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Mixed carbon dioxide and water vapour detection by using LWIR 14-16 μm high-sensitive VOx microbolometer camera – modelling and experimental results

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Abstract

This paper describes a simple model and IR measurements showing the possibilities of detecting carbon dioxide in the humid atmosphere. The detection is performed in LWIR 14-16 μm wavelength range using low-cost high sensitive VOx microbolometer camera with the extended spectral characteristic in long wavelength band.

1. Introduction

Carbon dioxide has 2 main absorption spectra in MWIR and LWIR ranges [4,8,10,11]. According many experimental data published and available today, there is a strong attenuation of passing radiation at 4.2 μm wavelength. Other absorption spectrum for CO_2 exists in LWIR range at 14-16 μm. The disadvantage of using LWIR attenuation spectrum of CO_2 for the detection is the partial overlapping with the attenuation of the water vapour. Fortunately, the water vapour absorbs radiation in LWIR range only if the absorption path is long enough as it can be seen in Figures 1,2 [4,8,11].

The LWIR 7-14 μm and broad-band 3-14 μm high-sensitive VOx bolometer cameras have been recently developed mainly for detection the different gases, such as methane [1,5,6,7]. The broad-band VOx bolometer camera (3-14 μm) has already been successfully applied with the dedicated software for methane detection [6,7]. Now, it is a new possibility to use such imaging for CO_2 detection. The developed cameras have a unique advantage of extended spectral range up 16 μm [6,7]. The long wavelength limit mainly depends on the spectral characteristic of IR window in the VOx detector and optics, and in our case it reaches 16 μm with 60-70 % attenuation. In addition, the high sensitivity of the developed cameras is the very important feature recommended for gas detection. In fact, for detection carbon dioxide, the typical 7-16 μm wavelength bolometer cameras can be a low-cost alternative solution.

2. A simplified model of mixed water vapour and carbon dioxide absorption

Let us start theoretical discussion from the very basic equation coming directly from the Beer-Lambert law describing the attenuation of radiation passing the material of the thickness *dx*.

$$\frac{dI}{I} = -\sigma \frac{n_i}{V} dx \tag{1}$$

where n_i denotes the number of particles of *i*-th gas component in an atmosphere absorbing radiation in volume *V* and σ stands for absorption cross-section (m^2).

The absorption cross-section corresponds to an effective area per one molecule of a material sample contributing to the attenuation of radiation and it is wavelength dependent. From Equation (1), the transmission of an atmosphere along the distance *L* can be derived as (2):

$$I(L) = I_0 e^{-\sigma \frac{n_i}{V} L} \tag{2}$$

where *I* the radiation intensity (W/m^2).

Assuming, that the considered gases are ideal, the concentration can be expressed in the form of equation (3)

$$\frac{n_i}{V} = \frac{p_i}{k_B T} \tag{3}$$

where p_i is the partial pressure of *i*-th gas in the mixture in temperature *T*, (K), $k_B = 1.380649\times10^{-23}$ J/K is the Boltzmann constant.

Form (2) and (3) one can derive the transmission coefficient along the path *L* for the humid air with the water vapour (at temperature *T* and relative humidity *RH*) [2,3].

$$\tau_{H_2O}(L) = e^{-\sigma_{H_2O}(\lambda)\frac{RHp_S}{k_B T}L} \tag{4}$$

Similarly, for carbon dioxide, the transmission of IR radiation can be presented as [2,3]:

$$\tau_{co_2}(L) = e^{-\sigma_{CO_2}(\lambda)\frac{\gamma p}{k_B T}L} \tag{5}$$

where γ is the volumetric concentration of the gas and *p* is the pressure of the atmosphere.

The absorption cross-section depends mainly on the wavelength and the material optical properties. There are databases available containing the sets of absorption cross-section values for different gasses, measured in the different conditions and for the different wavelength ranges, also the infra-red MWIR and LWIR [4,8].

In the research presented in this paper, the LWIR 14-16 μm wavelength range was selected. The reason was to elaborate a simple and low-cost method of CO_2 detection using microbolometer high-sensitive IR cameras. The LWIR 14-16 μm spectral range. I has to be noticed that there is strong IR light absorption by water vapour below 10 μm wavelength. In order to estimate the contribution of the water vapour and carbon dioxide in absorption of IR radiation, the average attenuation cross-section in the considered wavelength range (λ_1, λ_2) has to be determined for both elements (CO_2 and H_2O) of the atmosphere, as in Equation (6).

$$\bar{\sigma} = \frac{\int_{\lambda_1}^{\lambda_2} \sigma(\lambda) d\lambda}{\lambda_2 - \lambda_1} \tag{6}$$

The absorption cross-sections for water vapour and carbon dioxide according the literature data [xx] are as in Table 1 and graphically presented in Figures 1 and 2.

Table 1. Absorption cross-section for water vapour and carbon dioxide, averaged in 14-16 μm wavelength range, estimated by using data from [11], for normal conditions p = 900 hPa, T=385 K.

Water vapour	Carbon dioxide
10^{-27} m^2	$3{*}10^{-24}$ m^2

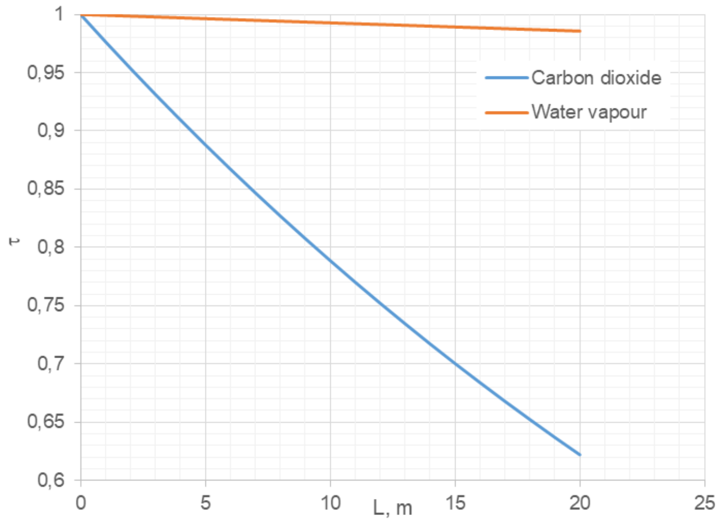


Fig. 1. *Transmission of IR radiation in the range 14 – 16 μm, p = 900 hPa, T = 285 K, γ = 330 ppm = 0.00033, RH = 100 % for water vapour and carbon dioxide, for L<20 m*

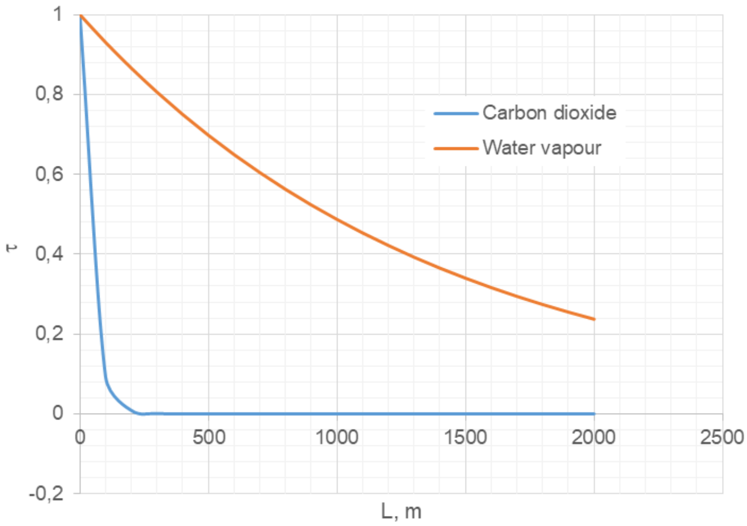
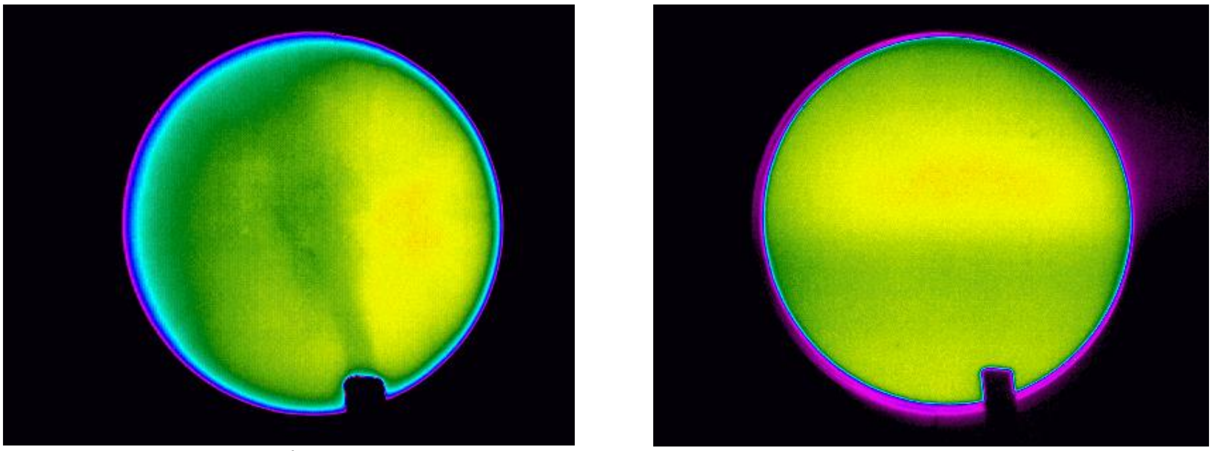


Fig. 2. *Transmission of IR radiation in the range 14 – 16 μm, p = 900 hPa, T=285 K, γ =330 ppm = 0.00033, RH = 100 % for water vapour and carbon dioxide, for L<2000 m*

3. Qualitative detection of high-concentrated carbon dioxide

Simple experiments were performed to visualize CO_2. The standard MWIR/LWIR black-body was used. Carbon dioxide was being delivered from the high-pressure bottle. The pressure was diminished using the local gas pressure reduction device mounted on the high pressure reservoir. The output pressure gas was reduced to the level a bit larger than the atmospheric one.



a) b)

Fig. 3. *Mixed CO_2 and H_2O vapour visualisation using BB 3-16* μm *VOx camera a) and with low-pass 3-10* μm *interference filter b)*

The developed camera has an extended spectral range with slightly lower sensitivity up to 16 μm wavelength, where CO_2 absorbs IR radiation. In order to improve the contrast while detecting the gases, the 10 μm low-pass interference filter can be used for image acquisition [9]. In Figure 3, the thermal images in full spectral (3-14 μm) and low pass (3-10 μm) bands are presented. The new idea is to display differential images to reduce the background impact – Figure 3.

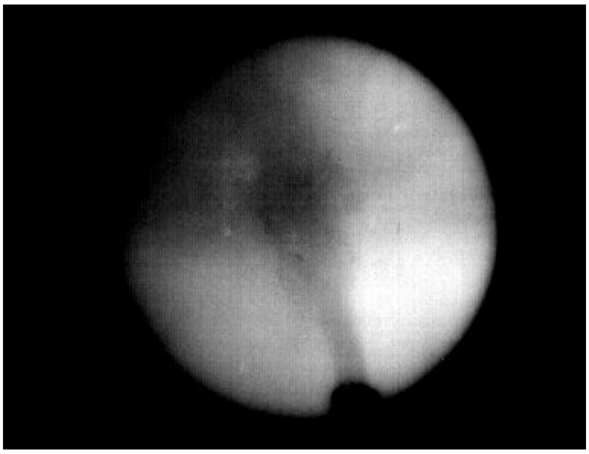
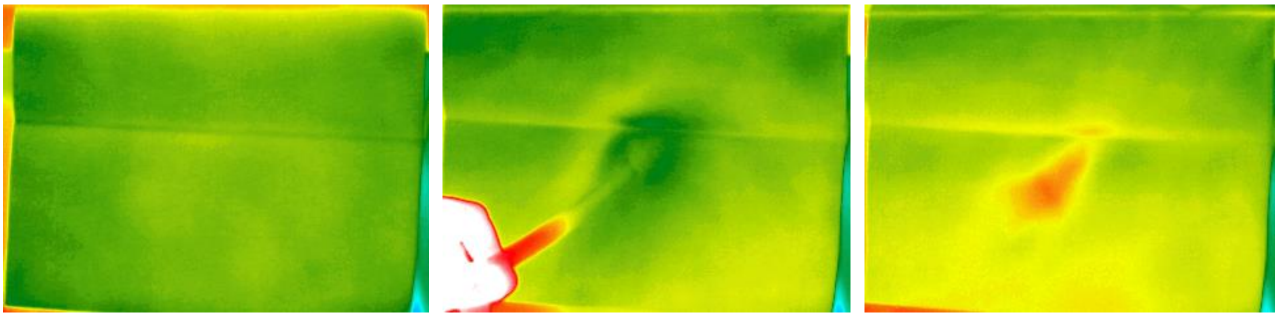


Fig. 4. *Differential image (full band 3-14* μm – low-pass band 3-10 μm*) for CO_2 detection*

During the next experiment the existence of vapour in the atmosphere was accidentally observed. Figure 5 shows the water vapour condensation during CO_2 decompression. The gas stream was directed on a dry sheet of paper _ Figure 5b. After removing the gas stream, the latent heat from the vapour is released and a sheet of paper is warming – Figure 5c. In order to separate the contribution of gas and vapour attenuation, the high-resolution IR spectrometry is planned to be implemented using the modelling. More details, results and examples will be presented in the extended paper.



a) b) c)

Fig. 5. *Water vapour condensation on a sheet of paper while decompressing of CO_2 under low pressure, a) a sheet before the experiment, b) during decompressing, c) after removing gas stream*

4. Conclusions

The research results presented in this paper confirms the possibility of using LWIR 14-16 μm IR wavelength band for carbon dioxide detection. As a result, the low-cost microbolometer can be used for warming gas detection. It is possible to measure quantitatively the content of CO_2 in the atmosphere with estimating the contribution of water vapour in the total attenuation of IR radiation in 14-16 μm wavelength band.

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