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New Optical Gas Sensor for Gas Concentration Measurement Using Digital Image Processing

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ABSTRACT

This paper proposes a new method for gas concentration measurement. The method relies on the principle of plasma emissions of gases under high voltage. We proposed a method that uses digital image processing to model the color mixing of the emissions of the gases. The application of the inverse model allows us to get the percentages of each gas in a mixture of up to four gases knowing already the color of emission of the whole mixture and the color of emission of each gas alone. Our proposed sensor has the advantages of high selectivity where it is not limited to a certain number of gases and is considered to be a good candidate for miniaturization.

1. Introduction

Gas sensors have plays a major role in many domains ranging from the industrial applications to environmental monitoring. In the past years many methods for gas detection and sensing have been developed but most with a high cost and specific to certain gases only [1]. In this paper we are trying to search for a new sensor which will be used to determine the concentration of each single gas in a mixture of previously known components. This sensor can be used to detect different kind of gases at the same time.

The sensor is based on the analyzing of the spectra of the emissions [2] of the studied gas; the emissions will be made by means of a gas discharge tube and captured through a CCD sensor. The images are then analyzed and processed to determine the concentration of each of the multi components in the mixture. The calibration of the color imaging sensor used in the experiment results in a great enhancement of the system.

The different approaches in gas sensing domain focus on sensors that measure either a certain type of gases or a limited number of them. The exceptions are gas analyzers like the gas chromatography [3], where it can detect many number of gases at the same time. However these analyzers are bulk, expensive, hard to use, and have a long response time.

In this paper we proposed a small, low cost with a relatively short response time sensor that is not limited to a certain gas rather to a wide range of gases and can determine the concentration of a group of gases (up to four) in a mixture.

2. State of the art

Gas sensing methods are wide and diverse due to the several physical and chemical effects that can be measured and reflect the gas characteristics [4]. Sensors like Metal Oxide Semi Conductor (MOS) gas sensors [5] are widely used in commercial sensors. Other new sensors like carbon nanotube based sensors [6] are relatively new. Optical methods in gases detection like ellipsometry, spectroscopy, interferometry and surface plasmon resonance (SPR) determine gas concentrations by measuring the refractive index, absorbance and fluorescence of the sensing material subjected to the gas [7]. The optical spectroscopy gives quantitative and qualitative information of gases, the emitted or absorbed electromagnetic radiation spectrum tells us about the concentration or the quantitative information, while the qualitative information is related to the wavelengths of the spectrum. Mainly three different techniques are used: atomic absorption spectrometry (AAS), optical emission spectrometry (OES) and atomic fluorescence spectrometry (AFS). These techniques are often used in chemical laboratories as analyzers, also they have been used in instruments

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for air pollutant measurements [8]. Small sized OES based sensor for exhaust emission has been reported [9] and another handheld micro system to analyze chemicals both in vapor and liquid phases using discharge spectroscopy was presented in [10].

The first optical gas sensors were based on the absorption spectrum difference measurement like the infrared IR gas detectors which have been in use for long time ago, they have long life time with greater stability over time. Their disadvantages are that they can only detect gases that are strongly absorbent in the infrared spectrum like hydrocarbons, they require a relatively large volume of gas for response testing and their ambient temperature is limited to 70 °C.

Optical spectroscopy gas detection techniques are rapid and often provide highly selective means of measuring gas concentration with good sensitivity they also have a good precision, their disadvantages are in being expensive and the measured gas must have a significant and distinct absorption, emission or scattering in a convenient region of the optical spectrum in order to be detectable [11]. Optical fiber based gas sensors offers some important advantages, their sides are coated with a fluorescent dye encapsulated in a polymer matrix, when interacted with gases the dye's optical properties such as intensity, spectrum, lifetime or wavelength shift in fluorescence are changed [12]. Optical fiber based gas sensors have small size and light weight, remotely operated, they have an electromagnetic immunity which enable them to work in high noise environment, and they are also passive devices and require no electric power in the sensing zone which makes them reliable in environments with flammable gases [13].

All of the previous methods relies on a high cost systems to analyze the spectrum of the emissions however in our proposed sensor we use the digital image processing to analyze the color of the emission that decrease the cost of the system in general and the overhead calculations and processing required.

3. Principle

The principle of our proposed sensor relies on the idea of optical gas emission under electric discharge. Simply saying, when an electric current is passed through a certain type of gas, the gas emits light. The color of the emitted light depends on the kind of the gas; so this color is considered as the gas identity. For example the color of Helium in the discharge tube is Pink.

The color of the emitted light is determined by the energy of the emitted photon. The energy of the light is related to its wavelength by the equation $E = hc/\lambda$, where λ is the wavelength, h is Planck's constant (6.63 × 10–34 J s), and c is the speed of light (3.00 × 108 m/s). Therefore, only certain wavelengths of light are emitted by gases in a discharge tube.

3.1. Spectrum addition of the emission of a mixture of two gases

Theoretically when two or more light sources are mixed, their spectral power distributions add and hence their intensities add. Let's consider the case of a mixture of two gases where it's under an electric field that causes the breakdown of the two gases that emit photons. Let $S_1(\lambda)$, $S_2(\lambda)$ be the spectrum of the emission of gas 1 and gas 2 respectively. Then theoretically the total spectrum S_T of the gas mixture will be the sum of the two spectrums:

$$S_T(\lambda) = S_1(\lambda) + S_2(\lambda)$$

The intensity of an emission of a certain gas depends on the number of photons emitted that depends on the density and temperature of the gas [14] and hence at constant temperature the intensity is proportional to the gas percentage in the mixture.

Consider the partial spectrum $S_T(\lambda)$ of a certain gas called i in a mixture of gases, where S_i represents the spectrum emitted by this gas i alone in the mixture. We consider that $S_i(\lambda)$ varies proportionally with the gas partial pressure p_i or its percentage in that mixture.

Let $S_{\text{Ref}}(\lambda)$ be the reference spectrum where it is the spectrum emitted by a certain gas at 100% concentration. Then we can consider the partial spectrum S_i to be:

$$S_i(\lambda) = p_i S_{\text{Ref}}(\lambda)$$

where p_i is the percentage of the Gas i in a mixture of gases that also corresponds to its partial pressure.

The total spectrum $S_T(\lambda)$ resulted from the mixing of two spectra $S_{p_1}(\lambda)$ and $S_{p_2}(\lambda)$ of two gases with different percentages will be:

$$S_T(\lambda) = S_{p_1}(\lambda) + S_{p_2}(\lambda)$$

$$S_T(\lambda) = p_1 S_1(\lambda) + p_2 S_2(\lambda) \tag{1}$$

where $S_i(\lambda)$ is the reference spectrum of the emission of Gas i.

3.2. Emission measurement

Measuring the gas electric discharge emissions with a spectrometer gives a detailed measurement at each wave length. However using imaging techniques gives less details at specific number of channels according to the type the imaging sensor. The trichromatic imaging sensor in the visible spectral region contains three channels x, y and z that gives integrated values describing the spectrum at three interlaced wavelength bands.

The response at any pixel of the imaging system sensor is:

$$x = \int_\lambda X(\lambda) S(\lambda)\, d\lambda$$

$$y = \int_\lambda Y(\lambda) S(\lambda)\, d\lambda$$

$$z = \int_\lambda Z(\lambda) S(\lambda) d\lambda$$

where $X(\lambda)$, $Y(\lambda)$ and $Z(\lambda)$ are the color matching functions of the sensor and λ is the wavelength in the visisble region [15].

Then the sensor's response to the emission of the mixture at channel x is:

$$x_T = \int_\lambda X(\lambda)((S_1 + S_2)(\lambda))\, d\lambda$$
$$x_T = \int_\lambda X(\lambda) S_1(\lambda) d\lambda + \int_\lambda X(\lambda) S_2(\lambda) d\lambda$$
$$x_T = x_1 + x_2$$

And the same apply for y and z channels:

$$x_T = x_1 + x_2$$

$$y_T = y_1 + y_2$$

$$z_T = z_1 + z_2$$

This is also known from Grassman's law [16] where in a trichromatic imaging system the matching between the spectrum and the three channels (x, y and z) is linear; that implies if we multiply the spectrum S of an emission with a constant and non negative number K the response on the three cannels is respectively K_x, K_y and K_z.