A Compact Optical Fiber Based Gas Sensing System for Carbon Dioxide Monitoring

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***Abstract*—This paper presents an approach to develop an optical fiber based gas leak sensor that can be used to detect and quantify carbon dioxide gas. The developed sensor system operates based on the principles of Infrared (IR) absorption spectroscopy using the dual channel and double wavelength method. Therefore, it is possible to eliminate the interference signal from the outside environment by using this method. The design of the Carbon Dioxide (CO_2) gas sensor system consists of a Broadband light source, two IR detectors with different Narrow Band Pass (NBP) filters for Active and Reference channel, chalcogenide infrared (CIR) fibers and a compact gas detection cell. The output of the sensor system is captured using in-house LabVIEW program with Data Acquisition (DAQ) capabilities and displayed in real time. Experimental results show that the developed optical fiber based gas sensor system is capable to detect and quantify concentrations of carbon dioxide gas for leak detection and also environmental monitoring applications.**

***Index Terms*—Carbon Dioxide Emission; Mid-Infrared Components; Optical Fiber Gas Sensor; Vehicle Exhaust System.**

I. Introduction

Carbon dioxide, a type of gas that cannot be seen, tasted or smelled, is one of the most common gases found in the atmosphere, and under normal condition, it is involved in the respiration process of animals and plants. The gas is also released into the atmosphere as a result of the combustion process of fossil fuels and from renewable fuels [1]. CO_2 gas, one of the greenhouse gases, when present in high concentration can contribute to the increase in the global temperature on the earth and in the sea, a phenomenon that is known as global warming. It has also been found that the burning of fossil fuels in energy, industry and transportation sectors is the largest source of carbon dioxide gas that contributes to the greenhouse effect, which has led to the increase of carbon dioxide gas emission into the atmosphere [2-3].

Many sectors currently produce high levels of carbon dioxide gas where the gas emission needs to be monitored. This is especially true with the industrial and domestic sectors and among one of the most prominent sources of carbon dioxide emission that needs monitoring is the exhaust emission from vehicle combustion engines [4]. The internal combustion process of fuel in vehicle engines produces various types of gases, which include carbon monoxide, carbon dioxide, oxides of sulphur and nitrogen, water vapor, smoke and particulate matters. Although CO_2 gas exists naturally in the atmosphere and is not considered a pollutant in normal condition, the excessive amount of the gas produced by road vehicles throughout the world has been considered as a major source and prime contributor to the global climate change [5]. Therefore, the development of a sensor technology, which can be used to monitor the emission of carbon dioxide gas direct from the exhaust engine of a vehicle, is vital. The output of the sensor can be used as a feedback into the engine controller unit which then can be used to control the internal combustion process, hence reducing the total carbon dioxide emission to comply with the set emission level of 95 g/km in the year 2020 [6].

Of the various types of gas sensors available for use by the automotive industry, lambda sensors are the most commonly used for monitoring of gas in exhaust systems. However, being electromechanical in nature, these sensors can exhibit some imperfections related to contamination and deposit build-up during long-term operation. As a result, the sensor has a much shorter lifetime compared to that of the motor vehicle on which it operates, and also additional pollution is produced due to the false signal emitted from the sensor. A number of similar conventional techniques have also been developed throughout the industry, and these include catalytic combustion sensors, field effect devices, semiconductor sensors and piezoelectric sensors [7]. Some of these conventional sensors offer possibilities for use as an exhaust gas monitoring sensor, selectivity is a major issue with all these sensors and a single gas sensor with minimal cross-sensitivity has not been achieved. In some situations, some accurate and sensitive dual-gas monitoring systems exist and could be used in the exhaust environment; these sensors still suffer from short life spans due to the ageing properties of the sensing technologies [8-9].

Previously developed gas sensor systems that are capable online measurements of carbon dioxide emissions from an automobile either suffer from selectivity issues or employ highly expensive radiation sources, optics and detectors. Thus there is no developed gas sensing system that is suitable for online measurements of carbon dioxide emissions within an exhaust system [10]. Hence, a working prototype of an optical based carbon dioxide gas sensor that utilizes economical mid-infrared components and can withstand the high temperature of the vehicle exhaust system is proposed in this paper. The sensor design is highly compact so as to allow the sensor to be fitted into the engine compartment of a vehicle for exhaust emission testing.

II. The Working Principle Of The Optical Fiber Based Carbon Dioxide Gas Sensor

The developed optical fiber based gas sensor works based on dual channel double wavelength detection method. The operation of the sensor is based on double wavelengths principle where it takes two signal channels from the detector outputs, one channel for the active output intensity due to the changes of the concentrations of the gas under study and another channel for the reference. The concentration of the gas presents in the gas detection cell is derived from the signal ratio between the Active channels to the Reference channel.

Figure 1 shows the graphical representation of Detector Output versus Time. It can be seen that there exist the relationship of the Active channel, Reference channel and the Signal Ratio of the outputs of the developed gas sensing system detector. The output intensity of the reference is measured at the wavelength of 3.95 µm where there is no significant absorption intensity of any gas. When there is an external interference such as vibration or movement of the input optical fiber or changes in term of input light intensity, the output signal is detected both at the Active channel and Reference channel. However, the Signal Ratio output will not be altered due to the external interference but significant change is observed with the CO_2 gas cloud. Therefore, it is possible to eliminate the external interference signal from the outside environment by using this method and maintained the CO_2 gas cloud as a baseline reference.

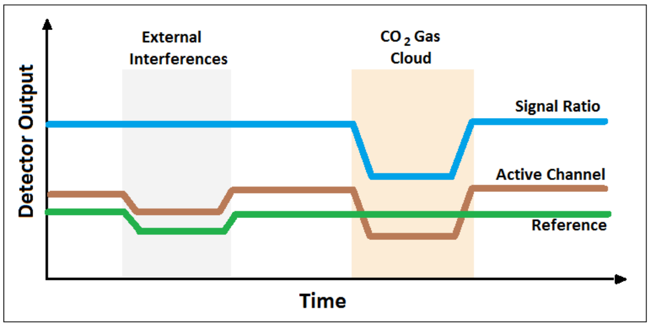

Figure 1: The relationship between the Active channel, Reference channel and the Signal Ratio of the outputs of the developed gas sensing system.

III. Experimental Setup

Figure 2 shows the initial experimental setup of the designed and developed optical fiber based carbon dioxide gas sensor system used in this study. It consists of Nitrogen and CO_2 gas supply, IR source, gas detection cell, Quintox Gas Analyzer, CIR fiber, main and reference detector and DAQ complete with computer and LabView software installed. The main objectives of the initial test are to ensure that all configured settings of the sensor system work and function as intended, and the sensor is capable of detecting and measuring quantitatively the presence of carbon dioxide gas in the gas detection cell.

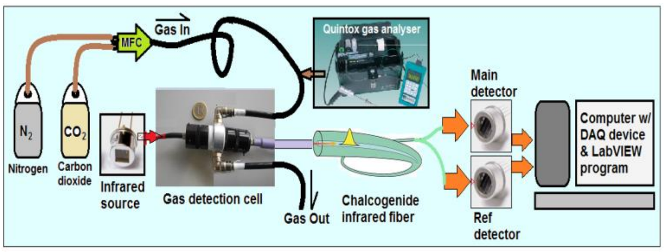

Figure 2: The experimental setup of the developed mid-infrared optical fiber-based gas sensor system.

A broadband infrared radiation signal with a wavelength range between 2.0 µm to 20.0 µm and pulsed modulated at the 1-Hz frequency is transmitted from an infrared light emitter into the gas detection cell via a multimode chalcogenide infrared optical fiber of 1-meter length. The infrared light emitter is supplied with a 2.2V square wave signal at 50 % duty cycle from a signal generator as suggested by the manufacturer. After the interaction process between the infrared signal and the gas under study occurs in the detection cell, the infrared signal is then transmitted to the infrared pyroelectric detectors via another multimode CIR fiber of similar length of 1-meter. Two different detectors are used in the system setup. The main detector is fitted with a carbon dioxide sensitive optical filter and whereas the second detector is fitted with a reference optical filter. The digitized output voltage data from the pyroelectric detectors is captured using a National Instrument PCI- 6013 DAQ device and a custom-designed virtual instrument developed using LabVIEW software before the data is input into the computer for later manipulation and analysis.

IV. Result and Discussion

The objective of the experimental test is to compare and confirm the theoretical analysis with the results obtained from the laboratory measurements. This comparison process is very important in order to confirm that the output results obtained from the developed gas sensor system are correct and reliable. Additionally, the output readings from the sensor system are also compared with reference measurements using a conventional and commercially available Quintox Gas Analyzer. If the output from the developed gas sensor is comparable to the output from the conventional commercial gas sensor, then it can be concluded that the developed gas sensor system is capable of detecting and measuring the presence of carbon dioxide in the environment.

A. Stability Test of Sensor Output

The operation of the developed optical fibre based gas sensor in this study is based on the principles of mid-infrared absorption spectroscopy. Generally, the absorption output intensity of carbon dioxide gas is measured for each given value of the concentration of the gas. The Active channel of the developed sensor system operates at a central wavelength of 4.23 µm where the characteristic absorption wavelength of CO_2 gas exists in the spectroscopic wavelength spectrum. The result of the Stability Test is as shown in Figure 3. The same figure also shows that the outputs of the sensor system remain relatively stable when the optical fiber based sensor system was operated for long-term operation (over 12- hours duration) when there are no changes to the concentration of the gas.

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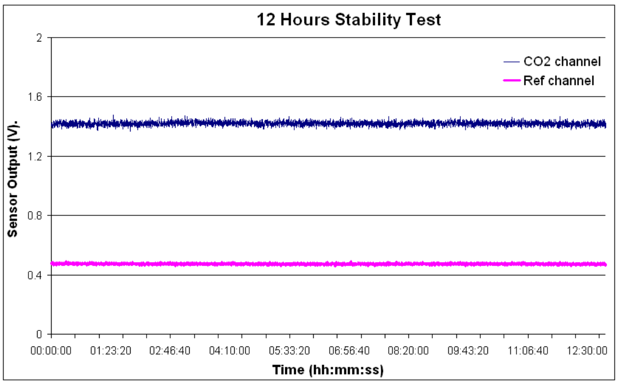

Figure 3: The result of the Stability Test for long-term operation (over 12-hours duration).

Figure 4 shows the actual measurement results of the developed gas sensing system for this study. The gas sensing system was set up in the laboratory as shown in Figure 1 previously. When the gas sensing system is active, carbon dioxide gas at 8% concentration is released into the gas detection cell, resulting in a sharp decrease in both the Active Gas detector as well as the Signal Ratio. However, the Reference signal is still maintained unchanged.

After a duration of 1-minutes, the flow of carbon dioxide gas is shut off, but the flow of Nitrogen gas is still allowed to flow resulting the in the flushing process of CO_2 gas from the gas detection cell, thus the reading detector output for Active channel quickly rises to the original level together with the Signal Ratio. However, in both case, the detector output from Reference channel is unchanged. This clearly shows that the change of concentration of the gas under study is effectively detected by this sensor system by changes in the Active channel. Besides, by using dual channel Ratio Signal, the sensor is capable to eliminate the noise signal from external sources that affect the reading of the developed optical fiber based gas sensing system.

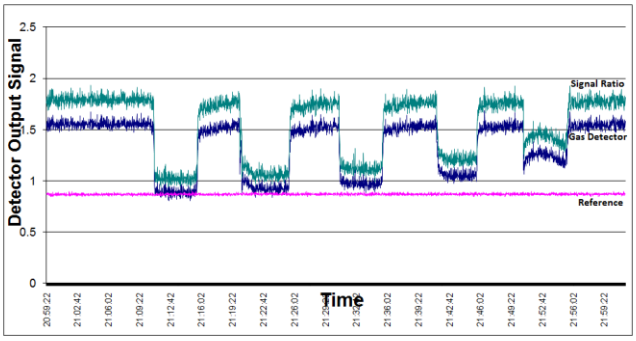

Figure 4: The relationship of the active channel, reference channel and the signal ratio.

B. *Repeatability Testing*

Repeatability test of measurement result which also known as precision is the ability to show same or similar result for repeated measurements or calculations of the same quantity. Repeatability test is vital for a novel or newly developed gas sensing system as it provides certain reliability level to the measurement results when the same input to the sensor system in certain initial condition can give the same expected results when measured at different time or location.

For the Repeatability Test, the developed gas sensor system is set up in the laboratory similar to the previous set up as shown in Figure 2. For this test, the gas concentration of carbon dioxide is set to flow constantly into the gas detection cell at 4.5% (45,000ppm). This concentration is achieved by setting the Mass Flow Controller 2 (MFC2) which controls the flow of CO_2 gas to open at 6.1% Full while allowing the MFC 1 which control the flow of Nitrogen gas to open at 100% Full Scale. This combination of MFC1 and MFC 2 percentage valve openings will result in 4.5% concentration of CO_2 gas will flow. The concentrations of the gas entering the detection cell of the sensor system are monitored simultaneously by using a Quintox commercial gas analyzer as a comparison to the output readings of the optical fiber based gas sensor.

Figure 5 shows the outputs of the developed optical fiber based gas sensing system to a constant concentration of the gas under study in the gas detection cell during the Repeatability Test of the sensor system. As the gas flows steadily at a controlled 4.5% concentration throughout the duration of the test, the LabVIEW program is tasked to make each measurement reading at every 10-minute intervals for the duration of 2 hours 30 minutes.

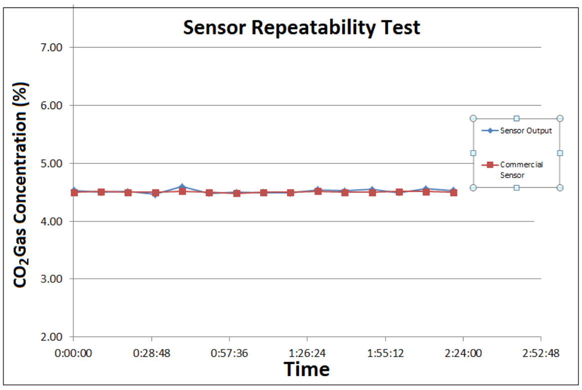

Figure 5: The results of developed optical fiber based gas sensor repeatability test.

This paper presents the experimental outputs of the developed optical fiber based carbon dioxide gas sensor framework. An optical-fiber-based gas sensor system with the capacity to detect and measure carbon dioxide gas discharged from engine vehicles has been produced. The basic role of building up the sensor system, which depends on point sensor setup, is to be utilized as a part of the car industry. The developed sensor framework which works in principle of double channel twofold wavelength detection technique, being cost-effective and robust in design, can be introduced and worked in the exhaust arrangement of an engine vehicle regardless of the extreme and high temperatures and confined space accessible in the car exhaust system.

V. Conclusion

We have successfully presented a reliability of optical fiber CO_2 gas sensor setup towards initiating a prototype of the compact, robust and cost-effective framework that can detect the concentration of CO_2 emission for the vehicle exhaust system under testing. The primary results exhibit its capability in reproducing the CO_2 concentration, in comparison with the recorded readings by the commercial gas analyzer. The carbon dioxide gas sensor can measure the concentration within the range of 2% to 15% gas concentrations and is capable of withstanding the harsh environment inside the vehicle exhaust system. However, more field tests need to be carried out in the future in a variety of conditions to find out whether the designed sensor can give out steady performance over a long period of time and possesses adequate life expectancy.

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