulated optical signal when it passes through the sample gas. The configuration of such a sample cell allows for 12-m optical path length within the 60-cm-long multi-pass cell. This results in more accurate determination of gas type, greater sensitivity, and more accurate gas concentration readings. The detector is a lead selenide device (SensArray Infrared, USA), which has good response performance between 1 and 10 µm.

There is a large concentration of humidity and CO\textsubscript{2} in many environments where NDIR NO analyzers are used. Both water vapor and CO\textsubscript{2} may have an IR absorption spectrum overlapping that of NO\cite{8}. Figure 3 shows the absorption line intensity comparison among CO\textsubscript{2}, H\textsubscript{2}O, and NO at the NO filter channel on the y-axis and the wavelength on the x-axis. The location of the primary

![Fig. 1. Functional layout of NO gas analyzer.](image)
absorption band of NO, shown between the two thick solid in Fig. 3, corresponds to some absorption by water vapor and CO₂. Therefore, without correction, filter #3 (which is designed to detect NO) would respond to CO₂, H₂O, and NO. Consequently, the sensitivity of the NDIR NO analyzer declines because of the two interfering gases[8–10].

To subtract the response due to water vapor from the output signal, the H₂O band pass filter must be designed to have a pass band with no absorption by NO. Moreover, to subtract the response due to CO₂ from the output signal, the CO₂ band pass filter must be designed to pass wavelengths associated with CO₂ absorption but not to transmit substantially at wavelengths associated with NO absorption. The two preferred filters are available in our analyzer.

The optical absorption of light due to the presence of the target gas in the sample cell is based on Lambert-Beer’s law as

\[ I(\lambda) = I_0(\lambda) \exp(-\alpha(\lambda)CL). \]  

(1)

When there are three absorbing species presented in the sample cell, Eq. (1) becomes

\[ I(\lambda) = I_0(\lambda) \exp(-\alpha C_1 L) \cdot \exp(-\beta C_2 L) \cdot \exp(-\gamma C_3 L), \]  

(2)

where \( I_0(\lambda) \) is the optical intensity measured while sampling high-purity zero air; \( I(\lambda) \) is the optical intensity measured while sampling the sample gas; \( \alpha, \beta, \gamma \) represent the absorption coefficients of three different gases; \( C_1, C_2, C_3 \) represent the corresponding concentration of the three gases; \( L \) is the path length as a result of reflections in the sample cell. When the arguments of the exponentials are small, the following approximation of Eq. (2) can be used for the three gases[9,10]:

\[ I(\lambda) = I_0(\lambda)(1 - \alpha C_1 L - \beta C_2 L - \gamma C_3 L). \]  

(3)

When considering all the three filter channels (and a reference filter channel to adjust for drift) simultaneously, three equations can be established. Lambert-Beer’s law from Eq. (3) can be written as

\[ I^N(\lambda) = I^N_0(\lambda)(1 - \alpha N C_N L - \beta N C_H L - \gamma N C_C L), \]  

(4)

\[ I^H(\lambda) = I^H_0(\lambda)(1 - \alpha H C_N L - \beta H C_H L - \gamma H C_C L), \]  

(5)

\[ I^C(\lambda) = I^C_0(\lambda)(1 - \alpha C C_N L - \beta C C_H L - \gamma C C_C L), \]  

(6)

where NO is represented by \( N \), water vapor by \( H \), and CO₂ by \( C \); \( \alpha N, \alpha H, \gamma C \) represent the absorption coefficients of NO at \( N \), H₂O, and CO₂ filter channels, respectively; \( \beta N, \beta H, \beta C \) represent the absorption coefficients of H₂O at \( N \), H₂O, and CO₂ filter channels, respectively; \( C_N, C_H, C_C \) represent the concentrations of NO, H₂O, and CO₂ presented in the sample cell, respectively.

The detector produces voltages that are proportional to the light-intensity signals received at each of the three filter channels. These voltages are given as

\[ V^N = V^N_0(1 - \alpha N C_N L - \beta N C_H L - \gamma N C_C L), \]  

(7)

\[ V^H = V^H_0(1 - \alpha H C_N L - \beta H C_H L - \gamma H C_C L), \]  

(8)

\[ V^C = V^C_0(1 - \alpha C C_N L - \beta C C_H L - \gamma C C_C L). \]  

(9)

Equations (7–9) can be deduced as

\[ A^N = \frac{V^N}{V^N_0} = (1 - \alpha N C_N L - \beta N C_H L - \gamma N C_C L), \]  

(10)

\[ A^H = \frac{V^H}{V^H_0} = (1 - \alpha H C_N L - \beta H C_H L - \gamma H C_C L), \]  

(11)

\[ A^C = \frac{V^C}{V^C_0} = (1 - \alpha C C_N L - \beta C C_H L - \gamma C C_C L), \]  

(12)

where \( A^N, A^H, A^C \) represent the total absorbances at NO, H₂O, and CO₂ filter channels, respectively. The absorption coefficients depend on the optical wavelengths selected using the appropriate band pass filters. In our analyzer, the filter characteristics are given such that the
The following relationships hold. (1) $\alpha_H \cong \gamma_H \cong 0$. H$_2$O channel has negligible response to NO and CO$_2$; (2) $\beta_C \cong \delta_C \cong 0$, the water vapor and NO response sensitivities of the CO$_2$ band pass filter are negligible with respect to the CO$_2$ one, such that Eqs. (11) and (12) can be written as

$$A^H = \frac{V^H}{V_0^H} = 1 - \beta_H C_H L, \quad (13)$$

$$A^C = \frac{V^C}{V_0^C} = 1 - \gamma_C C_C L. \quad (14)$$

Based on Eqs. (13) and (14), Eq. (10) can be given as

$$A^N = \frac{V^N}{V_0^N} = \left(1 - \alpha_N C_N L - \frac{\beta_N}{\beta_H} \beta_H C_H L - \frac{\gamma_N}{\gamma_C} \gamma_C C_C L\right)$$

$$= \left[1 - \alpha_N C_N L - \frac{\beta_N}{\beta_H} (1 - A^H) - \frac{\gamma_N}{\gamma_C} (1 - A^C)\right]. \quad (15)$$

Since $\gamma_N L$ is constant, $A_\text{NO} = \gamma_N C_N L$

$$= 1 - \frac{V^N}{V_0^N} - \frac{\beta_N}{\beta_H} \left(1 - \frac{V^H}{V_0^H}\right) - \frac{\gamma_N}{\gamma_C} \left(1 - \frac{V^C}{V_0^C}\right). \quad (16)$$

**Table 2. Response Coefficients of H$_2$O, NO, and CO$_2$ at Each Channel**

<table>
<thead>
<tr>
<th></th>
<th>1 Ref</th>
<th>2 H$_2$O</th>
<th>3 NO</th>
<th>4 CO$_2$</th>
</tr>
</thead>
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<tr>
<td>H$_2$O</td>
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<td>0</td>
<td>0</td>
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<tr>
<td>NO</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>0</td>
<td>0</td>
<td>0.011106</td>
<td>1</td>
</tr>
</tbody>
</table>

**Fig. 5. Calibration linearity of the NDIR NO analyzer.**

Vertical axis represents the type of gas. The response coefficient of H$_2$O at the NO filter channel is 0.04227, whereas that of CO$_2$ at the NO filter channel is 0.011106, i.e., in Eq. (16), $\frac{\delta_N}{\beta_H} = 0.04227$ and $\frac{\gamma_N}{\gamma_C} = 0.011106$.

When the sample cell is filled with different concentrations of H$_2$O and CO$_2$, we use the response coefficients available from Table 2 to correct the interference with the method mentioned above. The signal intensities at each filter channel after correction are shown in Fig. 4 (only a portion of the results is included because of the large amount of data). The figure shows that after interference correction, signal intensity at the NO filter channel has no change or negligible change, except at the interfering gas filter channel, even if the concentrations of interfering gases are different, which proves that the method for interference correction is feasible.

Figure 5 is the calibration linearity of the analyzer after interference correction. The fitting correlation coefficient is shown to be 0.9999. The concentration of NO varies linearly to its absorbance calculated through Eq. (16) and $\gamma_N L$ is constant. Thus, the absorbance can be regarded as a whole when is calibrated, which results in an easy and convenient calibration.
We also made a field experiment in a steel company (Tong-Ling, Anhui Province, China). The NDIR analyzer and the differential optical absorption (DOAS) analyzer were installed parallelly to the roof of a building near the stack in order to monitor smoke pollution sampled from about 50 m above the ground. Figure 6 shows the layout of each system in the field experiment. The two analyzers were placed inside the gas analysis equipment. The sample gas was pretreated before connecting to the analyzer to cool high-temperature gas and remove particulates. Concentration readings monitored by the analyzers were automatically transmitted to the data processor on the ground. When the readings are abnormal, the alarm system will be triggered. The two analyzers were used for monitoring continuously for two days. Figure 7 presents the online monitoring comparison between the NDIR NO and DOAS NO analyzers. The trend of NO concentration monitored by the NDIR NO analyzer has a good agreement with that of the DOAS NO analyzer, and small variations of NO concentration can be resolved. The measuring correlation coefficient of the two analyzers is 94.28%. A similar method can also be used to improve the detection sensitivity of other NDIR gas analyzers.

Fig. 6. Layout of each system in the field experiment.

Fig. 7. Online monitoring comparison between the NDIR NO and DOAS NO analyzers.

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