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Development of a low-cost NDIR system for ppm detection of carbon dioxide in exhaled breath analysis

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Abstract

The composition of exhaled breath contains important information regarding the health of our body. Measurements of the level of exhaled carbon dioxide can help both diagnose respiratory diseases and determine metabolic rate. A low-cost NDIR sensor has been developed that offers the detection of CO_2 from the ppm range up to 5% level in human breath. An innovative lock-in amplifier system allows a 10Hz drive signal to be recovered from the high frequency noise associated with a silicon thermopile infra-red detector. Laboratory experiments have demonstrated excellent stability (±0.10% in 25% RH) and repeatability between dry and humid conditions (±1.2% for 25% humidity increase). The response time is typically 2.4s, limited by the low drive frequency necessary for the MEMS-based wideband infra-red source. The current system has a resolution of ca. 10ppm of CO_2. Further refinement in signal processing and a higher drive frequency should permit even lower concentrations of CO_2 to be detected with an ultimate target of 1 ppm. Existing performance has been shown to be suitable for breath analysis using a side-stream analyser.

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Keywords: CO_2; NDIR; breath analysis; side-stream; ppm detection; human metabolism; respiratory disease diagnosis.

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1. Introduction

The concentration of carbon dioxide in exhaled breath can aid the diagnosis of respiratory diseases and offer a non-invasive insight into the health of a human body. In clinical care, capnographs and metabolic rate analysers use exhaled CO_2 levels to inform practitioners about the health of a person. However the current generation of commercial devices

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are expensive and are usually restricted to application in a clinical practice. Our prototype CO_2 device presented here, targets a low-cost solution for the analysis of exhaled CO_2; results can be presented in an easy to read format, such as on a smartphone or laptop computer. Breath-by-breath measurements of CO_2 require a sensor with a high dynamic response and robustness to high levels of humidity. Accurate determination of the metabolic rate, from a breath sample, requires known volumes of CO_2 produced and of O_2 consumed. Differential measurements, between environmental conditions inhaled and the gases exhaled are needed for accurate prediction.

The gas sensors will be exposed to fluctuating levels of humidity, temperature and flow rate as successive measurements of both inhalations and exhalations are recorded. Exhaled breath is known to contain volatile organic compounds (VOCs) to which the CO_2 sensor must be insensitive. Non-Dispersive Infrared (NDIR) sensors can offer response times required for the analysis of an exhalation with selectivity to the target gas. Our breath sensor developed has been tested over a range of gas concentrations expected in an exhalation. A lock-in amplifier system has been employed to recover the response to CO_2 from the noise present in the raw IR thermopile detector output. The design presented is limited to a lower drive frequency; higher drive frequencies are desired for faster response and removal of low frequency noise. The sensor has been tested in both dry and gases containing 25 % RH.

1.1. Background

NDIR sensors respond linearly to the concentration of a specific gas because the IR radiation produced by the source emitter is absorbed by the gas between the IR source and detector. Utilization of different absorption bands in the IR spectra allows the sensor to be specific to a desired gas. CO_2 strongly absorbs IR radiation at a wavelength of 4.3 µm [1]. Exhaled breath also contains VOCs and other gases which are also absorbed by infrared, such as carbon monoxide, but at ppb to ppm levels. The IR path length between the source and detector dictates the gas concentration the sensor is able to detect; the relationship is described by Beer's law. A longer optical path provides a greater distance for the gas to be absorbed with the signal falling exponentially. Consequently, a larger differential response is produced, allowing lower gas concentrations to be distinguished.

Measurements of exhaled human breath, at an elevated temperature (~ 36 °c) and extreme levels of humidity (near complete water saturation [2]) compared to ambient room conditions, require sensors insensitive to changes in environmental conditions. Furthermore, the sensor needs to capture a short exhale, of perhaps 3 seconds. Our goal here is to calculate the daily energy expenditure (EE) of a subject to 1% accuracy, based on measurements of metabolic rate over a 24 hour period. Data recorded from prior experiments in respiratory chambers demonstrated the concentration of CO_2 exhaled must be measured to within an accuracy of 1.2 %. Motivation to develop a breath analyser stems from both the needs of critically ill patients, and the economic impact of an obese population. Recovery times of ill patients may be affected by their calorific intake, which is often estimated.

Silicon thermopile IR detectors are very sensitive to changes in ambient temperature and are susceptible to noise pick-up from the environment because of the low currents generated. A lock-in amplifier has been developed to extract the response to CO_2, based on a drive signal from the IR source. The frequency extraction process enabled a fast sensor response as high order filters were not required. Capnographs and metabolic carts allow measurements of exhaled CO_2, however are not suitable for routine use in the community. Commercial CO_2 sensors are available that meet the needs of breath analysis [3]; however we report on a novel sensor that is low cost, physically small and has a fast response time and low power consumption.

1.2. Methodology

Our NDIR system comprises a wideband IR micro-hotplate source (CCS102, Cambridge CMOS Sensors Ltd, UK) with a silicon thermopile detector (J21, Heimann Sensor, Germany). A 4.3 µm IR filter (180 nm bandwidth) was employed to detect CO_2 to be detected but to minimize the cross-sensitivity to other gases such as CO and water vapour. The sensors were housed in a custom stainless steel chamber (Fig. 1) with adjustable path length between 40 mm and 80 mm. The system was tested to concentrations of CO_2 between 5 % and 50 ppm, in conditions of either dry gases or 25 % RH. Gas mixtures, between synthetic air and CO_2 were created on a gas testing rig, controlled via a LabVIEW interface (National Instruments, v2014). The system is being tested with exhaled breath using our novel handheld side-stream breath analyser shown in Fig. 1 (c) [4].

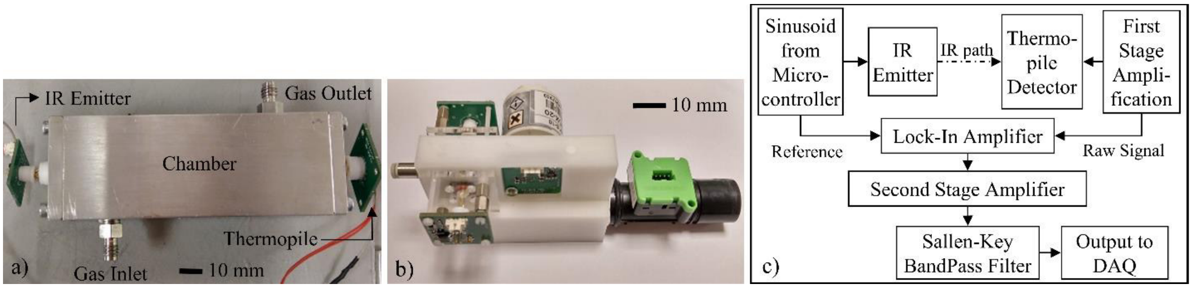


Fig. 1: (a) Photograph of NDIR gas sensor chamber, showing PCBs for IR emitter and thermopile detector; (b) Photograph of side-stream breath analyser, containing O2 and CO2 gas sensors and flow rate sensor [4]; (c) Block diagram of system with lock-in amplifier.

The sensor was tested to either one or two minute pulses of CO_2 returning to a baseline of synthetic air between concentrations. Mass flow controllers set the concentration of CO_2 and enabled step changes in gas concentration (total flow rate 0.5 SLPM). The IR emitter was driven by a continuous 10 Hz sinusoid pulse, generated via a low-cost microcontroller (ATtiny85, Atmel, US). A novel lock-in amplifier system (compares the received signal from the detector to the emitter source and recovers the sinusoid waveform (see Fig. 2). The output from the thermopile detector is in the micro-volt range. For the signal to be accurately recorded on a USB data acquisition module the raw output is amplified using two gain stages (factor ~3000, to amplify signals with variation in the µV range to the mV range). The band-pass filter following the lock-in amplifier removes remnants of noise on the 10 Hz signal. The change in amplitude of the sinusoid corresponds to the concentration of CO_2 to which the sensor is exposed.

2. Results and Discussion

Our bench-top prototype system was subjected to CO_2 concentrations from 50 ppm to 5 %, relative to a baseline of synthetic air. The operation of the lock-in amplifier is demonstrated in Fig. 2 (a) to (c), where the raw thermopile output signal is processed to allow concentrations of CO_2 to be resolved; namely a band-pass filter (centre frequency 10 Hz) was used to remove both low frequency drift and high frequency noise.

Fig 2 shows the response to low CO_2 concentrations (50 ppm to 2.5 %) with a shorter optical path length of 40 mm used. An 80 mm path length was used for higher concentrations (0.5% to 5.0 %) because of great absorption, see Figs. 3 (a), (b). The 40 mm path length of the system was chosen to allow concentrations similar to those found on breath (perhaps ~4 % [2]); however the path length can be decreased further if, a higher concentrations are present. The NDIR system is sensitive to small changes in ambient conditions during the course of an experiment. To correct for any drift during an experiment the amplitude of the recovered sinusoid was taken. The thermopile response was normalized relative to the average baseline value for direct comparison between experiments. Fig. 2 (d) demonstrates the sensor was stable, returning to a baseline (~1) for each step of 0.5 % CO_2.

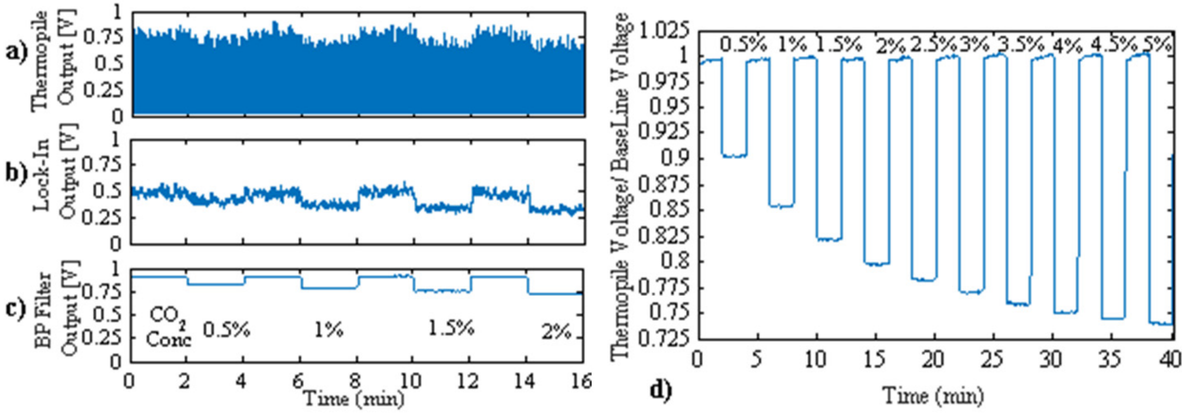
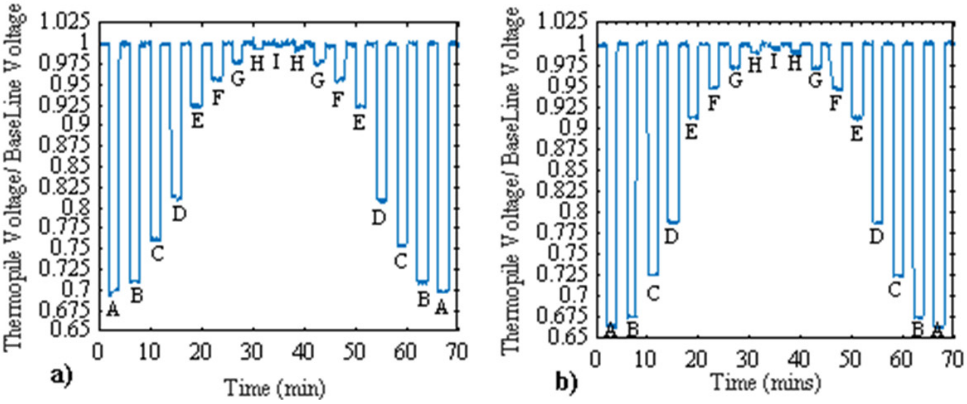


Fig. 2: Raw thermopile output (a) is compared to a reference sinusoid with a lock-in amplifier (b) and then output is filtered (c); (d) Sensor system output (relative to baseline voltage) for gas concentration steps of 0.5 % from a baseline of zero air (0% CO2) to 5 % CO2.



Concentration	
A	2.5 %
B	2 %
C	1%
D	0.5%
E	0.1%
F	500 ppm
G	250 ppm
H	100 ppm
I	50 ppm

Fig. 3: Sensor outputs (relative to baseline of zero air) with longer path length of 80 mm, showing detection of CO_2 in the range of 50 ppm to 2.5 %, (a) with dry gases and (b) in a constant environment of 25 % relative humidity.

The sensor response increases exponentially with CO_2 concentration up to the point of eventual saturation. Figs. 3 (a) and (b) demonstrate the resilience of the system to humidity, where the system is tested in dry gases and 25 % RH. The sensor was tested over a range of CO_2 concentrations from 50 ppm to 2.5 %. The sensor outputs display excellent stability. Concentrations from 100 ppm to 2.5 % were repeated twice during the experiment, with average variations of ~0.23 % and 0.10 % between the repetitions for dry and 25 % RH, respectively. The addition of humidity increased the stability of the sensor output, but decreased the normalised reading by an average of 1.2%.

The lock-in amplifier maintains a frequency lock throughout all the experiments, where no spurious spikes from other frequencies are generated. An average time of 2.4 s for the sensor to reach 90 % of final output (t_{90}) was calculated. The response time was limited partially by the low drive frequency and minimal filtering. Prior experiments demonstrated to reach our 1 % energy expenditure (EE) calculation target measurements of CO_2 were needed to 1.2 % accuracy. The current sensor outputs have demonstrated the system is capable of measuring CO_2 to within the necessary tolerance. However, the variation caused by humidity requires further experiments to verify the effect on the sensor response when it is subjected to the levels of humidity similar to breath. The setup is currently under test with a 12 mm path length in a side-stream breath analyser [4].

3. Conclusion

A low-cost fast NDIR CO_2 sensor system has been developed capable of measuring concentrations up to 5% with a resolution down to *ca*. 10 ppm. The lock-in amplifier design was employed to extract the small CO_2 signals from the noisy thermopile output. The frequency (10 Hz) of the drive is currently limited by the slow response time of the MEMS IR source (50 ms) but can be used in a side-stream system for real-time monitoring of exhaled breath. We believe that our NDIR system can be implemented in a low-cost CMOS version that will enable future point-of-care rather than clinical application for breath analysis.

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