GAS CAMERA – MOBILE IMAGING SYSTEM FOR VISUALISING METHANE PLUMES AT DISTANCES BETWEEN 0 M AND 100 M AND MORE

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1. ABSTRACT

In order to ensure the safe and economic operation of natural gas networks and gas plants, leaks should be detected as soon and efficient as possible. Currently, hand-held systems based on flame ionisation detectors or semiconductor gas sensors are used to inspect pipelines and plants.

Scanning imaging FTIR spectrometry is a new method for remote detection and imaging of gases in the atmosphere. Based on this method scientists of the Hamburg University of Technology in cooperation with E.ON Ruhrgas AG developed a tool for identifying and visualising natural gas clouds purposely or accidentally released from gas transport facilities during operation or construction. The superposition of a video image and a false colour image of the gas cloud allows the localisation of the source of methane.

Currently a field-portable gas camera system is under way that will provide an improved spatial resolution compared to realised systems and allows an real time imaging of a gas cloud containing a methane fraction. The new “Gas Camera” is based on of a focal plane array detector combined with a frequency-selective element selecting narrow IR frequency bands characteristic for methane emission. This system does not longer employ a mirror scanning infrared system. Similar to the FTIR system, a conventional digital video image taken in the visible frequency range is superimposed on the IR-image, in order to relate the infrared measurements of a cloud to the location of the release.

The new device will be a mobile imaging system for detecting and visualising methane plumes at distances between 0 m and 100 m. The project “Gas Camera” is funded by a GERG-Partner Group consisting of E.ON Ruhrgas AG, Snam Retegas, Gasuni e, Fluxys and Esders Engineering.

In this paper experiments that proved the effectiveness of both methods as well as first experiments with the measurement set-up that will be used for the planned detection system are presented.
2. Body of Paper

2.1 Introduction

In order to further improve the safe and economic operation of natural gas networks and gas plants it is advantageous to use remote and real time sensing systems for the detection of small gas leakages. Given that an effective system has to be mobile, highly sensitive and also easy to use, infrared multi spectral imaging had been chosen as basis for the design. In order to locate gas clouds easily and intuitively, a video image is superimposed onto the gas image.

Current passive remote detection systems available on the market are based on Fourier-transform infrared (FTIR) spectrometry. Based on this method, a scanning imaging remote sensing system has been developed at Hamburg University of Technology (TUHH). The system employs an interferometer with a single detector element (Bruker OPAG 22, Bruker Daltonics) in combination with a telescope and a synchronised scanning mirror. The results of the spectral analyses are displayed by an overlay of a false colour image, the “gas cloud image”, on a video image. In cooperation with E.ON Ruhrgas AG the system has been applied to the detection and visualisation of natural gas clouds.

Current FTIR systems like the mirror scanning systems are tested under hard field conditions, e.g. for detection of hazardous gas clouds in military applications. The disadvantage is that there is a speed limit given by the scanning rate which is necessary to get low detection limits. Furthermore those systems are too heavy to be manually transported. For an effective system a highly sensitive hand-held equipment, a “Gas Camera”, has to be developed which allows to see where gas exits are located. That means with a “Gas Camera” it is possible to monitor large areas and get an image of a gas cloud that is easy to interpret by the operator.

Gas cloud visualisation is the core of the innovation. The goal of the project “Gas Camera” is to develop a mobile, hand-held, unit suitable for detecting methane escaping from small leaks. The Gas Camera will cover distances from the gas source of 0 up to at least 100 m. The design should allow to detect and localise leaks efficiently in real time, several times per second, and cover a universal and broad range of applications. The newly designed remote sensing system is intended to increase the safety during construction or operation of gas transport facilities and pipelines.

The design should allow to detect and localise leaks efficiently in real time and cover a universal and broad range of applications. The expectation in remote sensing systems is to increase the safety issues during constructions or operation of power plants and pipelines by using a more effective gas detection system.
2.2 Passive Remote Sensing of Methane by Infrared Spectro-Radiometry

Gas clouds can be detected from a distance by infrared spectrometry. The detection is based on the analysis of radiation absorbed and emitted by the molecules of the clouds. The method is a passive detection method which exploits existing thermal background radiation for the analysis. Figure 2-1 illustrates the measurement set-up. In order to describe the characteristics of spectra measured by a passive infrared spectrometer a model in which the atmosphere is divided into plane-parallel homogeneous layers along the optical path may be used (Reference 1, 2). In most cases a model with three layers is sufficient to describe the basic characteristics of the measured radiation (Figure 2-1). Radiation from the background (layer 3) propagates through the vapour cloud (layer 2) and the atmosphere between the cloud and the spectrometer (layer 1). The cloud and atmospheric layers are considered homogeneous with regard to all physical and chemical properties. The radiation containing the signatures of all layers is measured by the spectrometer.

In this model the spectral radiance at the entrance aperture of the spectrometer $L_1$ is

$$L_1 = (1 - \tau_1)B_1 + \tau_1[(1 - \tau_2)B_2 + \tau_2L_3],$$  \hspace{1cm} (1)

where $\tau_i$ is the transmittance of layer $i$, $B_i$ is the spectral radiance of a blackbody at the temperature of layer $i$, $T_i$, $L_3$ is the radiance that enters the layer of the cloud from the background. The quantities in Equation (1) are frequency-dependent.
If the background layer is given by a topographical target, the radiation entering the cloud $L_3$ contains radiation emitted by the surface and reflected radiation.

$$L_3 = a \int_{\pi} F(\Omega_s, -\Omega') L_{\text{down}} (-\Omega') d\Omega' + \varepsilon(\Omega_s) B(T_{bg}).$$  \hspace{1cm} (2)$$

Here, $a$ is the surface albedo, $\Omega_s$ is the solid angle subtended by the aperture of the spectrometer. $F(\Omega_s, -\Omega')$ is the surface biconical reflectance function for incident solid angle $-\Omega$ and emergent solid angle $\Omega_s$. $\varepsilon(\Omega_s)$ is the directional surface emittance, and $B(T_{bg})$ is the radiance emitted by a blackbody at temperature $T_{bg}$. The radiation incident on the background $L_{\text{down}}$ contains ambient radiation ($L_{\text{am}}$) and radiation from the sky ($L_{\text{sky}}$). The dependence on frequency is left implicit again.

If the temperatures of the layers 1 and 2 are equal, Equation (1) can be simplified:

$$L_1 = B_1 + \tau_1 \tau_2 (L_3 - B_1)$$  \hspace{1cm} (3)$$

The spectral radiance difference caused by the cloud layer and the atmosphere $\Delta L = L_1 - L_3$ is given by

$$\Delta L = (1 - \tau_1 \tau_2) \Delta L_{13},$$  \hspace{1cm} (4)$$

where $\Delta L_{13} = B_1 - L_3$. Equation (4) shows that the signal is basically given by the transmittance of the cloud and the atmosphere multiplied with the spectral radiance difference $\Delta L_{13}$. $\Delta L_{13}$ is proportional to the difference between the temperature of the gas and the background (first order approximation for a background with high emittance).
2.3 Infrared Remote Sensing Systems

In this work, two passive infrared remote sensing systems were used. The first system is a passive scanning infrared gas imaging system (SIGIS) which was originally developed at TUHH for the identification and visualisation of pollutant clouds. It comprises an interferometer with a single detector element (OPAG 22, Bruker Daltonik, Leipzig, Germany), an azimuth-elevation-scanning mirror actuated by stepper motors, a data processing and control system with a digital signal processor, and a personal computer (Figure 2-2). The system is described in detail in Reference 3. As a first step towards the development of an imaging gas detection system, this system was adapted for the detection of methane.

For the visualisation of gas clouds, the scanning mirror is sequentially set to all positions within the field of regard. The size and the direction of the field of regard and the spatial resolution (i.e. the angle between adjacent fields of view) are variable. Each interferogram measured by the interferometer is recorded by the FTIR (Fourier Transform Infrared) DSP system, Fourier transformed, and the spectrum is transferred to the PC. A video processing system records and analyses images of a video camera. The spectrum is analysed and the results are visualized by a video image, overlaid by false colour images representing the density of the gas cloud. For a target compound, in our case methane, images of the coefficient of correlation between the measured spectrum and a reference spectrum of methane, the signal-to-noise ratio, and the temperature of the background are produced (Figure 2-2).

Figure 2-2: Block diagram of SIGIS.
The second system is a laboratory prototype of an imaging gas detection system, a “Gas Camera”. The system comprises an infrared detection system with a focal plane array (FPA, AIM Infrarot-Module GmbH, Heilbronn, Germany), a filter wheel with interference filters, and a personal computer. The interference filters have a narrow bandpass-characteristic. The passband of one Filter matches the absorption band of the target gas (target gas filter). The passband of a second filter does not contain strong absorption lines of the target gas (reference filter). The filter characteristics are illustrated in Figure 2-3. Moreover, Figure 2-3 shows the absorption band of methane that is used for the detection.

Figure 2-3: Selection of spectral bands using interference filters.
In order to perform first field tests, the laboratory prototype was equipped with portable electronics (Figure 2-4). A PC program controlling all required functions of the focal plane array and the filter system has been developed. The PC software acquires data from the FPA and accumulates images in the different spectral bands of the filters (Figure 2-3). These images or difference images are displayed as false colour images. The system allows measurements, analysis, and display of the resulting images in real time.

Figure 2-4: Prototype System.
2.4 Field Measurements

To examine the feasibility of infrared remote sensing for leak detection, measurements were performed with the SIGIS system described in chapter 2.3. In order to simulate a leak in a pipeline, methane was released approximately 1 m below the ground through a cylindrical probe stuck into the soil. The gas partial discharged through the ground and partial escaped through the tiny gap between probe and soil. Measurements with the SIGIS system were performed from the roof of a building at a distance of approximately 100 m. During the measurements weak winds prevailed. Figure 2-5 shows the location of the release of methane from the position of the remote sensing system. For each measurement, a field of regard consisting of 30 × 20 directions was scanned. For the detection of methane, the spectra were analysed in the spectral range 1280 - 1320 cm\(^{-1}\).

In order to examine the detection capabilities of the imaging system, measurements with the prototype gas camera were performed as the second development step. Figure 2-6 shows results of a measurement of a methane plume from a distance of approximately 20 m. The release rate of methane was 200 L/h from an 8 mm nozzle. The methane plume is clearly observable in Figure 2-6.
2.5 Results

Figure 2-5 shows results of measurements at a release rate of 50 m/h. The results are visualised in false colour images as described in chapter 2.4. In each direction of the scanning mirror, one interferogram was measured. Close to the position of the release of methane, the signal to noise ratio increases. Since the spatial resolution of the system is limited the point of release is difficult to identify.

The minimum gas escape detected was 25 L/h. The measurements confirm that natural gas clouds can be detected from a distance by passive infrared spectrometry.

![Image of methane release with false color overlay]

Figure 2-5: Location of the methane release with including video image overlay by false colour image.
Figure 2-6 exhibits a photograph of a release location overlaid by the results of the gas camera. The release rate of methane in this case was about 200 L/h. The methane plume is clearly observable as shown in Figure 2-6. These first tests show that the new technology enables the detection of small gas releases over large distances. Because the type of gas to be detected in the application envisaged is known and an unambiguous identification is not necessary, the spectral resolution may be lower, while good resolution in terms of space is required. Thus, a reproducing gas detection system like a “Gas Camera” can be designed by combining a focal plane array detector, consisting of many relatively small detector elements, with an element selective to frequency or wavelength.

The investigations confirmed that infrared multispectral imaging allows the detection and visualisation of gas clouds from long distances. In particular the second system, that employs an infrared array detector, is well-suited for leak detection at plants and pipelines and for surveillance of construction and maintenance tasks. Based on this device it is envisaged to develop a portable field prototype “Gas Camera” that will be evaluated by field tests under real conditions on-site during the next 3 years.
2.6 Conclusion

Scanning imaging FTIR spectrometry is a new method for remote detection and imaging of gases in the atmosphere. Based on this method scientists of the Hamburg University of Technology in cooperation with E.ON Ruhrgas AG developed a tool for identifying and visualising natural gas clouds purposely or accidentally released from gas transport facilities during operation or construction. The superposition of a video image by a false colour image of the gas cloud allows the localisation of the source of methane.

The investigation results suggest to base the new gas detection system “Gas Camera” on the combination of a focal plane array detector with frequency-selective elements selecting narrow IR frequency bands characteristic for methane. The first detection experiments with the laboratory system show that small leaks can be localised by the system.

It has been proven by the first tests performed by a laboratory set-up that a gas camera system will provide a good spatial resolution and real time imaging of a methane cloud. Similar to the FTIR system, a conventional video image taken in the visible frequency range is to be superimposed on the IR-image, in order to relate the infrared measurements of a cloud to the location of the release. The new device will be a mobile imaging system for detecting and visualising methane plumes at distances between 0 m and 100 m. The project “Gas Camera” is funded by a GERG-Partner group.
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