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Applied acoustics in space

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Abstract: - Oxidative stress is a multifaceted issue and represents a social and health care problem because it affects many systems. The main objective of the present research is the development of a photoacoustic system with application in the assessment of astronaut's health by measuring ethylene as a specific gas for oxidative stress level. A new way to measure noninvasively oxidative stress in humans is to measure free radical damage by analyzing early by-products of oxidation like exhaled hydrocarbons. Infrared laser absorption spectroscopy is an extremely effective tool for the detection and quantification of molecular trace gases, with a demonstrated sensitivity ranging from parts-per-million to parts-per-trillion levels depending on the specific gas species and the detection method employed. The ethylene absorption spectra show the strongest absorption band near 10.5 µm compared with that at 1.6 µm and 3.3 µm. The recent availability of the compact mid-IR QCLs allows the access of the strongest absorption band. In this research, a tunable PAS experimental system based on a CO2 laser was proposed for detection of different gases. Relationships between the photoacoustic signal and gas pressure, laser power and ethylene gas concentration were measured and discussed in detail, respectively.

Key-Words: - acoustic measurements, photoacoustic, oxidative stress, astronauts, laser absorption spectroscopy, ethylene gas

1 Introduction

One of the great concerns of space travel is to find preventive measures to improve quality of astronaut's life. Space provides a hostile environment for humans due to radiation, microgravity, high vacuum, sub-magnetic field, ultra-clean environment, and micro-environmental factors inside spacecraft [1].

Astronauts are exposed to hazardous agent's solar radiation including chemical contaminants or low wavelength electromagnetic radiations (such as gamma rays) that can induce several physiological alterations, one of which is the induction of oxidative stress [2, 3].

Exposure to toxics, namely space radiation and microgravity, have crucial impacts on oxidative stress in living organisms, including the over production of free radicals and the decreased function of antioxidant defence systems.

Hazardous factors can split water to generate the hydroxyl radical, very reactive at the site of its formation, which can initiate chain reactions leading to lipid peroxidation [1-3].

These reactive oxygen species (ROS) are shown to react with the non-radical molecules, leading to oxidative damage of lipids, proteins and DNA, causing various diseases.

Evaluation of ethylene as a by-product of oxidative stress is mandatory to safeguard the well-being of future astronauts or crew members and to prevent the occurrence of future damages.

Ethylene ($CH_2{=}CH_2$) from the human breath is an indicator of oxidant stress and can be directly correlated to physiological events in the patients (or biochemical events surrounding lipid peroxidation).

The objective of the research consists in the development of the system with applications in the monitoring of oxidative stress at humans during the space missions. Such experimental setup can be realized using an innovative, sensitive trace gas detection platform based on photoacoustic spectroscopy (PAS) [4].

The PAS technique offers several practically important advantages, such as high trace gas detection sensitivity with a sensing module and a wide dynamic range.

The PAS can benefit also from using continuous wave infrared laser sources capable of emitting high optical power.

2 Method

The main objective of the research consists in the development of new system for monitoring of oxidative stress at humans during the space missions. Such instrument can be realized using an innovative, sensitive trace gas detection platform based on photoacoustic spectroscopy (PAS).

The PAS technique offers several practically important advantages, such as high trace gas detection sensitivity with a sensing module and a wide dynamic range. The PAS can benefit also from using continuous wave infrared laser sources capable of emitting high optical power.

The acoustic oscillations of gas in PAS, are excited in the resonator by a laser source and the photoacoustic signal V, is related to the gas concentration by:

$$V = \alpha\, C\, S_M P_L\, c \qquad (1)$$

where α is the absorption coefficient of the target gas sample which is related to the gas concentration and absorption cross section, C-the “cell constant”, depending on geometry, measurement conditions, and modulation frequency, S_M is the sensitivity of the microphone, P_L is the optical power of the laser excitation source; and c is the trace gas concentration (usually given in units of per cent, ppmV, ppbV or pptV).

The laser photoacoustic spectroscopy (LPAS) technique assures the advantages of health state assessment by monitoring the concentration of gases (from astronauts) that can be metabolized inside the organism with adverse effects on human health.

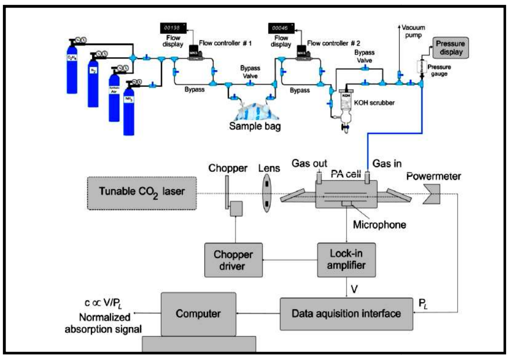

Fig 1. The LPAS configuration of the experimental set-up [4].

The LPAS system used as a lab-based (see figure 2) in the development of the new instrument has many important characteristics such as: can detect various gases including ethylene with a minimum of 0.9 ppb to 100 ppm; it is a “zero base line” method (no signal is generated in the absence of the absorbing molecules); the responsivity is independent of the wavelength of radiation; immune to interference; high sensitivity (able to measure gas concentrations at sub-ppb levels - partial pressure of 10^{-10}atm); a large dynamical range such as 7 orders of magnitude; real time analysis with quasi continuous measurements; operational simplicity [4-7].

3 Results

As illustrated in figure 2 of the ethylene absorption spectra (our available data results [5]), shows the strongest absorption band near 10.5 µm compared with that at 1.6 µm and 3.3 µm.

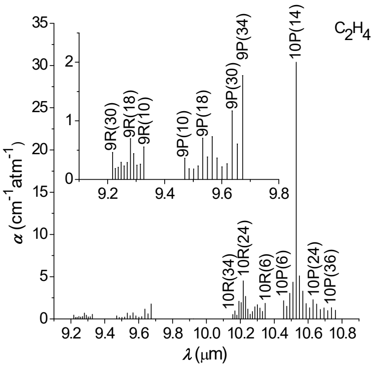

Fig 2. Absorption coefficients of ethylene at available CO_2 laser wavelengths. The inset shows an enlarged view of the measurements for the 9-µm band [5].

Recent availability of the compact mid-IR QCLs allows also the access of the strongest absorption band and the replacement of the available large size excitation source by a small size excitation source (see figure below).

Fig 3. (Left a) the home-built-frequency-stabilized CO_2 laser with the larger size; (Left b) the small size Quantum cascade laser; (Right) Cooling Unit for HHL packaged QCL size (WxHxD) 68x82x117 mm.

Available Quantum Cascade Lasers are able to properly access the strong ethylene feature near 10.5 µm and use Single Photon Continuum depopulation and Distributed Feedback (DFB) structures to emit mid-IR laser light under room temperature.

By controlling the operating temperature of the QCL through the Peltier element installed in the HHL package (see figure 3), it is possible to tune the emission wavelength without mode hopping while keeping longitudinal single mode operation.

A 10.5 µm DFB-QCL mounted in HHL housing were tested (see figure 4) as an excitation source (with a minimum output power of 20 mW).

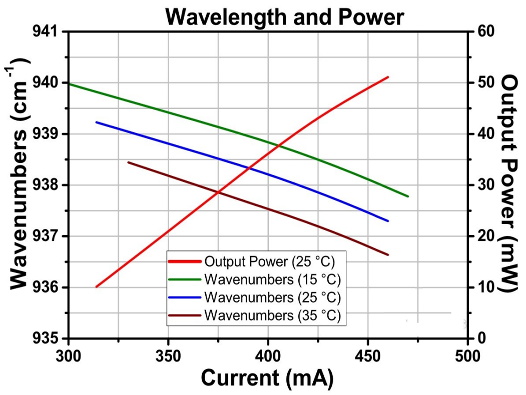

Fig 4. QCL Parameters.

In photoacoustic (PA) spectroscopy any absorbed radiation will be, in general, converted to thermal energy of the gas due to collisions thus leading to a modulated pressure detectable with a microphone. As any spectroscopic system, a PA detector presents the main advantage of being highly selective. To improve the sensitivity of the system, resonant cell schemes can be used, exploiting most of the time radial, azimuthally or longitudinal resonance of acoustic waves. Our sample photoacoustic cell the resonance is obtained by differential Helmholtz resonance. The heat produced in a photoacoustic cell by light absorption represents the source for acoustic waves.

4 Conclusion

Experimental investigations of different PAS set-ups are very time consuming and expensive. Addressing the related questions numerically is much more efficient. To detect low molecule concentrations one enhances the microphone signal by utilizing the acoustic resonances of the measuring chamber. The achievable amplification depends on the shape of the resonator and on the precise coupling of the laser profile and the acoustic modes.

The resulting instrument will be able to provide information on the oxidative stress of individuals, leading to a better understanding of the situation that can affect the balance of astronauts' body.

Assessing the level of oxidative stress would improve the operational safety and effectiveness of astronauts for long-term space flight.

Acknowledgments.

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