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Professional paper

THE TESTING OF HARMFUL GASES USING PASSIVE INFRARED THERMOGRAPHY

ISPITIVANJE ŠTETNIH GASOVA PRIMENOM PASIVNE INFRACRVENE TERMOGRAFIJE

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Abstract: This paper presented possibilities of passive infrared thermography method in harmful gases leakage testing. Gas detection is performed in suitable spectral range, by comparing background thermogram with and without presence of gas. To be able to form the quality thermograms, it is necessary to use suitable optical filters and gas correlation cells.

Key words: IR camera, IR spectra, gas leakage inspection, non-contact testing

Apstrakt: U ovom radu predstavljene su mogućnosti metode pasivne infracrvene termografije pri ispitivanju curenja štetnih gasova. Detekcija gasova vrši se u odgovarajućem talasnom opsegu, uporedjivanjem termograma pozadine sa i bez prisustva gasa. Radi formiranja kvalitetnih termograma neophodna je upotreba odgovarajućih optičkih filtra i gaskorelacionih ćelija.

Ključne reči: termovizijska kamera, IC spektri, inspekcija curenja gasova, beskontaktno ispitivanje

1. INTRODUCTION

Electromagnetic radiation in the segment of infrared (IR) spectral range from 0.78 to 1000 μm, invisible with naked eye, is of a great importance for science and engineering, and that is why the conversion of IR radiation spatial distribution to visible image provided by IR devices is exceptionally significant. First IR cameras were produced during 1960s. Because of the possibility for wide application, since the very beginning, they arouse great interest. Initially, they were generally used for military night observations, as well as in the conditions of reduced visibility during daytime or bad weather conditions (Rogalski, 2003). Nowadays they are used not only in military, but also in electronics, mechanical engineering, civil engineering, architecture, medical science and other fields, including chemical industry (Kulp et al. 1997) and mining industry (Stević et al. 2009). Besides the permanent and apparent commercial advancement of IR sensors, and the improvement of thermogram

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processing and analysis (visible images formed by conversion of IR radiation spatial distribution), there is interest for research in the field of "non-destructive" and "non-contact" testing of thermo physical material properties using IR thermography (IRT) (Maladague, 2001). For example, the ASTM standard published in 1988. defines passive IRT as standard method for locating the junction delamination at shipboards (ASTM, 2001). Passive techniques for detection use the natural background heat radiation (Kulp et al. 1997). The active approach (involving the use of active heat source) IRT, which applies for testing the defects in material (Tomić et al. 2012; Maierhofer et al. 2002), is more frequently used. The equipment is more available in terms of costs, so the IRT slowly becomes inevitable in systems for monitoring the equipment from safe distance during production process, where the conditions for control are risky. That is the case in harmful gases leakage detection, because the "contact" methods are still used, so the controllers are exposed to the harmful influence during the measurements because of immediate proximity, i.e. the measurements are performed strictly in the areas where gas leakage is suspected. IR camera can detect changes at observed objects by real time monitoring, i.e. there is a possibility of detecting accidents that can not be distinguished with the naked eye, and the measurements can be performed at safe distances depending on the needs (even over 150 m) (Darabi, 2000).

This technique can easy detect the accident location on a gas tank or train composition reservoir. Also, the inspection for leakage can be performed in chemical installations, petrochemical plants, reservoirs or pipe-lines. In closed working spaces we can conduct the surveillance of gas flow, entrances to air vents and exhaust pipes exits, extraction openings or local ventilation units. Natural eruption or evaporation of gases with geophysical origin in mines, volcanoes, geothermical areas, swamps, as well as in organic substances in agriculture, are also of interest for evaluation.

During gases detection, it is also important to determine their concentration, which requires the use of specifically adjusted IR cameras (Sandsten et al. 2000).

2. THEORETICAL BASIS OF THE METHOD

For optimizing the method for harmful gases detection using IR camera we should consider several factors: transmission of the atmosphere, total absorption power of gas molecules which is of interest and background radiation.

2.1. Earth's atmospheric transmittance of electromagnetic radiation

The Earth atmosphere gas composition causes the existence of wave areas in atmosphere with low attenuation, so the IR radiation can propagate (Ансамова et al. 1984). Namely, the Earth atmosphere is a mixture of gases (78% of nitrogen and less than 2% of oxygen, argon, neon, xenon, helium, carbon-dioxide), water vapor and aerosols (liquid or solid drops of dust, smoke etc.). Particles and impurities that can be found in atmosphere, with dimensions varying from 5 to 50 nm, affect the way the electromagnetic radiation propagates. The scattering at particles with dimensions much smaller than radiation wave length λ is, by Raley law, inversely proportional to forth power of wave length ($\sim 1/\lambda^4$). This explains why IR radiation propagates better through the atmosphere than visible radiation. The major absorbing components in atmosphere are hydrocarbons and water vapor. The radiation attenuation due to scattering is continual, and due to absorption is selective. The selective character of radiation attenuation while passing through the atmosphere in wave range from 1 to 15 μm is shown in Figure 1. The parts with relatively good transparency for IR radiation, so called "optical windows" can be distinguished.

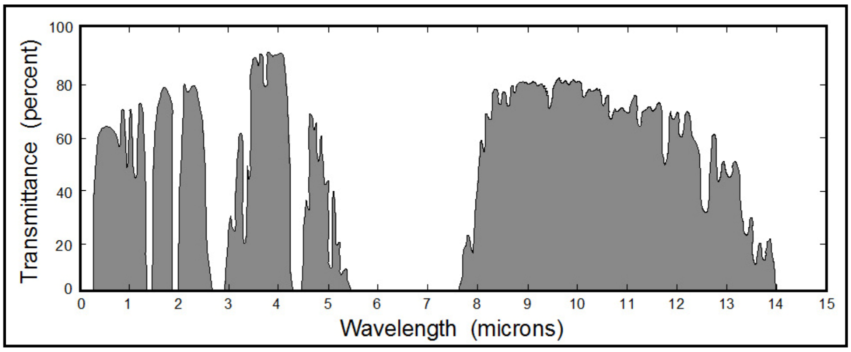

Figure 1 - Typical transmittance (transparence) of atmosphere in IR spectral range through 300 m of city air (Ансамова et al. 1984). The first, the second and the third optical window, 1.5 - 2.5 μm, 3 - 5 μm and 8 - 14 μm, respectively

2.2. Principle of gas detection using IR camera

By increasing the temperature of certain body, the mobility of atoms and molecules forming that body increases too, so it emits more energy in the mentioned spectrum segment, i.e. the IR radiation emanates from vibrations and rotation of atoms and molecules (Pokorni, 2004). Dependent on characteristics of material that bodies are made of, and environmental temperature, the bodies absorb different quantities of energy. The body warming up by heat source radiation, reflects a part of that radiation energy, absorbs a part, and a part transmits through the body. A parameter that describes the quantity of radiated energy in relation to incident radiation energy is body emissivity $\varepsilon(\lambda)$, which for real (gray) bodies has a value less than 1. The bigger this parameter is, the body absorbs bigger part of incident radiation energy and it is easier for detection. Practically, the energy absorbed by body registers by IR device. The factor that significantly influences body detection is background temperature.

Hydrocarbons have extremely high power of absorption in IR spectral range. Absorption is of interest for IR thermography technique, because important data can be obtained by spectral analysis in foregoing wave ranges. Vibro-rotational molecule spectra of hydrocarbons in wave range from 2 μm to 20 μm are quite suitable for detection of harmful gases in smaller quantities.

Methane (CH_4) is a gas without color and odor, easy flammable in contact with air or oxygen and explosive to a high degree. It can be found in coal mines, volcano and swamp gases, as well as in other organic substances. When the atmosphere is not polluted with harmful gases the percentage of methane is negligible, around $2\times10^{-4}\%$. At room temperature ammonia (NH_3) is in gaseous state, colorless, toxic, erodes skin, sharp (causes tears), with unpleasant smell. Ethylene (C_2H_4) is easy flammable gas, without color, odor and taste. It is clear, from stated gases characteristics, how important is to discover their presence or leakage in surrounding air.

Due to spectral characteristics, some more gases with homogenous core can be detected and quantified in particular IR wave range areas using IR camera: Benzene, Butane, Ethane, Ethylbenzene, Heptane, Hexane, Isoprene, Methyl Ethyl Ketone (MEK), Methanol, Octane, Pentane, 1-Pentane, Propane, Propylene, Toluene, Xylene etc.

Absorption of radiation in gases is described by Beer-Lamberts law:

$$\alpha(\lambda)=1-e^{-k(\lambda)\cdot p\cdot l} \tag{1}$$

where are:
α - a coefficient of absorption;
λ - a wave length;
$k(\lambda)$ - absorption constant at given wave length;
p - a partial pressure;
l - is thickness of absorbing layer.

We can notice that with increasing the gas layer thickness ($l\to\infty$), the absorption $\alpha(\lambda)\to1$. Emissivity of gas can be experimentally determined by measuring the dependence $\varepsilon=f(p\times l)$ or by implementation of empiric equation:

$$L=c\cdot T^n \tag{2}$$

where are:
c - a constant depending only on the value of partial pressure;
n - an exponent and approximately equals 3;
L - given in [W/m^2].

For obtaining IR images (thermograms) in real time, the environmental radiation is used, i.e. the method is passive.

3. MEASUREMENT EQUIPMENT AND OPTIMAL MEASURING CONDITIONS

Gases can be detected in a narrow spectral range, so for their detection we need IR camera which operates in suitable wave range. Fluctuations of environmental thermal radiation, reflectance and emissivity, can be compensated by using the gas correlation technique. For such spectral considerations a camera with temperature difference equivalent to noise NETD of 80 mK was chosen (Sandsten et al. 2000). IR cameras for gas detection differ from IR cameras for measuring temperature. In addition to other components, IR camera has a filter which cuts off the spectral range where the inspected gas can not be detected reduces the influence of other objects in environment radiating in wider spectral range; gives a high contrast response with total photons transmission in system. Optimal filter profile has been selected by changing the spectral range and its width and maximizing the ratio of total gas absorption which is of interest and total optical transmission of the system. In Figures 2 and 3 are shown the absorptions for benzene (C_6H_6) and sulfur hexafluor (SF_6) which is several thousand times more dangerous than carbon dioxide; the first one can be detected in 3.2 - 3.3 μm spectral range, and the second one in very narrow range around 10.6 μm.

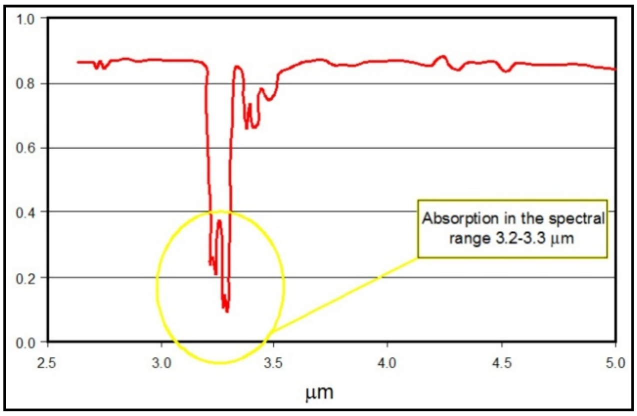

Figure 2 - C_6H_6 detection in the medium IR range

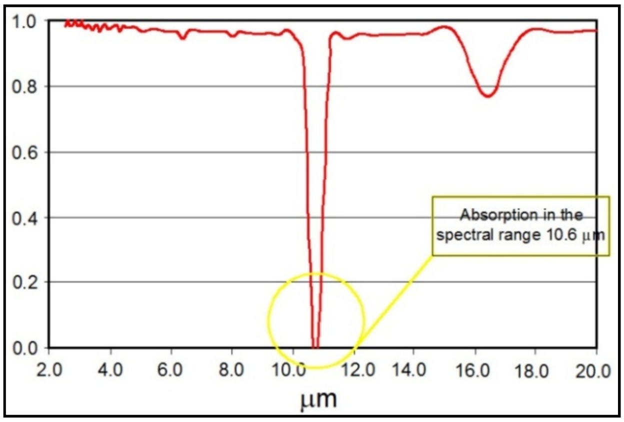

Figure 3 - SF_6 detection in far IR range

Gases that can be detected in the second atmospheric window are: ethane, butane, hexane, methane, octane, benzene. Gases that can be detected in the third atmospheric window are: furan, freon 12, bromine methane, propane, propylene, methyl ethyl ketone.

For the production of gas correlation cells can be used several materials which have transmission windows in wave range 2 - 12 μm, for example ZnSe and CaF_2, for gas samples with absorption at 10 μm and 8 μm, respectively (Figure 4) (Sandsten et al. 2000). To reduce the losses due to reflection, antireflective coatings can be deposited to ZnSe surface, which gives transmission of more than 90%, with maximum of 99% at

10.6 μm. In Figure 4 are also shown the transmittances of mentioned elements with total response convolution (black curves), ammonium and methane spectra for concentrations of 200 ppm × m in units for gas absorbance (red and orange lines) (Sandsten et al. 2000).

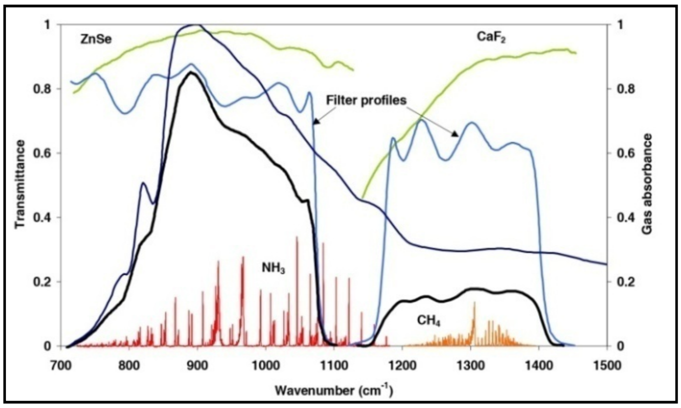

Figure 4 - The normalized spectral response of the IR camera (dark blue curve) is convoluted with the transmittance of different gas cell window materials and optical filter profiles, yielding two regions of relative response (black curves). The gases are both shown in absorbance at concentrations of 200 ppm × m (Wavenumber = 1/λ) (Sandsten et al. 2000)

Gas correlation particularity is that it provides the capability for complete distinction of spectral frequencies for specific absorptions in gases and transparent surfaces. The technique is based on comparing the direct recording (without gas cell) with the recording through gas (optically thick) absorbing cell.

Besides the selection and quality of measurement technique, conditions which can affect the thermogram quality (for outside measurements) are: wind, relative humidity, daytime because of the sun exposure, air temperature, environmental surface temperature and gas leakage rate.

Spectral range 8 - 14 μm (the third atmospheric window) contains more water vapor than spectral range 3 - 5 μm (the second atmospheric window), but the environmental radiation on Earth is 30 times stronger at temperature 300 K. In spectral range 8 - 14 μm absorption power is much higher for a lot of gases, because the presence of water in the atmosphere is not convenient in spectral range 7 - 8 μm. However this range has a strong influence on the signal, so it can be used for measuring methane using gas correlation technique.

4.1. Measurements

Measurements were performed outside. The recorded scene was corroded tank for gas with approximate emissivity 0.9, which represents background temperature of 303 - 313 K. For practical application of this method we use artificially (deliberately) induced leaking of harmful gas with known leakage rate. Gas containers were attached, which have long pipes filled with methane, ammonia and ethylene to simulate leaking rate 10 - 100 l/min. Previously measured (known) parameters are: sunny day without wind, time 2.30 pm, air temperature 291 - 294 K, relative humidity 48%, ZnSe gas cell containing ammonia at pressure 101325 Pa, filter type: Spectrogon LP9200. Optical equipment was set at 20 m distance from trailer with tank. We used IR camera AGEMA 900 LW with Cassegrain telescope. This camera uses Stirling cooler, MCT SPRITE detector and scanner (Sandsten et al. 2000). It generated IR image - thermogram, with line resolution 272 × 136 pixels. With the use of Cassegrain telescop the thermogram was divided in two areas (each with 136 × 136 pixels). Telescope has separate concave reflectors of total receiving area $2 \times 10\,\mathrm{cm}^2$. Reflective optics of telescope includes primary and secondary aluminum reflector. Aluminum with MgF_2 covering has reflectivity of 96% in IR camera operating spectral range. Primary reflectors positions are adjusted with fine winding screws, so the radiation is focused to secondary reflector shifted along shared optical axis. The camera is equipped with suitable interferent filters. Interference filters are placed at plate in front of the detector in camera. In front of the telescope, 20 mm thick gas cell is placed, and it additionally filters one of the images. Gas cell is filled with a specific gas, which makes it opaque at stronger absorbing lines. The two of such formed IR images are used for extraction of pure gas IR image and elimination of differences in environmental thermal radiation, as well as the noises brought in by other gases or particles. Simultaneous recording of the scene in the visible part of the spectrum was performed by using the camera located near the telescope. Thermograms generated this way point to limiting concentrations of 200 ppm × m.

Figure 5 (left) represents a tank (cistern) leaking gas benzene (thermogram right), while Figure 6 represents thermogram of the tank filled with gas. The images were taken with FLIR GL 320 camera.

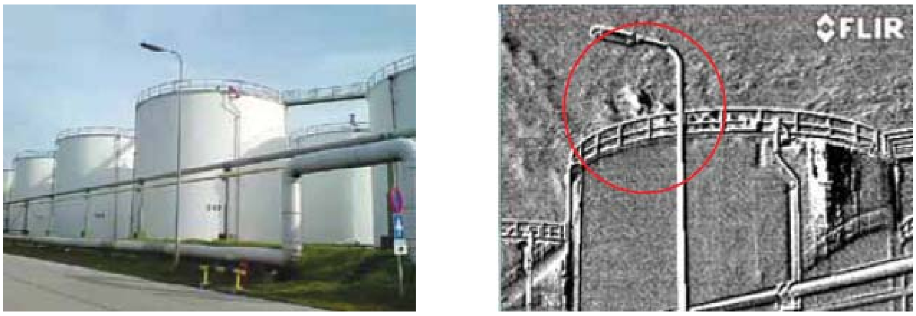

Figure 5 - Even tanks that have been emptied can still be leaking gas, such as this tank, which contained gasoline. This thermal image taken with the FLIR GF320 optical gas imaging camera shows that residual gasoline vapor is escaping into the atmosphere (www.flir.com)

Figure 6 - Thermogram of the tank filled with gas (www.flir.com)

4.2. Processing of the results

IR camera was connected to PC with hard disc, which enables the real-time recording of 12-bit image format, 272 × 136 pixels, frame rate 15 fr/s. Two images A and V were recorded at the same time using the Cassegrain telescope, IR camera and frame grabber. Image A is IR scene seen through one of the telescope apertures, and image V is the same scene but with gas cell in front of the other aperture. Image processing allows subtracting one image from the other (generating a suitable difference). Normalized image E from Cassegrain telescope is with measurement uncertainty due to asymmetric vignetting, two aperture light scattering ($E = A_o / B_o$). Image E was recorded with no presence of gas in the scene. Images were digitally overlapped by shifting and in the area of interest which contains gas the optimization was performed, and the next processing of the image excluded this area. Gas correlation estimated the resulting image $G = A/B/E$. Ammonia concentration levels represent the mean value obtained by simulation using the program GRAMS/32 (www.asdi.com) and calculation in Excel.

The simulation provided the characterization of optical transmitting system (except Cassegrain telescope, which does not significantly affect the spectral response). When the selection of suitable filter is considered, for optimizing sensitivity, two opposite requests should be equalized: the use of the low pass filters optimal for achieving high contrast response (from one side) and total photon transmission in the system (from the other side). For obtaining good signal/noise ratio, static noise in detector requires the photon flux to be higher that specified level. Because of that, the middle band-pass filter irradiates more than short-wave or long-wave pass filters. Changing the wave range, and range width, can maximize the ratio of total gas absorption (which is of interest) and total optical transmission of the system, which allows selection of optimal filter.

The results of this simulation show that the most convenient for ammonia and ethylene detection in spectral range 8 - 13 μm is the long-wave pass filter with cut-off wave length at 9.2 μm and 80% transmission, whilst for the methane detection is better wide range pass filter (half-power points are at wave lengths 7.5 μm and 8.5 μm), 60% transmission.

4.3. Gas concetration determination

During the determination of ammonia concentration, calibration can be performed by integration of relative transmittance of the system with the limiting wave lengths 9 μm and 14 μm. Total relative transmittance of system without gas is divided with descending total relative transmittance of the system with enhanced gas concentration. The procedure for the direct absorption measurements case is described in detail in papers (Kulp et al. 1997) (data base QASoft, molecular spectroscopic data base HITRAN and software GRAMS/32 (www.asdi.com) were used). The calculation was conducted for significant temperature differences between the environment (background) and gas. In practical situations the inherent gas radiation also must be considered. Gas can be detected on the basis of inherent radiation at absorbing lines with intensity $\left[(1-\tau)\times L_G\right]$, where L_G is the intensity of black body radiation (gas radiance) at temperature T_G, and τ is transmittance. The calculation can be done from the difference between transmitted intensity of environment at thermo-dynamic temperature T_V and intensity gas emission at temperature T_G. Transmittance correction as a function of concentration is conducted for usual experimental value $18K = \Delta T = T_V - T_G$ (i.e. ΔT must be known).

Theoretical value of total transmittance for different ΔT was experimentally tested in laboratory. One aluminum plate $8 \times 8\ \text{cm}^2$ with covering of highly emissive black paint, connected with Peltier element, was used as a target background. In front of this was placed thick gas cell (20 mm) filled with ammonia with concentration 20,000 ppm × m.

In the gas cell the constant temperature 294 K was maintained, while the temperature of target background was variable. The laboratory set introduces measurement uncertainty of several percent due to signal level variation detected by camera. Signal variation is the result of heat emission of camera, filter and telescope.

5. CONCLUSION

Infrared thermography as non-contact and non-destructive method which allows a real-time generating image has a wide application in industry. Real-time forming of harmful gases thermograms (for methane, ethylen, ammonia etc.) in working spaces has a goal to prevent explosions, eliminate fires and causing extensive damage. The method is passive - for gases detection it uses the natural heat radiation of environment and atmospheric transparence. Absorption, which is of interest for passive infrared thermography method occurs in visible or infrared spectrum part, so with spectrum analysis in these ranges we can obtain useful conclusions. Vibro-rotational spectra of hydrocarbons gas molecules in near (NIR) and middle (MIR) infrared range are suitable for detecting even lower gases concentrations at distances until 1.5 km.

This paper showed real-time visualization of harmful gas leakage using IR camera, and also a possibility to quantitatively monitor the harmful gas leakage. The technique relies on knowing precisely the temperature difference between the gas and the environment. The sensitivity of this technique is 200 ppm × m for ($\Delta T = 18\,\mathrm{K}$) at image frequency of 15 Hz. Time resolution of IR camera is $\Delta t = 66.66\,\mathrm{ms}$, i.e. 15 thermograms per second. The values of measurement uncertainties and restrictions during detection due to telescope imperfectness can be controlled by recording the IR image without the presence of the gas in the scene.

IR cameras working in the first atmospheric window are convenient for glass garden effect visualization, because they can be used for determining a gas concentration gradient. The gases which absorb IR radiation in the first atmospheric window influence the equilibrium of Sun-Earth radiation, which affects the temperature on the Earth. The technique is especially suitable at wave lengths of approximately 10 μm (the third atmospheric window) where the spectral radiance is maximal at all temperatures and the transparence of atmosphere is high.

Safety, economics and ecology aspects of environmental protection and preservation will surely, in times to come, place the passive IR thermography method to the very high place amongst suitable methods, when the chemical plants control and geology surroundings for leakage and high concentration of gases are considered.

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