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Acoustic CO_2 Gas Sensor Based on Phase Difference Measurement

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Abstract: In this research, an acoustic sensor has been successfully built to measure the concentration of CO_2 gas in a mixture of gases (N_2 and CO_2). The nitrogen and carbon dioxide gases used are ultra-high purity (UHP) gas. The measurement parameter used is the speed of sound by utilizing the phase shift between ultrasonic wave signals that are sent and received continuously. The acoustic method in this research is by using the speaker as an ultrasonic wave transmitter, and the microphone as an ultrasonic wave receiver emitted by the speaker on the gas medium. This acoustic phase shift method is very sensitive to be used to determine the speed of sound on a gas medium. From the sensor testing, the sensor has good linearity in detecting changes in CO_2 concentration in the gas mixture. The sensor test results have been validated theoretically and obtained an RMS error of 3.36 (3.36% with a maximum concentration of 100%), this proves that the work of the sensor is in accordance with the theory. In addition to theoretical validation, the work of the sensor has also been validated by looking at the direct relationship between sensor input and output through the inverse function, and an RMS error of 3.51 (3.51% with a maximum concentration of 100%) is obtained. From the overall results obtained, the acoustic CO_2 gas sensor that is built can detect changes in CO_2 concentrations in the gas mixture accurately, fabrication of the sensor is easy to do, and the costs required in the manufacturing process are cheap.

Keywords: *Acoustic gas sensor, CO_2 concentration, phase difference*

Introduction

CO_2 is a molecule consisting of two oxygen atoms bound to one carbon atom, which has a molecular weight of 44 grams/mol. CO_2 can be solid, liquid or gas depending on temperature [1]. Some CO2-producing sources include natural sources such as respiration, the decay of animals and plants, fires, volcanic activity, while anthropogenic sources include burning fossil fuels, industrial activities such as the cement industry and the ammonia industry, natural gas processing, etc [2], and other sources are human who indirectly produces CO_2, where all human activities produce 70 million tons of CO_2 into the atmosphere each day [3].

CO_2 is a greenhouse gas whose concentration is the most after water vapor. From the pre-industrial era, CO_2 concentrations increased by 30% resulting in the average temperature of the earth increasing and affecting climate and ecosystems [4]. Data from the Mauna Loa Observatory of Hawaii (NOAA) reports that in July 2019, the concentration of CO_2 gas in the atmosphere approached 411.77 ppm [5].

The CO_2 gas is safe in low concentrations (usually <1,000 ppm), but prolonged exposure to moderate levels (> 5,000 ppm) can cause various health problems such as sick building syndrome which causes symptoms such as fatigue [6]

CO_2 sensors are needed for optimal control of indoor air quality (IAQ) [7], [8] and CO_2 sensors are used to reduce energy use in heating, ventilation and air conditioning systems (HVAC) [9]. In addition, the measurement and monitoring of CO_2 concentrations are also important for various fields, including in the industrial sector, in the health sector, and in the chemical analysis [10].

Gas sensors used for CO_2 detection typically use various methods, including electrochemical (EC), infrared (IR), gas chromatographic (GC), and mass spectrometer (MS) methods [11]. At this time the detection of CO_2 by the acoustic method is also increasingly being used and developed. In addition, measurement methods by detecting thermal conductivity have also been tested for CO_2 detection [12]. In this study, acoustic methods are used to detect CO_2 concentrations in gas mixtures.

Acoustic methods can also be used as a solution to overcome the weakness of sensors with chemical methods including problems of short of lifetime [13], because the acoustic method has the advantages of long lifetime, easy manufacturing technology, and low production costs [14]. In this acoustic method, there are 3 categories of measurement parameters commonly used including sound speed, damping, and acoustic impedance. The sound velocity parameter can be used to determine a particular type of gas with a different sound speed than other gases in the gas mixture [15]. In addition to determining the type of gas, the sound speed parameter can be used to determine gas concentration based on mathematical calculations that are proportional to the difference in sound propagation time [16], and the speed of sound can also be used to calculate the molar mass composition of a gas in a gas mixture based on thermodynamic equations [17]

In this study, the parameter used as a reference for determining the concentration of CO_2 in a gas mixture is the speed of sound, by utilizing phase shifts between ultrasonic wave signals that are transmitted and received continuously. The phase difference between the sent and received ultrasonic wave signals is a function of the speed of sound [18]. In the gas mixture analysis, the sound velocity information obtained makes it possible to determine the percentage of gas composition in the gas mixture [19]. The acoustic method in this research is by using the speaker as an ultrasonic wave transmitter, and the microphone as an ultrasonic wave receiver emitted by the speaker on the gas medium. This acoustic phase shift method is very sensitive to be used to determine the speed of sound on a gas medium. This phase shift is obtained by measuring the phase difference between the transmitted and received waves, where the phase difference between waves is a function of the speed of sound [20].

Method

The design of the sensor can be seen in Figure 1, where the sensor consists of two aluminum tubes with a length of 40cm with a diameter of 2.5 cm, the two tubes are thermally connected. Detection of CO_2 gas in a gas mixture using two pairs of speakers and microphone, where a pair of speakers and a microphone function to detect carrier gas (N_2), and another pair of speakers and microphone function to detect mixed gas (N_2 and CO_2). The sensor is designed to work in the ultrasonic frequency area (25kHz) because at the 25kHz frequency the microphone can work optimally.

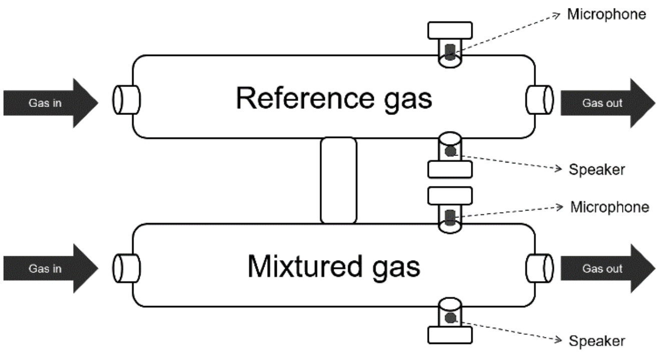

Figure 1. The design of sensor

Both speakers are supplied using a frequency generator with identical frequency and amplitude. Ultrasonic waves emitted by the speaker will be captured by the microphone, where the phase of the wave captured by both microphones will be shown on the oscilloscope. The concentration of gas in the tube will effect the phase value of the ultrasonic wave caught by the microphone. In the diagram, the measurement setup of the sensor can be seen in Figure 2.

As explained earlier, the phase difference between the signals sent and received is a function of the speed of sound. This method can be used to measure the speed of sound on the length of a small path that can have a length as short as one wavelength [18].

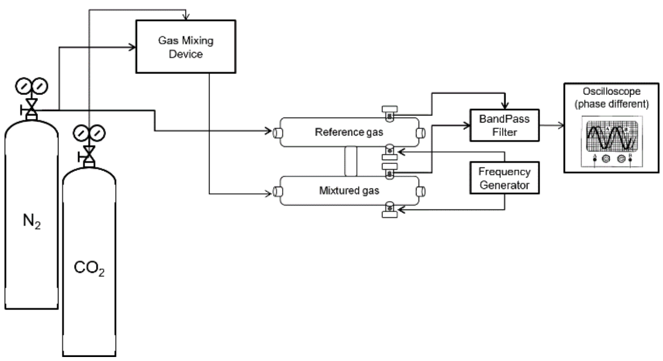

Figure 2. The mechanical setup of sensor

The relationship between ultrasonic wave speed and the phase difference of two signals from the microphone [20] can be seen in the following equation:

$$v = \frac{2\pi f d}{\emptyset} \quad \text{Eq.(1)}$$

where d is the distance between the speaker and the microphone, f is the ultrasonic frequency used and $\emptyset$ is the phase difference of the wave emitted by the speaker and the wave received by the microphone.

In the experiments to be carried out, the phase difference obtained is the phase difference between the ultrasonic waves captured by microphone-1 ($\emptyset_1$) and microphone-2 ($\emptyset_2$). Based on the value of the phase difference, the ultrasonic wave velocity in the gas mixture can be determined assuming the ultrasonic wave velocity value of the reference gas is fixed. The ultrasonic wave velocity at the gas reference (N2) can be calculated using the following equation,

$$v_{N2} = \frac{2\pi f d}{\emptyset_1} \quad \text{Eq.(2)}$$

where $\emptyset_1$ is the phase difference between the speaker and microphone that detects the gas reference (N_2).

In gas mixtures, ultrasonic wave velocity can be calculated using the following equation,

$$v_{N2} = \frac{2\pi f d}{\emptyset_1} \quad \text{Eq.(3)}$$

where $\emptyset_2$ is the phase difference between the speaker and the microphone that detects the mixture of gases.

Based on Eq.(2) and Eq. (3), the relationship between the microphone-1 and microphone-2 phase differences with the ultrasonic wave velocity in the gas mixture can be seen in the following equation,

$$\emptyset_1 = \frac{2\pi f d}{v_{N_2}}$$

$$\emptyset_2 = \frac{2\pi f d}{v_{mix}}$$

$$\phi_1 - \phi_2 = \frac{2\pi f d}{v_{N_2}} - \frac{2\pi f d}{v_{mix}} \quad \text{Eq.(4)}$$

Based on Eq.(4), ultrasonic wave velocity values can be obtained based on experimental results. This result will be validated by the equation commonly used to determine the speed of sound in a gas mixture that can be seen in the equation:

$$v_o^{\,2} = R_o T \frac{\sum_{i=1}^{n} x_i C_{pi}}{\sum_{i=1}^{n} x_i M_i \sum_{i=1}^{n} x_i (C_{pi} - R_o)} \quad \text{Eq.(5)}$$

where R_o is the universal gas constant, absolute temperature T, x_i the mole fraction of component i, M_i is the molecular weight and C_{pi} the heat capacity at constant pressure [19].

Results And Discussion

Figure 3 shows the sensor response in phase difference due to changes in CO_2 gas concentration. Experimental, phase difference can be obtained by measuring the phase difference between sound waves detected by the two microphones on an oscilloscope. Theoretically, the phase difference can be obtained by using equation Eq.(4).

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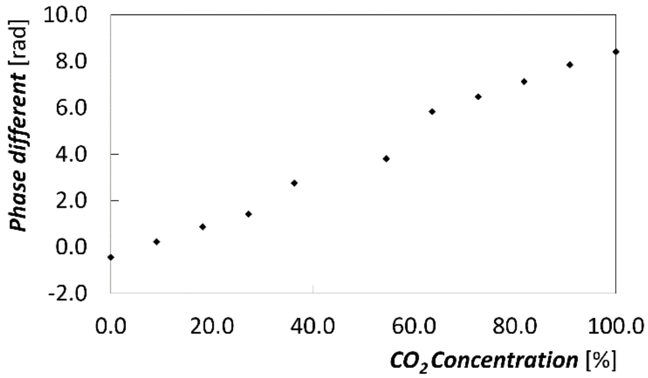

Figure 3. The sensor response in the form of phase difference due to changes in carbon dioxide concentration

In equation (4), the calculation requires the value of the ultrasonic wave velocity on the gas medium used. The ultrasonic wave velocity values in the gas mixture calculated based on equation (5) can be seen in Figure 4.

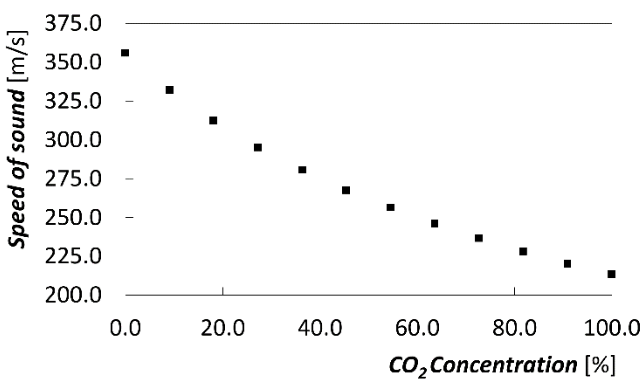

Figure 4. The Ultrasonic Wave Speed Values in Gas Mixes based on Experimental Data

From Figure 6, it can get the equation of the relationship between the phase difference and the CO_2 concentration, can be written with the following equation:

$$CO_2Concentration = 10,509\Delta\emptyset + 8,0558 \quad \text{Eq.(6)}$$

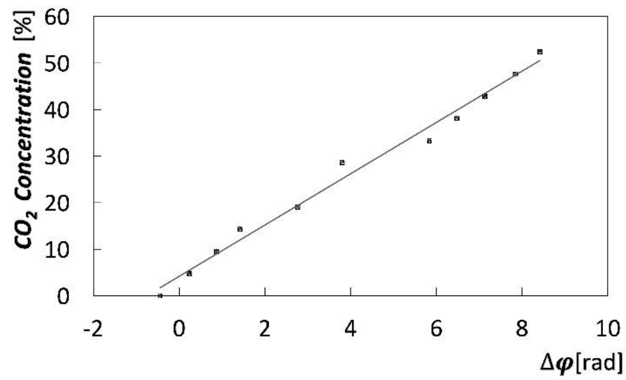

Figure 6. The inverse function is the relationship between sensor test input and output with the acoustic method

The validation results obtained from equation (6) by comparing the value of the CO_2 concentration obtained from the test results with the actual value of the CO_2 concentration, obtained an error of RMS for the detection of CO_2 concentrations using acoustic method of 3.51. Based on the value of inaccuracies (errors) from sensor measurements with the relatively small acoustic method, it can be said that the sensors built can work well in detecting CO_2 gas concentration.

The stability of the sensor measurements by this acoustic method is determined from repeated experiments of five times with the same measurement conditions. From the five experiments that have been carried out, it can be seen in Table 1, that the maximum standard deviation of the sensor measurement is 3.82×10^{-3} mV at 9.09% CO_2. With a standard deviation value of the sensor below 3.82×10^{-3} mV, it can be said that the sensor has a good level of precision and stability.

Table 1 Experimental data for five repetitions (testing using the acoustic method)

CO_2 (%)	Phase Difference (rad)					δx ($\times 10^{-3}$)
	Exp.1	Exp.2	Exp. 3	Exp.4	Exp. 5	
0.00	-0.443	-0.440	-0.440	-0.443	-0.443	1.912
9.09	0.227	0.234	0.227	0.234	0.234	3.824
18.18	0.867	0.871	0.871	0.867	0.874	2.920
27.27	1.415	1.417	1.415	1.419	1.417	1.460
36.36	2.761	2.765	2.759	2.761	2.763	1.990
54.55	3.800	3.803	3.798	3.800	3.794	3.171
63.64	5.831	5.833	5.835	5.835	5.836	1.990
72.73	6.479	6.477	6.480	6.477	6.484	2.920
81.82	7.133	7.131	7.135	7.131	7.128	2.589
90.91	7.847	7.842	7.847	7.849	7.847	2.647
100.00	8.412	8.411	8.409	8.412	8.414	1.990

Conclusions

The presented method of CO_2 concentration detection is based on the measurement of the phase difference between the sent and received ultrasonic waves continuously. The sensor has been successfully to measure the concentration of CO_2 gas in a mixture of gases (N_2 and CO_2). The nitrogen and carbon dioxide gases used are ultra-high purity (UHP) gas. In the measurement system, the sensor consists of the speaker transmits the ultrasonic wave, and the microphone receives that ultrasonic wave in gas. The sensor test results have been validated theoretically and obtained an RMS error of 3.36 (3.36% with a maximum concentration of 100%), this proves that the work of the sensor is in accordance with the theory. In addition to theoretical validation, the work of the sensor has also been validated by looking at the direct relationship between sensor input and output through the inverse function, and an RMS error of 3.51 (3.51% with a maximum concentration of 100%) is obtained. From the overall results obtained, the acoustic CO_2 gas sensor that is built can detect changes in CO_2 concentrations in the gas mixture accurately, fabrication of the sensor is easy to do, and the costs required in the manufacturing process are cheap.

Conflicts of interest

There are no conflicts to declare.

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