Strategies for Passive Sensitivity Improvement of NDIR Ethylene Gas Detectors

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Abstract

Three sensitivity improvement strategies for non-dispersive-infrared (NDIR) ethylene gas detectors were defined and examined: the application of low-cost Fresnel lenses, usage of a conically shaped measurement chamber and a simple digital signal processing lead to a seven times better IR-radiation efficiency compared to a system configuration without consideration of these methods. The approaches don’t affect IR-detectors, IR-sources or the optical pathway and thus, the methods can be called “passive”. It was shown that usage of lock-in amplifiers is not necessary to achieve good sensitivity results and noise equivalent concentrations of about 6 ppmv.

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Keywords: Ethylene detector; ethylene sensor; NDIR gas measurement; sensitivity improvement; IR gas measurement

1. Introduction

Gas measurement systems which provide detection of low concentrations of ethylene (C₂H₄) gas within ppmv and ppbv range are important for quality and ripeness monitoring in food logistic and post-harvest applications. The main challenge in the development process of such systems is to obtain good selectivity and sensitivity to C₂H₄. One approach for realisation of new miniaturized C₂H₄ concentration measurement systems is the non-dispersive infrared (NDIR) spectroscopy based on the Lambert-Beer law [1, 2]. The main advantages of detectors based on the NDIR approach are robustness and selectivity. This is given by the non-complicated system assembly and the measurement of light absorbed by the target gas molecules within their specific adsorption wavelength. The main disadvantage of NDIR measurement systems is their limited sensitivity to C₂H₄ gas. This is induced by the C₂H₄ adsorption band within the IR-

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spectrum at about 10.5 $\mu$m. Here the radiation intensity and thus the sensitivity are smaller by the factor of 4 compared to the 4.3 $\mu$m region which is used for CO$_2$ detection [3]. Sensitivities achieved for C$_2$H$_4$ measurement are between 10 ppmv and 40 ppmv [4]. Thus, when planning NDIR-measurement systems for C$_2$H$_4$ detection, the sensitivity optimisation has to be in focus of system design, especially when the application is related to fruit logistics where low C$_2$H$_4$ concentrations have to be expected. In this paper three passive approaches for sensitivity improvement are examined. The focus of the experiments was on the shape of the measurement chamber, signal processing and application of Fresnel lenses.

2. Experimental & Results

Four different measurement setups were used for examination of the influence of the chamber’s shape and of the Fresnel lenses on the signal sensitivity: a rectangular shaped chamber as well as a conically shaped chamber, both with and without lenses (fig 1). The chambers were made of aluminium; the internal walls were polished to maximize the reflection.

On one side of the chambers two thermopile detectors TPS 434 were applied as IR-sensitive elements with a radiation sensitivity of 35 V/W, a noise of 21 nV $\cdot$ Hz$^{-0.5}$ and a time constant of 20 ms. One detector was equipped with an optical filter with a centre transmission wavelength of 11 $\mu$m and a transmission bandwidth of ±3 $\mu$m for C$_2$H$_4$ detection. The other detector was used as a reference detector with an optical filter with 4 $\mu$m centre wavelength and a bandwidth of ±0.1 $\mu$m. At the other end of the chamber a standard IR-source was applied. Overall three different IR-sources were used: IR-55, HSL-EMIRS and MIRL-17 (fig 2). The sources were driven by an electrically chopped rectangular signal with active-high amplitudes recommended by the manufacturers and a duty cycle of 50%. To analyse the influence on the measurement signal caused by the choice of the radiation source and the system dynamics, the devices were driven with frequencies from 2 Hz up to 50 Hz. Clean synthetic air was applied into the measurement chamber and the measurement signals were logged for 10 minutes at each frequency. The measurement signals were amplified by an analogue low noise amplifier circuit. Source control, signal acquisition and processing were realised using a DAQ-card and a LabView application on a standard laptop computer. As signal processing algorithm a peak-to-peak signal calculation was used. The measurements were started 10 min after activation of the IR-source to ensure temperature equilibrium in the system.
Figure 3 shows the resulting measurement signal strengths versus the modulation frequency for the three IR-sources and for the rectangular chamber without lenses and the conically chamber with lenses. The application of the MIRL-17 device together with Fresnel lenses in a conically shaped chamber give the best result concerning the signal strength and thus the sensitivity and efficiency.

![Graphs showing signal strength versus modulation frequency for different IR-sources and chambers](image)

The best chopping frequency for the application is 2 Hz because of the low-pass behaviour of the system and its low -3dB frequency of about 15 Hz. A comparison between the results achieved with the different setups is given in table 1.

Table 1: Signal strength influenced by the chamber shape and lens application (modulation frequency of 2 Hz)

<table>
<thead>
<tr>
<th>Shape</th>
<th>Lenses</th>
<th>IR-55 Peak-to-peak measurement signal / V</th>
<th>MIRL-17</th>
<th>HSL-EMIRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular</td>
<td></td>
<td>0.313</td>
<td>0.466</td>
<td>0.603</td>
</tr>
<tr>
<td>Conically</td>
<td></td>
<td>0.347</td>
<td>0.509</td>
<td>0.733</td>
</tr>
<tr>
<td>Rectangular</td>
<td>X</td>
<td>0.725</td>
<td>1.195</td>
<td>0.875</td>
</tr>
<tr>
<td>Conically</td>
<td>X</td>
<td>2.549</td>
<td>3.712</td>
<td>3.225</td>
</tr>
</tbody>
</table>

A best case improvement of about 20 % of the signal strength is reached by usage of the conically shaped measurement chamber without lenses compared to the rectangular shaped chamber without lenses when the source HSL-EMIRS is used. The application of lenses gives the best improvement for the MIRL-17 of about factor 1.6 for the rectangular shaped chamber and about 6.3 for the conically shaped chamber. Both, the change of the chambers shape and the application of lenses give a detector signal improvement by a factor of 7 for the same IR-source.

In the second measurement run the direct sensitivity to C<sub>2</sub>H<sub>4</sub> was examined. Therefor the conically shaped chamber with Fresnel lenses was used. Different values for the C<sub>2</sub>H<sub>4</sub> concentration in synthetic air were applied into the measurement chamber with a constant flow rate of 200 sccm. The concentrations were varied between 0 ppmv and 500 ppmv in 25 ppmv and 50 ppmv steps. Data acquisition was realized as described above. In these measurements two different signal processing methods were applied. First was a standard peak-to-peak signal measurement for each chopping period and a median calculation each 5s (U<sub>p-p</sub>). In the other method the medians of the active-high area and the active-low area of the measurement signal were calculated. Afterwards the difference of both values was computed (U<sub>H-LO</sub>). Additionally, a standard lock-in amplifier (FEMTO LIA-MV-200-L) was used as reference (U<sub>Lockin</sub>). Its output was also acquired by the DAQ-system and the median was calculated every 5s. The resulting detection limits for C<sub>2</sub>H<sub>4</sub> from the measurements are ±26.5 ppmv for U<sub>H-LO</sub>, ±11.2 ppmv for U<sub>p-p</sub> and ±8.26 ppmv for U<sub>Lockin</sub> referred to ±2 σ. This shows that the usage of U<sub>p-p</sub> is the better choice than U<sub>H-LO</sub>.
The long term results of the sensitivity measurements are shown in figure 4 for the peak-to-peak signal processing and the lock-in amplifier signal.

Table 2: Comparison of some determined specific parameters for the NDIR-system with conically shaped chamber, Fresnel lenses (Source: MIRL-17 @ 2Hz).

<table>
<thead>
<tr>
<th></th>
<th>peak-to-peak</th>
<th>lock-in</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR for 25 ppmv</td>
<td>22</td>
<td>27</td>
</tr>
<tr>
<td>Sensitivity μV/ ppmv</td>
<td>120</td>
<td>172</td>
</tr>
<tr>
<td>Noise equivalent voltage / μV</td>
<td>644</td>
<td>836</td>
</tr>
<tr>
<td>Noise equivalent concentration/ ppmv</td>
<td>5.4</td>
<td>4.9</td>
</tr>
</tbody>
</table>

Fig. 4: Top: Digitally calculated peak- to peak Voltage. Middle: Output voltage of a lock-in amplifier. Bottom: Ethylene concentration profile.

It is remarkable that the quality of the $U_{pp}$ signal and $U_{Lockin}$ signal are very similar. This is pointed out in table 2 where the SNR and the noise equivalent concentration values resulting from the measurements can be found. The response of the system is about $120 \mu V/ppmv$ for the $U_{pp}$ calculation and $172 \mu V/ppmv$ for the lock-in amplifier. The noise equivalent concentration is about 5 ppmv in both cases for measurement electronics with a bandwidth of 10 Hz. For a $C_{C2H4}$ concentration of 25 ppmv the signal to noise ratio was over 20.

3. Conclusion

The influence of the measurement chamber, Fresnel lenses and signal processing on the sensitivity of NDIR ethylene measurement systems was examined. The presented approaches provide a significant improvement of the measurement signal and the sensitivity by just small system adjustments. It was shown that a conically shaped chamber and Fresnel lenses can improve the measurement signal up to the factor of 7 and that a simple digital signal processing provides noise equivalent concentrations of about 5 ppmv which is similar to the values achieved with standard lock-in amplifiers. The achieved sensitivity matches the results of other works [4], but in comparison by using much simpler system architecture, low-cost commercially available devices and without the application of lock-in amplifiers. This shows the potential of the presented approaches for further development of NDIR gas detection system.

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References