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Development of Fast-Response Portable NDIR Analyzer Using Semiconductor Devices

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In this paper, a novel fast response NDIR analyzer (FRNDIR), which uses an electrically pulsed semiconductor emitter and dual type PbSe detector for the PPM-level detection of carbon dioxide (CO_2) at a wavelength of 4.28 μm, is described. Modulation of conventional NDIR energy typically occurs at 1 to 20 Hz. To achieve real time high-speed measurement, the new analyzer employs a semiconductor light emitter that can be modulated by electrical chopping. Updated measurements are obtained every one millisecond. The detector has two independent lead selenide (PbSe) with IR band pass filters. Both the emitter accuracy and the detector sensitivity are increased by thermoelectric cooling of up to −20 degrees C in all semiconductor devices. Here we report the use of semiconductor devices to achieve improved performance such that these devices have potential application to CO_2 gas measurement and, in particular, the measurement of fast response CO_2 concentration at millisecond level.

Key Words : Fast-Response NDIR Analyzer(FRNDIR), CO_2 Concentration, Lead Selenide, Light Emitter, Dual Type Detector, Detector Sensitivity, Transit Time, Time Constant

Nomenclature

A_{vt} : Total cascade gain of the filter
α : The absorption efficiency (constant)
c : The concentration of CO_2 [%]
f : Cut off frequency [Hz]
F1 : Lowpass filtering −3db frequency [Hz]
F2 : Highpass filtering −3db frequency [Hz]
I : intensity [Volt]
I_0 : Initial intensity [Volt]
L : The optical path length (constant)
τ : Time [ms]
V_0 : Circuit output voltage [Volt]
V_{in} : Circuit input voltage [Volt]

Subscript

τ_t : Transit time [ms]
τ_{90-10} : Time constant [ms]

1. Introduction

While modern engines are generally capable of meeting emission legislation in steady state operating modes, future standards will require engine control strategies that significantly improve the emissions performance under transient conditions. The necessity of measuring engine emissions in real time in response to current and future legislation is well documented. The response to this has been the design and use of fast response analyzers for measuring unburned hydrocarbons, oxides of nitrogen and carbon diox-

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ide etc.(Collings and Willey, 1987 etc.)

The strong infrared absorption bands of a number of automobile exhaust gases, such as CO_2, NO_x and CO, lie in the spectral region beyond 5 μm, where the conventional method is to analyze gas concentration using the principle of non-dispersive infrared detection. Conventional exhaust gas analyzers are based upon non-dispersive infrared measuring techniques using a photo-acoustic detector with microphone. They have high accuracy under range in the parts per million to parts to billion range. However, the photo-acoustic detector is not suitable for fast response concentration analysis because the responsivity and sensitivity of a detector is dependent on chopping frequency.(Vincent, 1990)

Conventional NDIR instruments use the method which chops the light source with a very high frequency in order to eliminate long term drift and noise. It is common to equip the mechanical chopper with a high speed rotating wheel to modulate radiation in front of detector. Also, it is necessary to equip the detection system near the engine in order to minimize the response time. These demand a complex and bulky configuration.(Sutela et al., 1999 etc.)

Semiconductor lasers emit light through stimulated emission. As a result of the fundamental differences between spontaneous and stimulated emission, they are not only capable of emitting high powers ($\sim$100 mW), but also have other advantages related to the coherent nature of emitted light. A relatively narrow angular spread of the output beam compared with LEDs permits high coupling efficiency into the various applications. Furthermore, semiconductor lasers can be modulated directly at high frequencies (up to 25 GHz) because of a short recombination time associated with stimulated emission.(Agrawal, 2002)

Lead selenide (PbSe) detectors for temperatures below 300K operation offer a number of advantages, including high detectivity in the 4.0 μm range, high responsivity, and a short time constant. The PbSe detector is clearly superior to any of the other detectors over the range of 3.5 μm to 4.7 μm. In addition, the time constant of the ITO(intermediate-temperature-operation) PbSe detector decreases significantly as the temperature is reduced and the signal approaches the background limit. Therefore, the signal to noise ratio, sensitivity responsivity and detectivity of the semiconductor detector depends on operating temperature and can be improved by operating at lower temperature.(Johnson et al., 1965 etc.)

In this study, the development of a fast-response portable NDIR analyzer, which is composed with semiconductor infrared emitter, dual type PbSe detector, sampling equipments, and data analysis system is reported. Furthermore, the system response and the calibration of the analyzer are carried out and the performances of the system are illustrated.

2. Device Description

The analyzer is based upon the absorption of infrared radiation by CO_2 along the optical path. The system detects the transmission of the strongest C-O vibrational-rotational absorption band of CO_2 which is centered around a wavelength of 4.28 μm. The amount of radiation transmitted at given wavelength can be related to the spatially averaged concentration of CO_2 by the Beer-Lambert law :

$$I = I_o \times e^{-\alpha \times c \times L} \tag{1}$$

where I is the measured intensity of the radiation detected at a given wavelength in the 4.28 μm band, I_0 is the intensity of radiation detected with no CO_2 present, α is the absorption cross-section of the CO_2, C is the average CO_2 concentration, L is the optical path length. The sensitivity of I to small concentration changes is given by :

$$\frac{dI/I}{dc/c} = -\alpha \times c \times L \tag{2}$$

The maximum change in intensity results in the same change in detector resistance and, therefore, the maximum change of a concentration is obtained from the sensor. As optical path length increases, the sensitivity is increased. However, the length of sample cell as other consideration includes the limitation that has an effect on the time of gas exchange. The most important constraint is the response time of sensor that is limited by how quickly a change of sample gas in the chamber can be executed. A prototype-sampling module for this research is designed and applied at the limited condition.

Sampling parts - A schematic of the fast response CO_2 sensor developed is shown in Figure 1. The device includes a heated sample tube connecting the constant pressure camber and the sample cell. The temperatures of all devices are controlled and sample cell intersects an infrared radiation path. One of the factors limiting response time of NDIR analyzers is the time that it takes to exchange the gas in the sample cell. While sample cell must provide sufficient path length for sensitivity, the volume of the cell is minimized to construct the fast instrument. Therefore, the sample cell is designed with a volume of 0.05 cc as a compromise.

The constant pressure camber(CP chamber) and the sample cell are controlled to a pressure well below the minimum sampling pressure.

Optical part - The optical path begins with semiconductor light emitter set in front of thermoelectric cooler. The front face of emitter is a sapphire window, which has transmittance up to 85% under the range of 0.4~6.0 μm and is almost not influenced by water and vapor, and composes of one half of the sample cell. The infra-red emitter based on Pb halcohenide is intended to operate in the 2.0~5.0 μm spectral range. Characteristics of emitter are as a following ; Peak emission wavelength 4.2±0.2 μm, spectral full width at half maximum (FWHM) 0.75 μm, electrical chopping response speed(Max) 2.0 μs, emission power 300 μW at the 1 kHz frequency modulated and the 10% duty pulse. The light from emitter source was modulated electrically by chopped emitter power (on/off) using the designed electric circuit.

The other side of the cell is a simple sapphire window that leads to the detector. A photoconductive lead selenide dual (measurement and reference) type detector is chosen for its fast response and good sensitivity in the wavelengths of interest at moderate temperatures. The dual element detector consists of two photosensitive elements equipped with narrow band interference filter ; one filter is near the absorption band of CO_2 gas, the other one is far from the absorption band, mounted in the sealed metal-window of an anti-reflection coated $CaFe_2$ package.

Semiconductor devices have a miniature single stage thermoelectric cooler with thermistor. Sensitive dual detector elements with film filters are placed onto the cooling surface of the thermo-

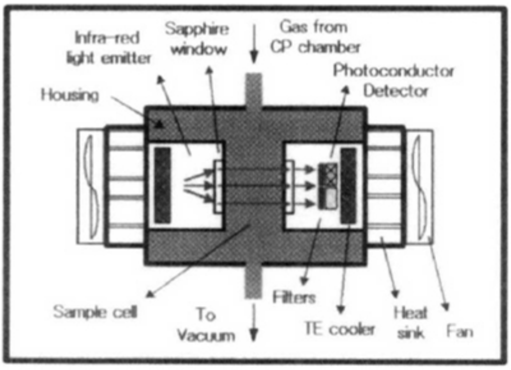

Fig. 1 Schematic diagram of fast response NDIR analyzer

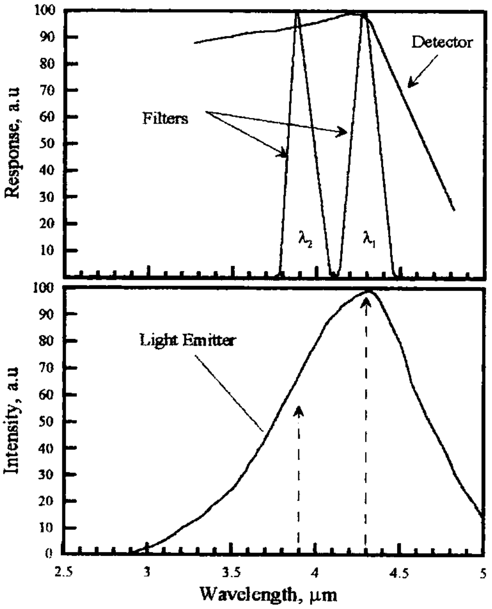

Fig. 2 Spectral responses of photo detector with narrow-band pass filters and light emitter

electric cooler and the thermistor is used for thermal stabilization. Figure 2 shows the optical characteristics which are applied to the developed analyzer.

3. Experiment Details

An experiment was set up to calibrate the detector, measure the system response and judge the compatibility as an analyzer for testing condition. The apparatus was designed to apply a step change in CO_2 concentration at the inlet of the NDIR sample system. This was accomplished by modifying a solenoid valve as shown in Figure 3.

The NDIR sampling tube was installed at the outlet of solenoid valve, just downstream of the valve needle seat. For this application, the response time of the solenoid valve should be as small as possible. A miniature valve(Parker General Valve) with the response time of 6 milliseconds was chosen for the study. This response time of the solenoid valve could be determined by measuring the current through the solenoid valve. Figure 4 shows the measured response time delay of the solenoid valve.

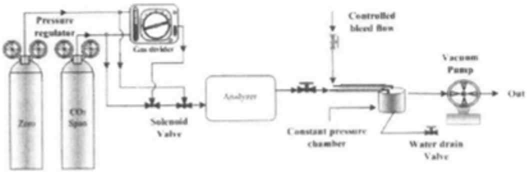

Fig. 3 Schematic diagram of test equipment for calibration and system response measurement of FRNDIR

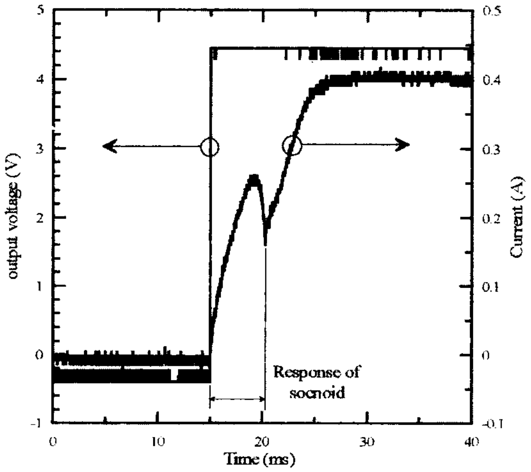

Fig. 4 Measurement about the response time of the solenoid valve

Calibration - Calibration was carried out with the inlet condition of a sample probe is at 1 atm. Using a vacuum pump, pressure drop across the sampling cell should be kept 0.5 bar. Because of such a pressure difference, N_2 and CO_2 gases can pass through the sample capillary tube. Calibration of the system is achieved by zeroing the instrument with N_2 and using the span gas of known CO_2 concentration controlled by a gas divider close to that in the sample to be analyzed.

A HORIBA Model SGD-710C gas divider was used to characterize the sensor response at 10 points known concentration of CO_2 between 0 and 20%. Before and after each set of tests, the characterization curve for the detector was generated using the gas divider. According to the Beer Larmbert law's assumption, the infrared absorption ratio is proportionately changed by a concentration change. However, it is a contradictory assumption on real conditions. The output signal of an analyzer is non-linear due to the contradiction. Therefore, the calibration and linearization of output signal is required. The calibration and linear characteristics for the system can be produced as compared with the output voltage of detector about the CO_2 concentration change.

System response - Figure 5 is the definition of system response that is illustrated by detector output signal and solenoid valve operating signal.

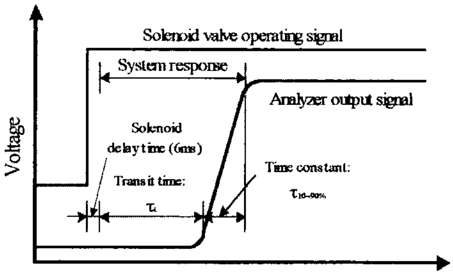

Fig. 5 Definition of characteristic transit time and time constant with the FRNDIR

Two important parameters of system response associated with operation of the analyzer are sample transit time and time constant. System response means the sum of transit time and time constant. The transit time refers to the elapsing time until the detector output signal reaches up to 10% of full scale plotted against the concentration of span gas, after operating a solenoid valve. Because dispersion happens when the CO_2 sample travels along the tube, the output of the detector takes a certain amount of time to change from zero to full value. In this paper, time constant (τ_{10-90}) is defined as the time for the signal to change from 10% to 90% of the full concentration value. Transit time (τ_t) is the time that sample transfers from the sampling point to 10% of the detector full output value.

Therefore, the output signal of analyzer from the initial operating point of solenoid is acquired at each point on real time, and the system response of a novel fast response NDIR is grasped from it

4. Signal Processing and Acquisition

The detector signal contains white, radiometric, and other noise of very small magnitude (μV ~ mV level). Therefore, signal reconstruction processing using hardware and software to increase the signal to noise ratio and improve acquisition of the significant detector signal are required. The signal reconstruction and the data analysis cycle are illustrated schematically in Figure 6.

Hardware processing - The individual detector signals are amplified using a differential amplifier to increase the signal to noise ratio. To further reduce the effect of this noise, the signal processing circuit employs a low noise amplifier, band pass filter, differential amplifier, and VCVS filters.

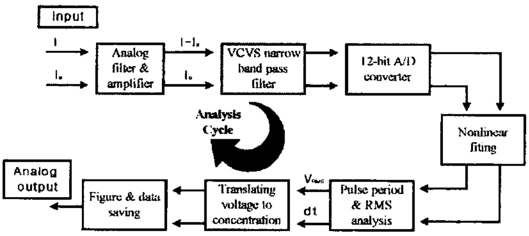

Fig. 6 Schematic diagram of the data reconstruction and analysis system used to determine CO_2 concentration from measured detector signal.

The gain of the overall VCVS bandpass filter within the passband is the product of the two individual gains(low pass and high pass): $A_{vt} = A_{vl} \cdot A_{vh}$. The gain magnitude term of this form of filter is found by

$$\left|\frac{V_0}{V_1}\right| = \frac{A_{VT}(f/F1)}{[(1+(f/F1)^2)(1+(f/F2)^2)]^{1/2}} \tag{3}$$

where V_0 is the output signal voltage, V_{in} the input signal voltage, f the applied frequency, F1 the lower −3dB point frequency, F2 the upper −3dB point frequency, and A_{vt} the total cascade gain of the filter. Detector signals that pass through hardware electric circuit are the sinusoid with frequency of light source modulated.

Software processing - An on-line data analysis system was developed to acquire and analyze the signals measured by the reference and measurement detector on real time. A personal computer (Pentium 4, 2.4G) served as a computational platform using Labview as the graphical programming language.

There are conventional two methods to convert

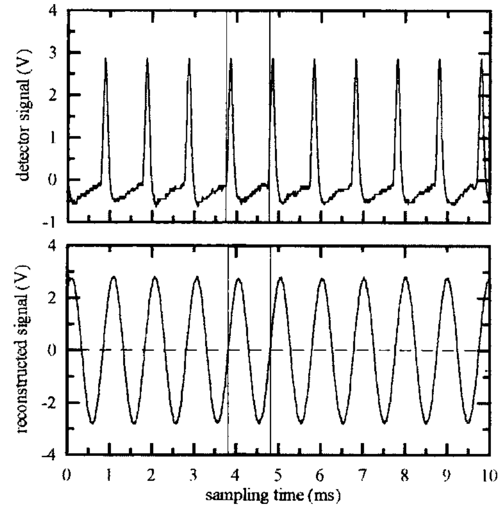

Fig. 7 Infrared emitting event prior to signal reconstruction (top) and after signal reconstruction (bottom) by hardware signal processing

the sinusoid to physical value, either peak-to-peak or RMS value measurement. Because the peak-to-peak measurement is not suitable to various frequency and noise conditions, we measure the cycle RMS value and calculate the cycle period of sinusoid signal.

The signal from a detector is indicated as the converted signal of 1kHz like Figure 7 obtained through the hardware signal reconstruction processing.

The RMS values measured from each cycle are converted into a concentration, and are represented with cycle period on X-Y chart.

5. Results and Discussion

The capacity of the signal processing system used in this work was checked in order to improve non-linearity about concentration changes through a calibration of the developed novel fast response NDIR analyzer system. Also, the characteristic of the time constant and the transit time was grasped by the experiment for a system response, which was considered to be the most important factor of developing the FRNDIR.

Figure 8 shows a calibration curve about the system that was developed by this work, in case of being linearly corresponded to the concentration with the cycle RMS value and the period of sinusoid obtained through hardware processing, and carrying out the signal reconstruction using the software processing including linearization step. The non-linear characteristic of signal can have effect on conversion to concentration as the factor of error increase, and it is unsuitable characteristic for the analyzer, because its resolution and accuracy can be fluctuated by the range of concentration change. The former shows exponential curve corresponding to a concentration, but the latter shows linearity within the maximum error range of ±1.35%FS. Through the results mentioned above, it was able to verify that the application of the signal processing system used in this work was adequate.

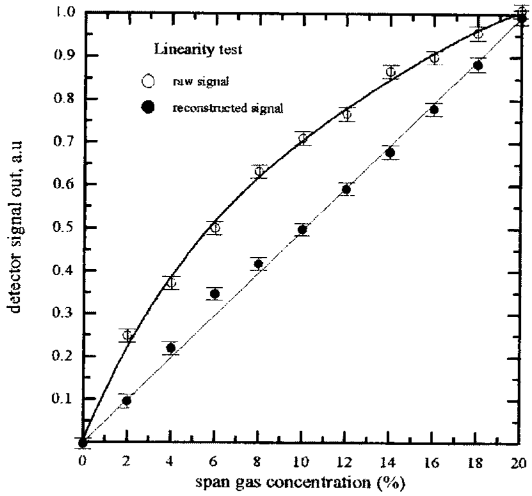

Fig. 8 Comparison of the calibration curve between linearization and non-linearization by software signal processing

Figure 9 shows the system response time of FRNDIR. The factors having influence on the system response were the sample gas conditions such as the pressure and temperature of sample gas, and the dimension of sample probe and a detection cell etc, but this experiment was performed on the condition that the pressure drop and the temperature of the sample gas were kept constant. If solenoid valve is operated while the span gas is supplied at a sample probe, the gases of the probe will exchange for the zero gas as shown in the top of Figure 9. Here, the transit time was about 7.5 ms, and the time constant was

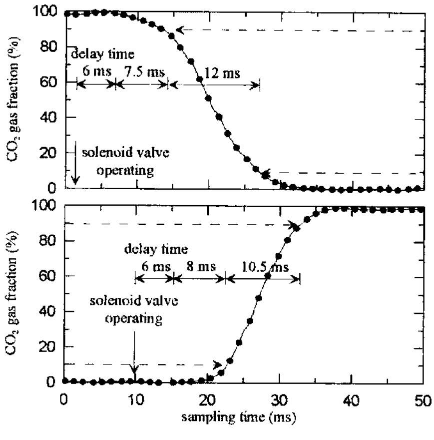

Fig. 9 Measurement of system response with operating solenoid valve at gas flow rate 2.5 l/min, $\Delta P = 0.5$ bar, span gas (CO_2) 20%, zero gas (N_2) 99.999%

about 12 ms. Therefore, system response (total) was about 19.5 ms. Likewise, if solenoid valve is operated while the zero gas is supplied at a sample prove, the gases of the prove will exchange for the span gas as shown in the bottom of Figure 9 as well. Here, the transit time was about 8 ms, and the time constant was about 10.5 ms. Therefore, system response (total) was about 18.5 ms. It should be possible to measure the cycle-by-cycle concentrations of engine, because FRNDIR was invented to grasp the characteristic of exhaust gas on transient conditions. If the engine (4-stroke) is operating at 6000 rpm max, the elapsing time per each cycle is 20 ms. Also, under the fuel economy test mode ruled by international standards (FTP-75, Euro-3, Highway), the elapsing time per a cycle is below 20 ms because the primary operating velocity interval of engine is 1000～3000 rpm. Therefore, the system response of an analyzer should be maintained below 20 ms to measure the cycle-by-cycle concentration, and total system response of FRNDIR developed by this work is 18.5～19.5 ms. That is, it is possible to measure the cycle-by-cycle concentration of the engine through the application of this instrument.

6. Conclusions

When a conventional NDIR analyzer used for the engine emission analysis was applied to the study on the transient conditions of engine and the cycle-by-cycle characteristics of combustion, the problems mentioned above occurred. In order to reduce these problems, a fast response portable NDIR analyzer using semiconductor devices has been developed.

Experiment results about the efficiency of a system and the application possibility in engine are as follows ;

(1) Fast (1 kHz) infrared chopping has been accomplished by using an electrical chopper with a semiconductor light emitter. It is found that an error about the frequency changes of a light source has been generated up to ±0.01%FS.

(2) The adequacy of a hardware and software instrument for processing output signal from a detector has been confirmed by comparing the calibration characteristic curves plotted against the CO_2 concentration.

(3) The transit time (τ_t), the elapsing period until a sample gas is reached to the optical cell, is acquired about 7.5～8 ms from the system response test. The time constant (τ_{90-10}) concerning a CO_2 concentration change (from 90 to 10) is shown 12 ms, and the opposite case (from 10 to 90) is shown 10.5 ms.

(4) FRNDIR is the instrument developed for the study on transient conditions of engine. The system response time concerning a concentration change of the instrument has been verified to be 18.5～19.5 ms, confirming that the instrument is able to study the cycle by cycle exhaust gas of engine operated at 6000 rpm max.

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