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INVESTIGACIÓN

Monitor de CO_2 para medida de la ventilación en ambientes cerrados, prevención del COVID-19 y mejora del rendimiento laboral

CO_2 monitor for measurement of ventilation in closed environments, COVID-19 prevention, and improvement of work performance

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Abstract

Objective: Humans produce and exhale CO_2, thus the concentration of this gas increases in closed environments. The CO_2 concentration of air is often used as a reference to measure the ventilation rate. The typical outdoor CO_2 concentration is approximately 400 ppm, although it can be as high as 500 ppm. Concentrations greater than 20000 ppm result in deep breathing, higher than 100000 ppm cause visual disturbances and tremors with possible loss of consciousness and over 250000 ppm may cause death. In buildings with no change on their ventilation rate, high CO_2 concentrations have negative effects on decision making and working performance. At 1000 ppm, performance is significantly reduced in six of nine decision-making metrics compared to 600 ppm. In this work, a CO_2 flexible monitor is designed to measure ventilation in closed environments.

Methodology: Electrolytic and infrared CO_2 sensors with a detection range of 350 to up to 10000 ppm were used. The used sensors have good sensitivity and selectivity to CO_2. The gas monitor has a simple calibration system, whereby software

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automatically adjusts the calibration curve parameters after circulating clean air. The design of a gas bench used to verify sensor calibration is also shown.
Results: A set of measurements were performed with electrochemical gas sensors and infrared (IR) gas sensors to test the functionality of the equipment. Experimental work has shown sensors have a satisfactory response for this application. The margins of error are +5% of the reading value.
Conclusions: A low cost, flexible gas monitor for indoor environments like schools, offices, laboratories, and industries was designed in this work. Due to the flexible design, a network of gas monitors strategically distributed in the different spaces of the buildings is proposed.
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Keywords: Gas sensors, environmental monitoring, COVID-19, data processing, carbon dioxide.

RESUMEN

Objetivo: Los humanos producimos y exhalamos CO_2, por lo que la concentración de este gas aumenta en ambientes cerrados. La concentración de gas CO_2 en el aire se utiliza a menudo como referencia para medir la tasa de ventilación. La concentración típica de CO_2 al aire libre es de aproximadamente 400 ppm, aunque puede llegar a 500 ppm. Las concentraciones superiores a 20000 ppm dan como resultado una respiración profunda, superiores a 100000 ppm provocan alteraciones visuales y temblores con posible pérdida del conocimiento y superiores a 250000 ppm pueden provocar la muerte. En edificios sin cambios en su tasa de ventilación, las altas concentraciones de CO_2 tienen efectos negativos en la toma de decisiones y el rendimiento laboral. A 1000 ppm, el rendimiento se reduce significativamente en seis de las nueve métricas de toma de decisiones en comparación con 600 ppm. En este trabajo se diseña un monitor flexible de CO_2 para medir la ventilación en ambientes cerrados.
Metodología: Se utilizaron sensores de CO_2 electrolíticos y sensores infrarrojos con un rango de detección de 350 hasta 10000 ppm. Los sensores utilizados tienen buena sensibilidad y selectividad al CO_2. El monitor de gas tiene un sistema de calibración simple, mediante el cual el software ajusta automáticamente los parámetros de la curva de calibración después de hacer circular aire limpio. También se muestra el diseño de un banco de gases utilizado para verificar la calibración del sensor.
Resultados: Se realizaron un conjunto de mediciones, con sensores de gases electrolíticos químicos y sensores de gases infrarrojos (IR) probando la funcionalidad del equipo. El trabajo experimental ha demostrado que los sensores tienen una respuesta satisfactoria para esta aplicación. Los márgenes de error son 5% del valor de lectura.
Conclusiones: En este trabajo se diseñó un monitor de gas flexible y de bajo costo para ambientes interiores como escuelas, oficinas, laboratorios e industrias. Debido al diseño flexible, se propone una red de monitores de gas distribuidos estratégicamente en los distintos espacios de los edificios.
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Palabras clave: Sensores de gas, monitoreo ambiental, COVID-19, procesamiento de datos, dióxido de carbono.

1 INTRODUCTION

Current scientific studies show that there are three possible means of COVID-19 transmission: contact with contaminated surfaces, a respiratory route and possibly a fecal-oral route (Allen *et al.*, 2016). Regarding the respiratory route, the presence of the virus in droplets from sneezing (with a diameter of more than 5 µm) must be considered (Schibuola & Tambani, 2021). Those fall quickly to the ground, remaining in the air for a short period of time. The formation of smaller droplets (0.1 to 0.5 µm) must be considered too; these are aerosols that remain floating in indoor environments (Freire-Vinueza *et al.*, 2021). The virus can remain for hours in aerosols and a few days on surfaces. In indoor spaces, the spread of the virus by aerosols is greater than in outdoor spaces, with higher risks if ventilation is poor (Chen *et al.*, 2021). It is important to ensure proper ventilation in indoor spaces (Quesada Carvajal *et al.*, 2018). This ventilation can be natural or forced (using ventilation/air conditioning systems). Some recommendations by government/multilateral organizations specify that the minimum air renewal should be $30m^3$ of clean air per hour per worker (Vorobioff *et al.*, 2020). However, for health reasons, air currents with speeds greater than 0.25 m/s are not recommended for work in non-hot environments (Li & Tang, 2021).

CO_2 concentration can be used as a good ventilation indicator (Zivelonghi & Lai, 2021). The atmospheric CO_2 level is approximately 450 ppm and this value is taken as a reference level. On the other hand, the concentration of CO_2 in exhaled air is in the order of 40000 ppm (Di Gilio *et al.*, 2021). Therefore, a measurement of 850 ppm means that 1% of the air in a room was exhaled by a person (Persily & de Jonge, 2017). The indicator P, the probability of contagion, which is a function of the time of exposure to contaminated air, is used. See Eq. (1).

$$P = 1 - e^{\left(-\int_0^T \sigma(n) f \frac{I}{n} q dt\right)} \tag{1}$$

where T is the exposure time, n is the number of people in a space, I is the number of people infected, $\sigma(n)$ is 1 if $n > 0$, otherwise 0, q is a unit of infection or a value determined as a function of activity and specific people (Satish *et al.*, 2012). The variable f (see Eq. 2) is the fraction of air rebreathed, estimated based on the measured CO_2 concentration C, the exhaled concentration C_a and the concentration in open environments C_0 (García Alvarado *et al.*, 2016).

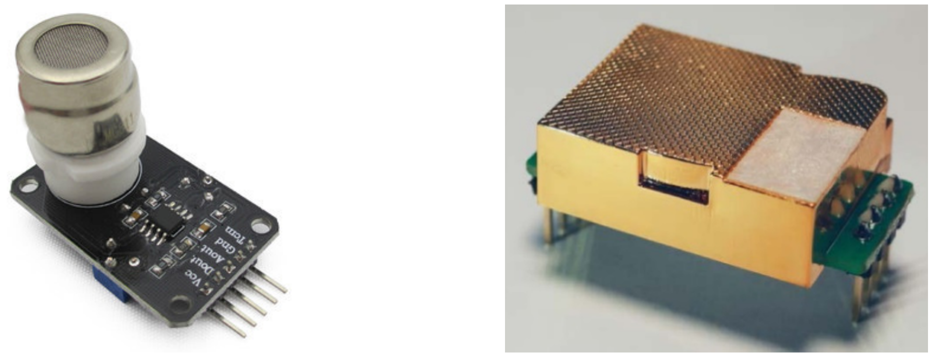
$$f = \frac{C - C_0}{C_a} \tag{2}$$

Many organizations recommend a maximum threshold of 800 ppm (Tusman *et al.*, 2020). The UK Health and Safety Executive Agency in its guidance for air conditioning and ventilation during the Coronavirus pandemic recommends that CO_2 measurements should be used as an indicator to in-

door ventilation rather than treating them as safe limits (Ostro *et al.*, 2000). Outdoor levels around 400 ppm and indoor levels with a consistent CO_2 value of less than 800 ppm are likely to indicate that a space is properly ventilated (Gil-Baez *et al.*, 2021). In a similar way, the Argentine Ministry of Health says that "One strategy to indirectly assess the degree of indoor air tightness is CO_2 (carbon dioxide) monitoring. It is recommended to increase how opened are doors and windows when the level of CO_2 exceeds 700 ppm (parts per million of air mass)" (Sanchez Quintero *et al.*, 2021).
In buildings with no change on their ventilation rate, high CO_2 concentrations have negative effects on decision making and working performance. At 1000 ppm, performance is significantly reduced in six of nine decision-making metrics compared to 600 ppm. At 2500 ppm CO_2, performance is reduced in seven of nine performance metrics (Satish *et al.*, 2012).

2 METHODOLOGY

A small, portable, low cost and flexible gas monitor was designed and built. Electrochemical gas sensors model MG811 and infrared (IR) gas sensors model MH-Z19C (manufactured by Winsen) were used (see Fig.1).
The MG811 sensor works through an electrochemical reaction that occurs when carbon dioxide passes over the sensor (Shen, 2014). The output voltage is measured to estimate CO_2 concentration, with 350ppm to 10000ppm detection ranges. The used sensors show good sensitivity and selectivity to CO_2, low dependence to temperature and humidity, good stability and repeatability, and low cost (Rodríguez *et al.*, 2019).
The IR gas sensor is a general use sensor that utilizes NDIR (non-dispersive infrared) principles to detect CO_2 concentration in the air. It has good selectivity, temperature compensation and a long useful life (Massacane *et al.*, 2010). Measurements can be made via serial, analogical or PWM output; all of them work simultaneously. It combines a reliable IR absorption gas detection technology with low cost and a reduced size.



(a) Sensor MG811 **(b)** MH-Z19C

Fig. 1. Gas monitor

***Source**: Authors*

The gas monitor uses the previously mentioned sensors, and it can use up to eight sensors. It also has a simple calibration system which can set a reference level by means of a micro-pump that circulates clean ambient or synthetic air (Acosta Pérez *et al.*, 2016), as shown in Fig. 2. The calibration curve parameters are adjusted automatically by software, to indicate the concentration levels in ppm (Díaz, 2021). Exhaled breath measurements were made on indoor conditions. It was also measured with a gas bench for sensor calibration that can mix CO_2 and synthetic air in controlled flow and concentration conditions is available too.

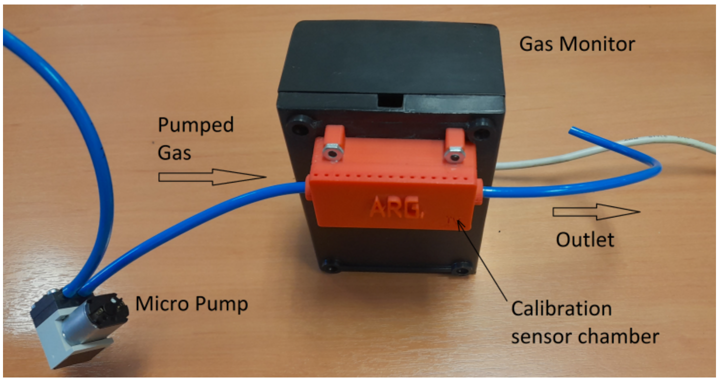


Fig. 2. Gas monitor with calibration sensor chamber

***Source**: Authors*

CO_2 monitor results are indicated on LCD display and via computer software. Optionally, wireless transmission can be added to display the results on cellphones.

MG811 sensor calibration

The measured concentration can be calculated using Eq. 3:

$$c = d^{(a-v)/b} \tag{3}$$

Where:

c – CO_2 concentration in ppm

d – Constant equal to 400

v – Sensor voltage measurement in mV

a – A parameter adjusted during calibration with an initial value of 1500

b – Constant equal to 600

To calibrate the chemical sensor, a is calculated using Eq. 4:

$$a = v + b\frac{ln(c_1)}{\ln(d)} \tag{4}$$

Where c_1 is the real concentration value. For example, for a well ventilated room it would be 400ppm. In practice, it is assumed that $d = c_1$ and in this case the adjustment equation will be:

$$a = v + b \tag{5}$$

If a decision is made to change c_1 then b and d should be changed using Eq. 6 and 7:

$$d = c_1 \tag{6}$$

$$b = 100lnc_1 \tag{7}$$

Once sensors are calibrated, the chamber is removed.

Gas bench

A gas bench was used to calibrate the sensors. This control system can mix different gases with precision; those gases flow through the sensor chamber described on the previous section. The system is controlled by a computer connected to a hardware controller. This hardware includes gas lines, four mass flow controllers (MFC), electrovalves, humidifiers and a command module responsible for the gas mix with controlled caudal, humidity and concentration. Synthetic air (99.999%) and CO_2 (2000ppm) tubes provided by Indura Argentina S.A fed the bench.

Gas lines can provide a gas mix with controlled humidity at the desired concentration range. The mix procedure is accomplished with high precision thanks to the use of MFCs. Once the desired mix is obtained, it's injected into a measurement chamber where sensors are located. The gas line has 4 input lines connected to high pressure tubes (see Fig. 3). Lines 1 and 2 are both connected to the synthetic air tube while lines 3 and 4 are connected to target gases/pollutants (in this case CO_2). MFCs allow the flow of gas from a specific line through a voltage signal.
MFC connected to the second allows a 100cm^3/min maximum flow and the MFCs connected to the other lines allow a 500cm^3/min maximum flow.
The gas bench guarantees the purity of gas mixes injected into the chamber, controlling the flow and concentration of any external pollutant/gas connected to one of the lines.

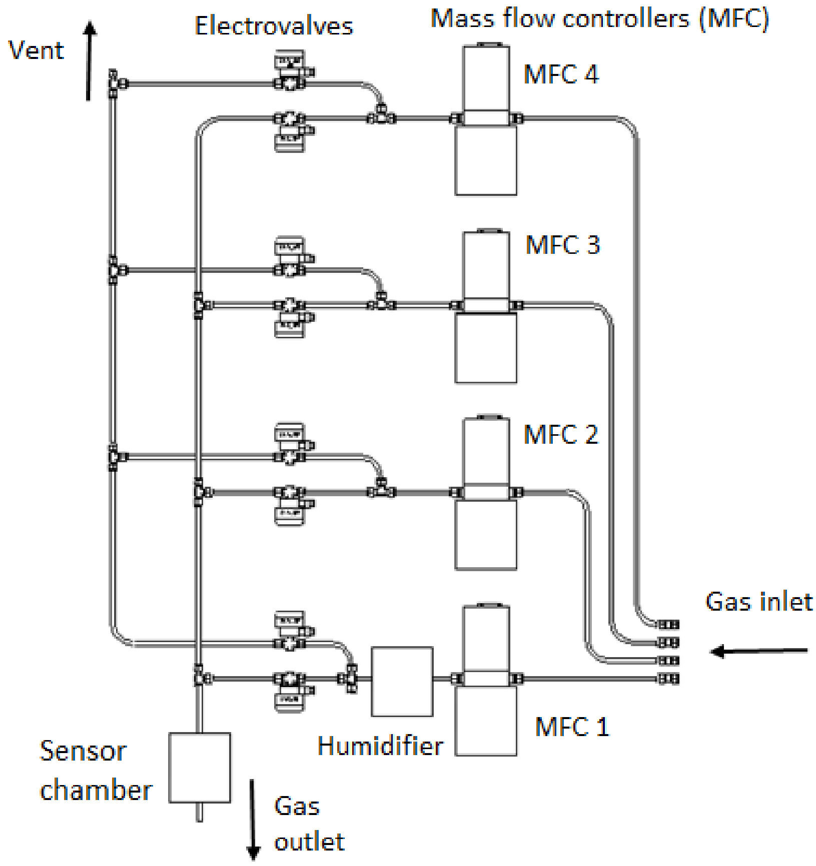


Fig. 3. Simplified gas line scheme.

Source: *own preparation*

Four MFCs (MKS instruments, model 1179A01352CS1BV) are used to control the flow of the lines with a 500/100cm^3/min maximum range. Those MFCs adjust and measure the desired flow. An MFC command module model SDPROC Version 1.03, manufactured by Aalborg, is used to control and read the MFCs. This controller connects to the computer to send data and execute commands via an RS-232 to USB converter.

Software was developed to communicate with MFCs, register flows for each line, and control the closure and aperture of electrovalves. The implemented algorithms calculate the value of those flows. Gas mix procedures can be automatized by setting concentration sequences. These sequences are composed of different mixes at different time intervals. Flow levels are plotted in real time. Gas sensors levels can be read at the gas monitor software interface and optionally through the gas bench software. Fig. 4 shows the bench's graphical interface. The total flow, desired output concentrations, incoming flow levels, interval times and repetitions per sequence can be set.

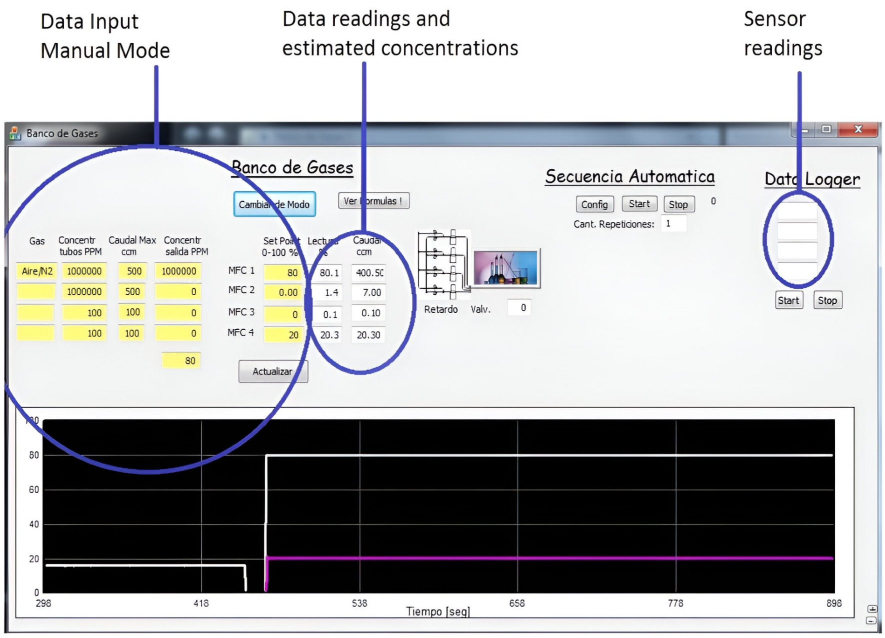


Fig. 4. Gas bench graphic interface

Source: *Authors*

Because the gas tubes have a specific gas concentration, the desired concentration of a gas to measure is achieved by diluting specific gases in a carrier gas (e.g., nitrogen, pure air, etc.). The proportion (for each gas to measure) of the configured total flow to the gas chamber is chosen in such a way that the diluted concentration is the desired one. This is done indirectly through MFC set points (percentage of the max flow of a tube), as seen in Eq. 8. The flow of carrier gas (therefore its set point, SP(1)) is constrained by the other flows and the configured total flow, as seen in Eq. 9.

$$SP\left(i\right)=\frac{C\left(i\right)100}{CM\left(i\right)}=\frac{p\left(i\right)\cdot CT\cdot 100}{CM\left(i\right)}=$$

$$=\frac{concentr_{out(i)}\cdot CT\cdot 100}{concentr_{tube(i)}\cdot CM\left(i\right)};i=2,3,4 \quad (8)$$

$$SP\left(1\right)=\frac{C\left(1\right)100}{CM\left(1\right)}=\frac{100}{CM\left(1\right)}\cdot\left[CT-\sum_{i=2}^{4}C\left(i\right)\right]=$$

$$=\frac{100}{CM\left(1\right)}\cdot\left[CT-\sum_{i=2}^{4}\frac{SP\left(i\right)}{100}CM\left(i\right)\right] \quad (9)$$

Where:

$i=2,3,4\ (gases\ to\ measure)\ ; i=1\ (carrier\ gas)$

CT: configured total flow

$concentr_{out}\left(i\right)$: desired output concentration for line i

$concentr_{tubo}\left(i\right)$: configured tube concentration i

$C\left(i\right)$: Flow for MFC i

$p\left(i\right)$: Proportion of total flow for MFC i

$CM\left(i\right)$: Max flow for MFC i (100 cm^3/min if i=3,4 or 500 cm^3/min if i=1,2)

$SP\left(i\right)$: set point sent to MFC i, expressed in percentage

In this work, only two MFCs are used, one for CO_2 and one for the carrier (pure air).

Gas chamber

The sensors were mounted in chambers made of plastic bottles, with inlet tubes to connect to the gas bench and outlet to the environment. Those tubes were sealed to avoid leakages (see Fig. 5). Small bottles were chosen to avoid the need for an excessive gas volume to fill the chamber.

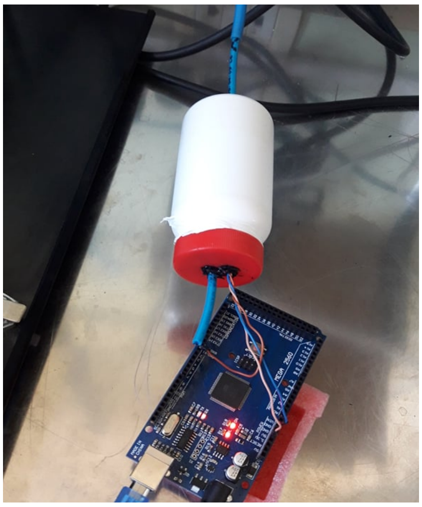


Fig. 5. Gas chamber

Source: *Authors*

Measurement procedures

MH-Z19C sensor measurements were made injecting a mix of synthetic air and CO_2 as it is shown in Table 1. The first step was a purge with conditions similar to well ventilated environments (400ppm). Later steps increment the concentration level up to the sensor's limit detection range.

Table 1. Gas mixture concentrations

Source: own preparation

Desired CO_2 concentration [ppm]	**Set Point 1 Synthetic air [%]**	**Set Point 4 CO_2 (2000ppm) [%]**	**Time [minutes]**
400	16	20	11
800	12	40	11
1200	8	60	11
2000	0	100	11

MG811 sensor measurements were made on an indoor environment, by exposing it to exhaled breath to observe the transient response of the sensor. The room where the measurements were made was properly ventilated and vacant (except for the person responsible for the measurement itself), and the sensor was blown repeatedly with 3 minutes pauses between every attempt, to be able to observe transient effects.

MHZ19C response can be seen in Fig. 6. Sensor response can be divided in three stages: an initial stage where air flows into the chamber replacing old air with a different concentration, a transient stage where the sensor reacts to the new concentration and a stationary stage where the current concentration level can be measured.

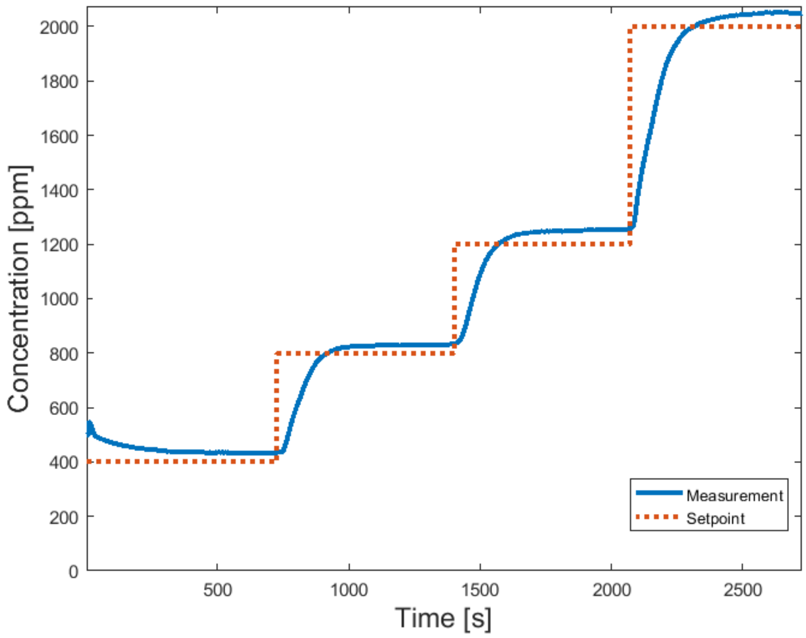


Fig. 6. MHZ19C response to different CO_2 concentrations.

Source: *Authors*

The measured concentrations and setting time can be seen in Table 2. Observed values are within the error margins given by the sensor accuracy ($\pm 50ppm + 5\%$ reading value) and MFC accuracy (1% max range).

MG811 response can be seen in Fig. 7. As expected, the signal is stronger after exposure to exhaled breath because of the increased CO_2 levels, yet there are transient effects because of sensor saturation. Those effects can last a few minutes to wear off. The procedure is repeated 5 times obtaining adequate results.

Table 2. Setpoint, setting time and measured concentration

Source: own preparation

Set point [ppm]	Concentration [ppm]	Setting time [s]
400	430	455
800	830	253
1200	1255	409
2000	2052	552

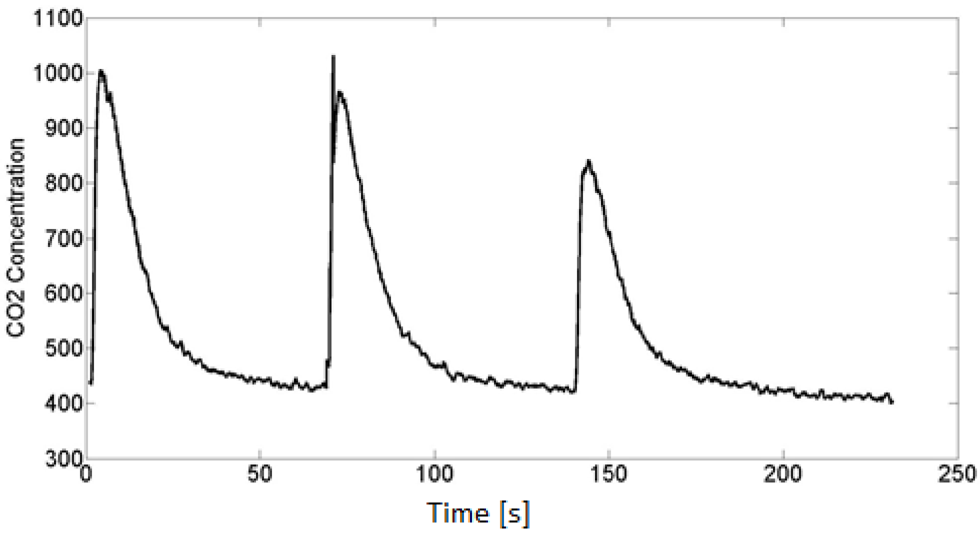


Fig. 7. MG811 response to multiple exhalations.

Source: *Authors*

3 CONCLUSIONS

CO2 level is a good indicator of COVID-19 contagion risk on indoor environments. It is also important to analyze gas levels to avoid diminished labor performance. A low cost, flexible gas monitor for indoor environments like schools, offices, laboratories and industries was designed in this work. Gas sensors were calibrated using a gas bench, to improve measurement reliability. Gas monitors have an alarm that warns the need to ventilate the environment. Experimental work demonstrated that sensors have a satisfactory response for this application. As future work, it remains to study possible interfering substances that cause an increase in the signal produced by CO2 as false positives or in the event that the interferents displace CO2, as false negatives, in order to modify the correlation between the level of CO2 and the possible presence of COVID. Different models of sensors should be tested and their sensitivity and specificity compared to different gases should be compared.

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