

## IR imaging of CO<sub>2</sub>: basics, experiments, and potential industrial application

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### Introduction

The detection of gases by thermal imaging due to absorption, scattering, or emission of IR radiation is a rather new application in the field of infrared thermal imaging (see [1] and refs. therein). Strong absorption/ emission features allow detection of some gases already with broad band IR cameras in the MW and LW range. The industrial importance of several gases led to the development of sensitive cameras using narrowband cold filters in front of the detector. Such cameras are commercially available for detection of volatile organic compounds, SF<sub>6</sub>, and CO. Quantitative analysis of gas concentrations or gas flows is complicated although in principle also possible. In this work, we focus on CO<sub>2</sub> which is probably the most important gas of the 21<sup>st</sup> century. The absorption bands for room temperature CO<sub>2</sub> gas lie around a wavelength of 4.3 μm (Fig. 1) within the spectral range of MW IR cameras.

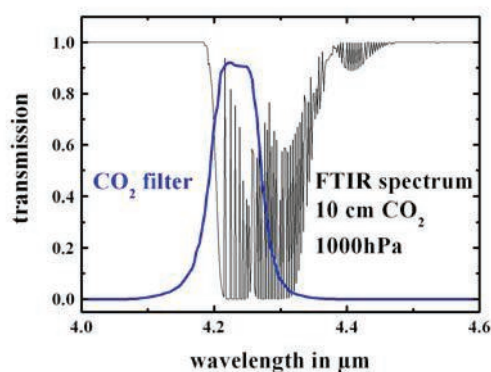


Fig. 1: Expanded view of 4.2 μm absorption band with position of the CO<sub>2</sub> filter used in the experiments.

Carbon dioxide (CO<sub>2</sub>) is a natural gas which has found numerous applications in industry. Besides, it is a byproduct of the combustion of carbon based energy sources. As a result, it gives at present the most important contribution to the anthropogenic greenhouse effect [2]. In order to mitigate climate change due to anthropogenic emission of greenhouse gases many big corporations in the field of the energy industries plan to introduce so called carbon capture and storage (CCS) technologies. The concept of CCS is briefly summarized in Fig. 2 (from [3]). CO<sub>2</sub> from primary sources, e.g. large power plants is captured and transported to several storage sites (mostly in pipelines). Storage can, e.g., occur in deep geological formations, oil wells, the deep ocean or in the form of mineral carbonates.

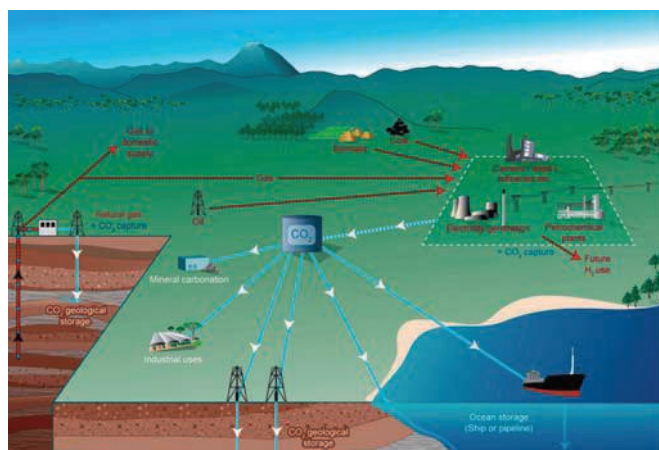


Fig. 2: CCS systems showing the carbon sources for which CCS might be relevant and options for the transport and storage of CO<sub>2</sub> (reproduced from [3], Chapter 4: Energy Supply, Fig. 4.22).

The introduction of CCS technologies will raise the issue of

- 1) Verification, that the power plants do indeed no longer emit CO<sub>2</sub>.
- 2) Verification that pipelines do not leak.
- 3) Verification that underground storage is safe, i.e., that there are no leakages.

For all of these verification issues, analytical tools are needed which easily allow monitoring of pipelines or sites by sensitive detection systems for gaseous CO<sub>2</sub>.

We suggest that IR thermal imaging provides an excellent tool for this purpose. As imaging device it offers in particular the possibility of fast leak detection in large areas. Once leaks are localized, the method may be combined with other conventional and very sensitive spot measurement techniques for CO<sub>2</sub>.

So far commercial gas find cameras operate in a qualitative manner, only. The reasons are manifold: IR radiation passing through gases is attenuated mostly according to absorption due to excitations within ro-vibrational bands. These attenuation losses are described by Bouguer's (Lambert-Beer's) law, where the relevant parameter is  $\tau(\lambda, c, L)$ , the optical thickness of the gas, which depends on wavelength  $\lambda$ , gas concentration  $c$  and length  $L$  of optical path through the gas. For a gas at constant pressure  $p$  and dimension  $L$  one uses the form  $\tau = k(\lambda) \cdot p \cdot L$  with  $k$  being the gas absorption coefficient. The pressure  $p$  is proportional to volume concentration. The optical thickness relates to the transmission  $T$  of the gas according to

$T(\lambda, p, L) = e^{-k(\lambda) \cdot p \cdot L}$ . From laboratory experiments and theoretical models,  $k$ -values for gases are known.

Therefore, it is possible to compute transmission of IR radiation through a gas once the spectral range of the radiation is defined by a filter and the spectrum of the gas species is known. Vice versa, the attenuation of IR radiation should allow to compute respective partial pressures of the gas and, hence, volume concentrations. Problems are due to several reasons. First, spectra sensitively depend on total pressure, since pressure broadening affects the line widths of the individual lines. Second, the precise value of the absorption constant in the line center must be known. Measured spectra like those with FTIR can only be used if the spectral resolution is below the typical value for pressure broadening (order of 0.1 cm<sup>-1</sup> for CO<sub>2</sub> at atmospheric pressure). Third, in real measurement conditions, gases are not homogeneously distributed, i.e. the optical density must be computed via integration along the optical path between source and camera, which is often not precisely known.

### Experiments

A number of laboratory experiments have been performed to test the potentials of IR imaging for CO<sub>2</sub> detection (more details, see [4,5]). Two types of cameras were used, first a broadband MW camera (Agema THV 550, cooled PtSi detector array, 320x240 pixels,  $\lambda$ -range 3-5  $\mu$ m) and second an extended MW camera (FLIR SC 6000, cooled InSb detector array, 640x512 pixels,  $\lambda$ -range 1.5-5  $\mu$ m) including a narrow (not cooled) band path filter (here Spectrogon Filter 4235) with transmission around  $\lambda=4.2$  and 4.3  $\mu$ m (Fig. 1). The experimental configurations used in this work are schematically depicted in Fig. 3.

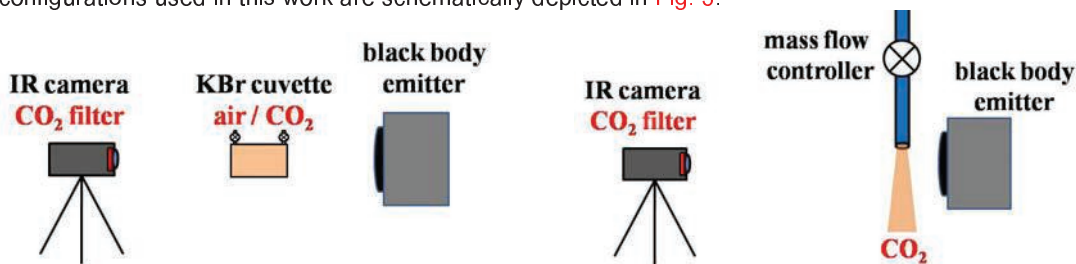


Fig. 3: Experimental set up for experiments (some experiments were performed without filter)

Either a cuvette of defined length was filled with gas of known concentration or a gas with well known mass flow was emitted from a tube. Observations were made with the gas in front of black body emitters.

### COMPARISON BETWEEN BROADBAND AND NARROWBAND DETECTION

Although broad band MW cameras may detect CO<sub>2</sub> gas by its absorption, it is customary to use narrow band filters. The reason becomes obvious from Fig. 4, which depicts a comparison between IR images of a broadband MW camera (3 $\mu$ m-5 $\mu$ m) and a narrowband camera (SC6000 with warm filter). The filter is adjusted to the spectral band at 4.3 $\mu$ m (see Fig. 1). Both cameras observe the same CO<sub>2</sub> gas flow in front of a blackbody source, operated at around 50°C.

Whereas the broadband camera hardly detects this small CO<sub>2</sub> flow of only 100ml/min, the narrowband detection considerably improves the sensitivity of the camera. Reducing the gas flow allows to estimate the differences in sensitivity. In the present case for the given conditions ( $T_{BB}=50^\circ\text{C}$ , gas flow from tube with 6mm inner diameter), the difference in the lowest detectable gas flows was around a factor of 20 to 30, i.e. the narrowband camera system allows to detect gas flows which were a factor of 20 to 30 smaller than the ones observed with a broadband camera (detection limits, see below). For the practitioner, we also note, that the smallest detectable gas flows will always be seen as signal changes in life image sequences. This is due to the fact, that the image processing within the brain is in general very sensitive to movements in our field of view, i.e. image changes as a function of time. In still images, it is much harder to detect such small variations of gas concentrations.

In the following, all experiments (with the exception of the one with SF<sub>6</sub> and emission of hot gases) were recorded with the narrowband camera systems (SC 6000 plus room temperature filter).

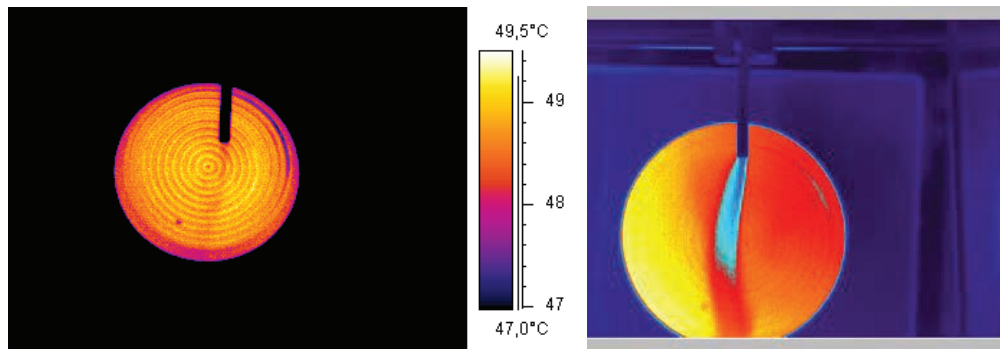


Fig. 4: Comparison of detection of the same flow of CO<sub>2</sub> gas (100ml/min, tube inner diameter 6 mm) with a broadband MW camera (THV 550, left) and a narrowband camera (SC6000 plus filter, right). Obviously, the use of the warm filter considerably increases the signal quality and in particular the lower detection limit (see below). In addition, the InSb detector of the SC6000 camera is more sensitive than the PtSi detector of the THV 550 camera.

### DETECTING VOLUME CONCENTRATION OF CO<sub>2</sub> IN EXHALED AIR

Carbon dioxide is directly related to human energy production upon oxygen intake. It is the “exhaust gas” of human breathing. The average CO<sub>2</sub> concentration in the air is about 390 ppm (in the open air) and around 400 – 800 ppm in closed rooms (depending on size of room, number of people in room as function of time, ventilation of room,...). The increase of CO<sub>2</sub> concentration in closed rooms is due to breathing. The typical carbon dioxide concentration in exhaled air is around 4 to 5 volume percent (40,000 to 50,000 ppm), i.e. around a factor of 100 larger than typical concentrations in fresh air. These concentrations are easily detectable with IR cameras [4].

### ABSORPTION VERSUS THERMAL EMISSION OF IR RADIATION

Fig. 5 depicts an impressive example of the transition from absorption to thermal emission by sulfur hexafluoride (the same should be observable for CO<sub>2</sub> although it has not yet been tested). The gas was filled into a flexible container and put into an oven. Thereby the gas was cooled down to -20°C or heated up to 80°C.

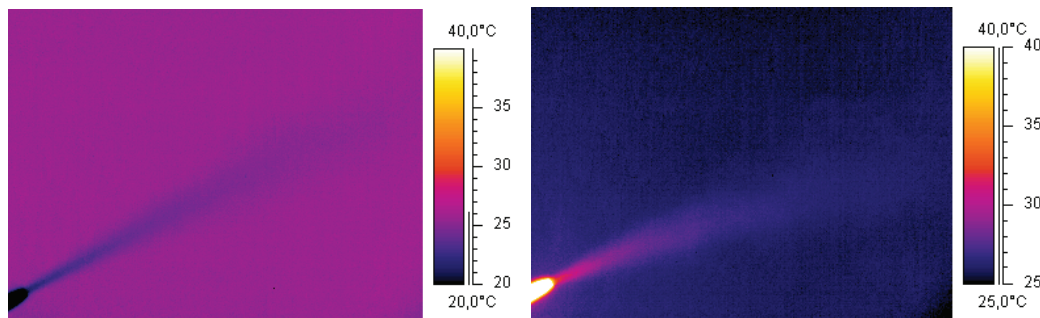


Fig. 5: Broadband detection of cold ((T=-20°C, left) and warm (T=80°C, right) SF<sub>6</sub> in front of a room temperature wall (T=25°C) (after [1]). A LW IR camera (FLIR SC2000) was used since the strong absorption feature is around 10μm.

The oven was located several meters away from the experimental set up. The oven door was shut after removing the gas and the outside parts of the oven were only slightly above room temperature. Therefore, the only warm or hot object around, while performing these experiments was the experimenter himself, who was also several meters away from the gas. As a consequence, no scattering of IR radiation from neighboring hot objects was detectable.

### DETECTING CO<sub>2</sub> IN THE EXHAUST OF COMBUSTION PROCESSES

The thermal emission of IR radiation from CO<sub>2</sub> can be detected very often when studying combustion processes.

Fig. 6 depicts the exhaust pipe of a motorcycle (Suzuki 1100 GSXF, 98 HP) in front of a heating plate which had an inhomogeneous temperature distribution with an average temperature of about 80°C.

The left image shows CO<sub>2</sub> absorption in the exhaust after starting the engine but just running it at low power. Obviously, the exhaust gases had enough time to cool down within the exhaust pipe. Hence, one may not observe any thermal emission, but only some absorption of IR radiation in front of the warm background. However, while the engine was operated (for a short time) at full power, rather hot exhaust gases were emitted, which showed up in the IR image (right).

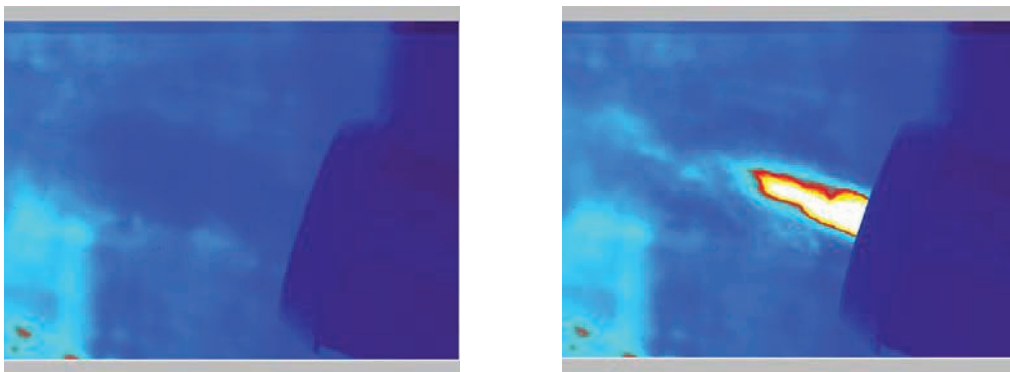


Fig. 6: Warm (left) and hot (right) CO<sub>2</sub> exhaust gas from combustion in a motorcycle engine. The background was at a temperature of about 80°C.

#### DETECTING MINUTE AMOUNTS OF CO<sub>2</sub> IN AIR OVER A PATH LENGTH OF 10CM

A first step towards quantitative measurements of CO<sub>2</sub> consists in using a cell of 10 cm length with KBr windows of about 95% transmission. It can be filled with any desired partial pressure. In order to test the sensitivity of CO<sub>2</sub> detection, the cell was evacuated and observed while ambient air was streaming in with typical CO<sub>2</sub> volume concentrations in closed rooms of around 400-800 ppm (see above). Fig. 7 shows the result: The change in CO<sub>2</sub> content is due to the 10 cm cell while the total measurement distance was about 1m. The observed change means that minute changes in CO<sub>2</sub> concentrations of 40 to 80 ppm over measurement distances of 1m can be detected.

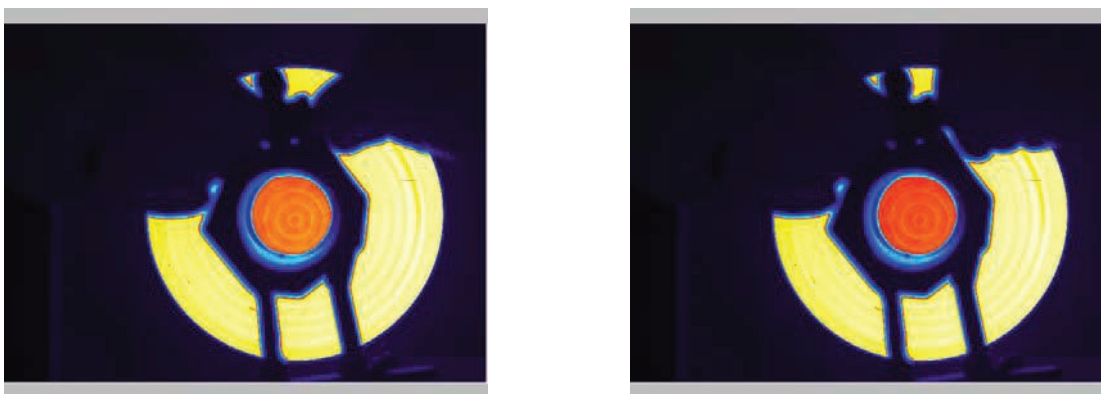


Fig. 7. Cell with vacuum (left) and filled with room temperature air (CO<sub>2</sub> concentration 400 to 800 ppm).

#### DETECTING PRESSURE BROADENING OF CO<sub>2</sub> WITH IR IMAGING

Similar experiments can be done for a total pressure of around 1000 hPa (atmospheric pressure) and varying CO<sub>2</sub> partial pressures. As expected, the larger the CO<sub>2</sub> concentration, the stronger the attenuation of IR radiation (Fig. 8). The measurements are even sensitive enough to demonstrate the pressure broadening effect of the

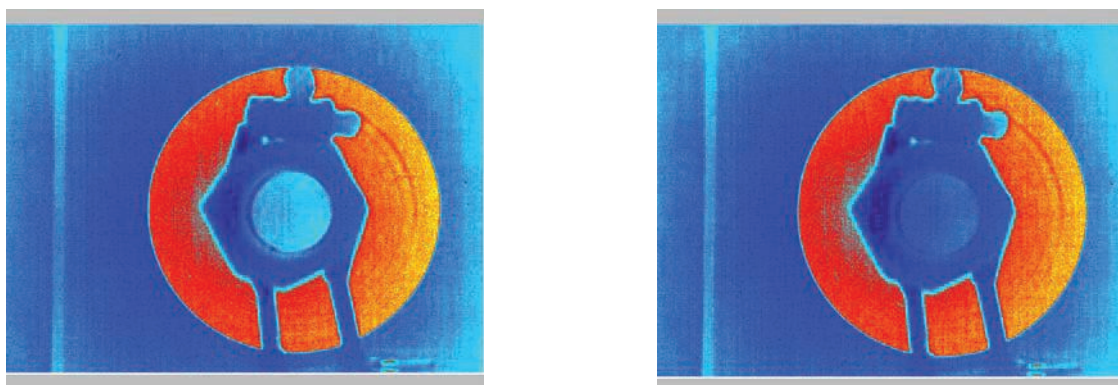


Fig. 8. Pressure broadening in CO<sub>2</sub> spectra: cell of 10cm length with KBr windows in front of blackbody source (T= 35 °C). The CO<sub>2</sub> partial pressure was 51 hPa with total pressures of 51 hPa (left) and 1029 hPa (right).

individual ro-vibrational lines of the absorption spectra. Fig. 8 compares the signals of the same partial pressure of CO<sub>2</sub> (51 hPa) for two different total pressures of 51 hPa (i.e. pure CO<sub>2</sub>) and 1029 hPa. The higher atmospheric pressure leads to pressure broadening and therefore to a larger attenuation of the IR radiation.

#### DETECTION OF WELL DEFINED CO<sub>2</sub> GAS FLOWS FROM A TUBE

The most important application of any GasFind camera should be its leak detection capability. Fig. 9 depicts results for varying CO<sub>2</sub> flow in front of a blackbody source operating at around 50°C. The CO<sub>2</sub> flow (100 vol%) was adjusted using a mass flow controller, the gas was exiting a tube of 6 mm inner diameter several cm in front of the source.

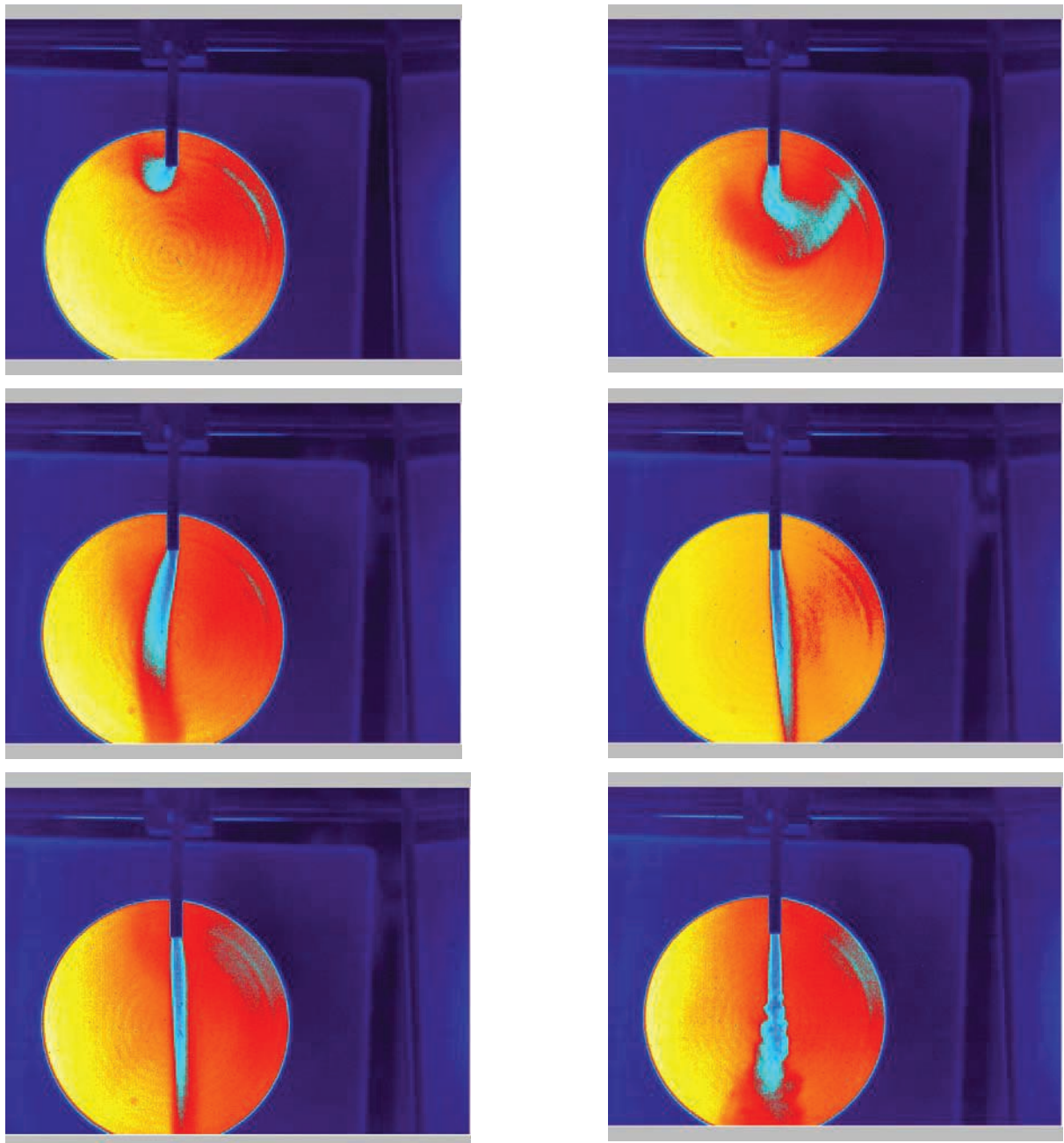


Fig. 9. Raw data of detected CO<sub>2</sub> flows (in ml/min): 5 (top, left), 20 (top right), 100 (middle row, left), 300 (middle row, right), 500 (bottom left) and 1000 (bottom, right). The SC 6000 camera was operated with an uncooled narrow band filter in front of a black body emitter operated at T= 50°C.

The sequence in Fig. 9 shows results for mass flows between 5 and 1000 ml/min. Despite the large density of CO<sub>2</sub> compared to air, small flow rates lead to fumes which are easily driven by currents of the surrounding air. Flow rates between 100 and 500 ml/min result in nearly laminar flow. For flow rates above 1000ml/min, turbulences are clearly developing.

Of course, the main question concerns the lower limit of detectable gas flow. It depends on a combination of background signal and chosen integration time for the detector (most commercial IR cameras do not allow the user to select integration time!). In order to more closely resemble typical outdoor situations, experiments were carried out for background temperatures only slightly above room temperature ( $T_{BB}=35^{\circ}\text{C}$ ). Due to the corresponding lower radiation signal (with respect to a  $50^{\circ}\text{C}$  blackbody) longer integration times could be used, yielding a better signal-to-noise ratio. Fig. 10 depicts an example for a gas flow as low as 1 ml/min. In still images like this one this flow was sometimes hard to detect, however, the temporal changes in live images suggest, that such a small gas flow can be reproducibly detected in this set up.

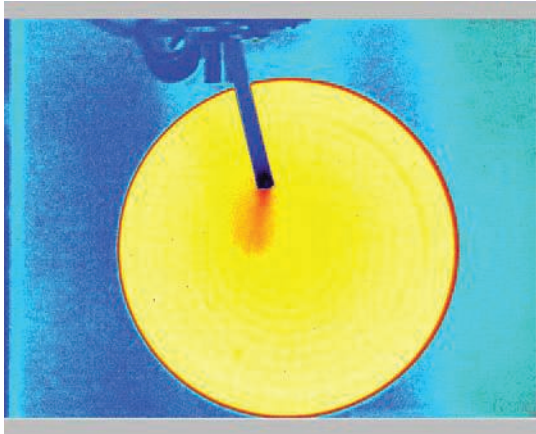


Fig. 10. CO<sub>2</sub> gas flow of 1 ml/min detected in front of a black body emitter operated at  $T = 35^{\circ}\text{C}$ . The integration time was set to 3ms.

## SUMMARY AND CONCLUSIONS

Preliminary experiments dealing with attenuation of IR radiation by CO<sub>2</sub> using sensitive commercial MW cameras with room temperature narrowband filters proves the suitability of IR imaging for CO<sub>2</sub> detection and monitoring. Besides qualitative visualization of a variety of CO<sub>2</sub> sources from different origin, gas flows and concentrations, the method is particularly suited for analyzing gas leaks. For background temperatures of  $35^{\circ}\text{C}$ , gas flows as low as 1 ml/min could be detected.

Such flows would correspond of 0.06 liters/hour, 1.44 liters/day, or  $\approx 0.5 \text{ m}^3/\text{year}$ . Using the density of CO<sub>2</sub> which is about  $2 \text{ kg/m}^3$ , it is therefore possible to detect emissions of as low as about 1 kg/year from individual leaks! Even for much less favorable conditions in industry, lowest detectable gas flows of say 100 ml/min, i.e. about  $50 \text{ m}^3/\text{year}$  or  $\approx 100 \text{ kg/year}$  should be readily observable. As a consequence, we are convinced that CO<sub>2</sub> sensitive IR cameras are very well suited for leak detection of CO<sub>2</sub> for industrial applications, in particular in the future field of carbon capture and storage technologies. Once leaks are localized, the method may be combined with other more sensitive CO<sub>2</sub> spot measurement techniques.

So far experiments were performed with a research camera SC 6000, which is not suited for field use. However, if the need for development of hand held cameras for field use becomes obvious, i.e. if a market for such systems evolves within the process of introducing CCS technologies, it will just be a matter of time before commercial products are available. As is well known from other GasFind cameras, such specialized cameras may then be produced using fixed cold filters which can additionally lower the detection limit compared to cameras with warm filters. Therefore detection conditions will most probably be even more favorable.

## References:

- [1] M. Vollmer, K.-P. Möllmann, *Infrared Thermal Imaging – Fundamentals, Research and Applications*, Wiley (2010)
- [2] Climate Change 2007, The Physical Science Basis, Contribution of Working Group I to 4th Assessment Report of the Intergovernmental Panel on Climate Change, Eds. S. Solomon et al., IPCC (2007)
- [3] Climate Change 2007, Mitigation of Climate Change, Contribution of Working Group III to 4th Assessment Report of the Intergovernmental Panel on Climate Change, Eds. B. Metz et al., IPCC (2007)
- [4] M. Vollmer, K.-P. Möllmann, *IR imaging of gases: potential applications for CO2 cameras*, Inframation 2009, Proc. Vol 10, p.113-124, and *IR imaging of gases: quantitative analysis*, p.99-112
- [5] M.Vollmer, K.-P. Möllmann, Perspectives of IR imaging for industrial detection and monitoring of CO<sub>2</sub>, Proceedings Temperatur 2009, Ed.:PTB Berlin, p.27-36 (2009)