

## A NEW METHODOLOGY FOR CALIBRATION OF TRANSDUCERS FOR ENVIRONMENTAL POLLUTERS – CO<sub>2</sub> CASE STUDY

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**Abstract:** The transducers employed to measure the concentration of CO<sub>2</sub> launched to the atmosphere are only calibrated in a static manner. Thus, the transient effects of the flow of such gas are not properly recorded. This study aims at presenting a new methodology to characterize the dynamic performance of carbon dioxide transducers, and to experimentally determine its transference function. To achieve this goal, a device was developed in which the variables influencing the measures are controlled, allowing the transducer's dynamic response to be assessed.

**Key-words:** Dynamic Metrology, CO<sub>2</sub> Transducers, Carbon Dioxide, Carbon Sequestration

### 1. INTRODUCTION

The large forest areas, combined with the vast surfaces occupied by agriculture, indicate that in Brazil there is a significant surplus in carbon's flux in the atmosphere. Such conclusion provides the country with great potential to borrow funds using Certificates of Carbon Sequestration, as foreseen in the Clean Development Mechanisms (CDM) of the Kyoto Protocol.

Recent measurements suggest that indeed the quantity of CO<sub>2</sub> absorbed in photosynthesis is higher than the one released by breathing or by organic materials decomposing. However, native forests were withdrawn from the CDM, on grounds that as these are already formed their carbon results would be equal to zero. But such assumption is contrary to the results of tests performed, which shows that CO<sub>2</sub> absorption balance in mature rain forests is positive. Studies [1] show experiments performed in the Amazon's central region and in Rondônia, where the environmental variables were measured using a tower and a captive balloon, and the CO<sub>2</sub> flux [2] was calculated using the methods of Gradient-Flow and of Eddy Correlation. The results indicated that the forest acted as a bottomless pit. Other experiments [3], carried out at Sao Paulo's State savanna region, also using the Eddy Correlation methodology to calculate the carbon quantity absorbed by the vegetation, showed a fluctuation of 0.1 to 0.3 tons per hectare per year. The Large Scale Bio-

Atmosphere Test in Amazon (LBA) is a research group led by Brazil, which aims at better understanding climatic, ecological, bio-geo-chemic and hydrologic phenomena in the Amazon. Reports from LBA [4] and [5] have shown results indicating that Amazon absorbs 0.8 to 7 tons of carbon per hectare per year.

These unitary values are way below the expectations, and extremely disperse. When we consider the 4,000 million hectares of native forests, the net quantity of retained carbon – even under the most conservative conditions – may be equivalent to 10% of all CO<sub>2</sub> launched in the planet every year. To calculate the quantity of carbon that is absorbed, apart from the CO<sub>2</sub> flow, the calculation of the forest's biomass is also used. The estimation of the latter is also hugely dispersed.

The dispersion observed in the quantity of carbon absorbed by a forest is due to the different assessment methods employed, and to the uncertainties linked to the measurement systems. Studies [6] show the technical difficulties and the uncertainties associated to the bio-mass calculation of the Amazon forest. For instance, the uncertainty linked to the measurement of the field variables involved in the process can be grossly estimated in  $\pm 20\%$  above average, for a reliability intermission of 95%.

The CO<sub>2</sub> flux calculation involves, basically, the field measurement of carbon dioxide concentration and of wind direction and intensity, during prolonged measurement campaigns. The main uncertainty sources in such measures regards the metrological characterizations of the instruments, and dynamic effects such as the fluctuation of the measured subject. The uncertainty linked to the magnitude of carbon bottomless pits yields about 50% [7].

Regarding the metrological characterization of measuring instruments, particularly the CO<sub>2</sub> concentration transducers, it is noticed that there are few studies about their calibration, mainly for the infrared ones, which are most commonly used. Normally the manufacturers only assess the static response of the instruments, by means of passing a discharge with known concentration through the trans-

ducer's path-length. This method is not sufficient to characterize the transducer, as it does not provide information about the measurement's uncertainty. The method also does not assess the influence quantities, and much less the transducer's dynamic characteristics. As such, the results are vague, with low rate of repetition, and do not fully describe the physical process. Consequently, the development of more reliable and broader measurement and calibration methods is paramount. The purpose of this study is to discuss the proposal of a new calibration method, which will allow a metrological characterization for the dynamic performance of a CO<sub>2</sub> transducer and an assessment of the interference of influence quantities.

## 2. THEORETICAL BASIS

The development of the new calibration method encompassed the following stages: characterization of the mass movement of carbon dioxide; characterization of the transducer; utilization of classic calibration devices; and construction of a new calibration device.

### 2.1 CO<sub>2</sub> Mass Movement – Mass Diffusion.

CO<sub>2</sub> transportation occurs by means of a mass diffusion process, characterized by the mass conservation law (Eq. 1), defined as “The rate at which a specie enters a volume of control, less the rate at which the mass of such specie leaves the volume of control, equal to the rate at which the specie mass is accumulated inside dp volume of control” [8].

$$\dot{M}_e + \dot{M}_g - \dot{M}_s = \frac{dM}{dt} \equiv \dot{M}_{AC} \quad (1)$$

where indices  $e$ ,  $g$ ,  $s$  and  $AC$  represent, respectively, the incoming mass, generated mass, outgoing mass, and the mass accumulated inside the volume of control.

Considering a binary mixture of specie  $A$  in  $B$ , the mass flow (Eq. 2) is represented by the summation of the diffusive and convective flows.

$$\bar{n}_A'' = \bar{j}_A + \rho_A \cdot v \quad (2)$$

where  $\bar{j}_A$  is the diffusive term (Fick's law) and  $v$  is the average velocity of the mixture.

Using Eq. (1), and considering that there is no mass accumulation and generation, and that the mass movement takes place only in one direction, Eq. (3) is given.

$$D_{AB} \cdot \frac{\partial^2 \rho_A}{\partial x^2} - v \frac{\partial \rho_A}{\partial x} = \frac{\partial \rho_A}{\partial t} \quad (3)$$

where  $D_{AB}$  is the binary diffusive coefficient and  $\rho_A$  is the mass concentration of specie  $A$ .

Considering the case in which the mass transport only occurs by diffusion (pure diffusion), i.e., the mass velocity of the mixture equals zero, Eq. (3) can be analytically resolved, Eq. (4).

$$\rho_{CO_2}(x, t) = \rho_0 \cdot \operatorname{erfc} \left( \frac{x}{2 \cdot (D_{CO_2Ar} \cdot t)^{1/2}} \right) \quad (4)$$

Considering that the mixture's mass velocity is sufficiently high, so that the diffusive term can be ignored, the solution of Eq. (3) is

$$\rho_{CO_2} = \rho_0 \cdot H \left( t - \frac{x}{v} \right) \quad (5)$$

where the  $H$  function represents one Heaviside step.

From Equations (4) and (5), the curves of concentration increase were drawn for a point located at a distance of  $x$  from the CO<sub>2</sub> source with concentration equal to 1% (figs. 1 and 2).

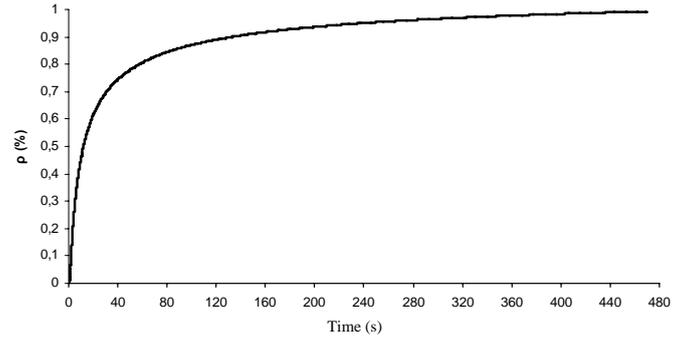


Fig. 1 – Curve for pure diffusion.

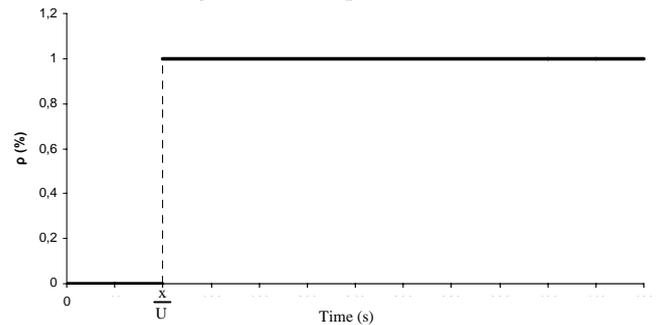


Fig. 2 – Schematic for pure convection Curve.

### 2.2 Transducer Characterization

The most used method to measure CO<sub>2</sub> concentration in the atmosphere is molecular spectroscopy [9], which employs the interaction between light and molecules. For gases measurement, such interaction is specific, consisting in the main advantage of such method.

For CO<sub>2</sub>, the standard technique is NDIR (Non-Dispersive InfraRed), which uses an infrared light (IR) to excite the CO<sub>2</sub> molecules. This technique employs a range of wavelengths to determine the concentration of the gas.

Basically, a NDIR transducer is formed by an IR source, a filter and a photo-detector. As a range of wavelengths is employed, the transducers use two photo-detectors: one detects the intensity of the specific CO<sub>2</sub> wavelength (active sign), and another to detect the presence of other gases (reference sign). With that, the concentration is provided by the ration between photo-detectors outputs.

The transducer used in the study (Fig. 3) has – apart from the photo-detectors and respective filters – a thermistor, an IR source, and the electronic handling of the output. All components, save for electronics, are inside an optical

cavity, which has high reflectivity to IR radiation. The thermistor has the function of monitoring temperature inside this optical cavity, correcting with that the measured value. The transducer's utilization range is from 0% to 5% of CO<sub>2</sub>.



Fig. 3. CO<sub>2</sub>. Transducer

To determine the CO<sub>2</sub> concentration, the transducer employs Eq. 6, which derives from the Beer-Lambert law.

$$c = \left( \frac{\ln \left( 1 - \left( 1 - \frac{R}{Z/S} \right) \right) \right)^{\frac{1}{b}}}{a} \quad (6)$$

where  $R$  is the ratio between the active and reference signs;  $Z$  is the ratio between the active and reference signs in the absence of gas;  $S$  is the spam;  $a$  and  $b$  are constant.

Constants  $a$ ,  $b$ ,  $Z$  and  $S$  are determined during the transducer's static calibration.

### 3. EXPERIMENTAL DEVELOPMENT

Initially, attention was given to dynamic calibration, which consists in experimentally determining the transference function of a transducer stimulated with a known input (generally 1 degree), and the dynamic characteristics: time constant, rise time, response time, amongst others. Firstly, tests were performed with classic devices, which are worldly renowned in dynamic metrology.

#### 3.1 Tests with the Quick Opening Device

The Fast Opening Device (FOD) [10] is one of the classic devices used in dynamic calibration of low frequency pressure transducers. The FOD comprises 2 chambers, with a rate between volumes equal to 1000, and a quick opening system, which establishes communication between the chambers. Due to the rate between the volumes of the chambers, the degree generated when the valve is opened has infinite duration [11].

The tests with FOD were performed in association with the Laboratoire de Metrologie Dynamique from ENSAM-Paris (LMD). To perform the tests, structural changes were needed in the FOD in order to allow the generation of a concentration degree. The changes involved: constructing a new, smaller chamber; installing components to keep the mixture homogeneous; pressure control.

To determine the transference function, experimental assemblies were made to generate a response from the trans-

ducer, subjected to pure diffusion and convection processes (figs. 1 and 2).

For pure convection, a fan was installed. Such fan blew mixture inside the smaller chamber. However, results have shown that the rise time, from 10% to 90% of the stabilization level, was 200 s, which does not characterize a concentration degree. For pure diffusion, with the fan turned off, even with an acquisition time of 520 s the response did not stabilize.

The structural and geometrical characteristics of the FOD were the main factors responsible for the long time for stabilization. The relative position of the chambers, and the higher CO<sub>2</sub> density compared to the air, hinder carbon dioxide diffusion processes. Besides, the bottleneck present in the communication between the chambers offers an additional resistance to the diffusion process. As such, it was necessary to develop a new device (fig. 4), specific to calibrate concentration transducers, which could overcome the difficulties faced by the FOD, embodying its advantages. The basic functioning principle of the new device is based in the FOD. It comprises a larger chamber, a smaller chamber and a quick opening system capable of generating a function concentration degree, without interferences from the differences in density, and without the adverse effects of the bottleneck.

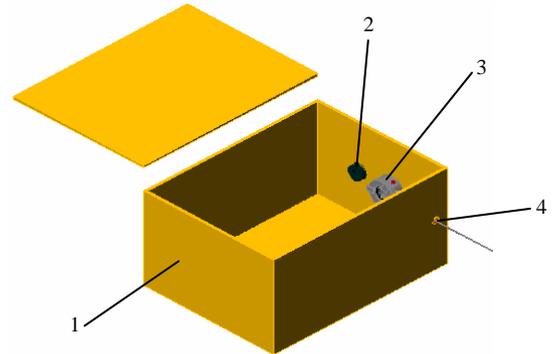


Fig 4. New Device: 1 – Larger Chamber; 2 – Larger Chamber's Transducer; 3 – Smaller Chamber and 4 – Opening System.

This new calibration mean was called Device of Fast Exposure to Emissions (DERE).

#### 3.2 DERE

The DERE was developed with structural and operational features that could ensure repetitions and quick tests.

##### 3.2.1 Larger Chamber

The larger chamber is a rectangular reservoir, built in acrylic. This material was chosen to facilitate the observation of the installed devices, and to allow control of luminosity, which is one of the parameters that may influence the transducer's performance. The working pressure of the DERE is  $\pm 200$  mbar, a range that caters for usage pressures of most of transducers' applications.

##### 3.2.2 Smaller Chamber

The smaller chamber (fig. 5) is anchored to the DERE by a cylindrical aluminum part, where the sealing mechanism of the opening system was slotted. The control of pressure

and concentration is done by pipes installed in the smaller chamber. The volume rate between both chambers is around 2000.

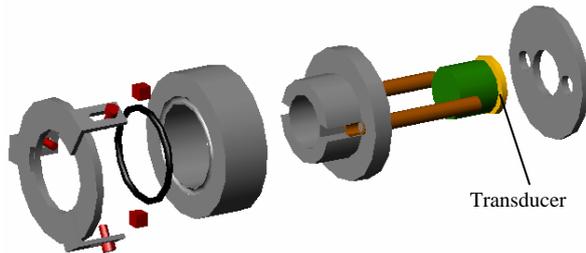


Fig. 5 – Schematic drawing of the smaller chamber's assembly.

### 3.2.3 Opening System

The opening system consists of a rod that has a piston inside. It is attached to a pneumatic piston, and at its edge there is a component that closes the smaller chamber. The rod's piston is inside a cylinder that is mounted in the larger chamber's wall. As such, the system can be activated without prejudice to the DERE's sealing (fig. 6).

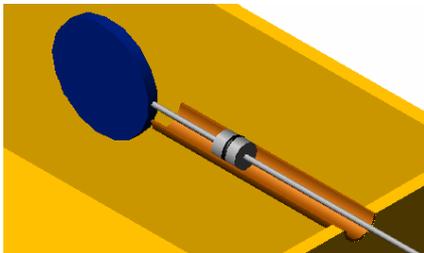


Fig. 6 – Opening System.

The pneumatic piston is controlled by a three-way valve, and the opening speed can be controlled, changing the pressure that acts over the piston (1 to 6 bar). The valve's opening time for a 4 bar pressure is 70 ms.

### 3.2.4 Fan

Differently from the FOD, in the DERE the fan can be mounted in several positions (fig. 7), allowing the assessment of the influence from the induced discharged on the transducer's performance. Such arrangement allows analyzing cases in which the mass movement takes place by pure convection or diffusion.

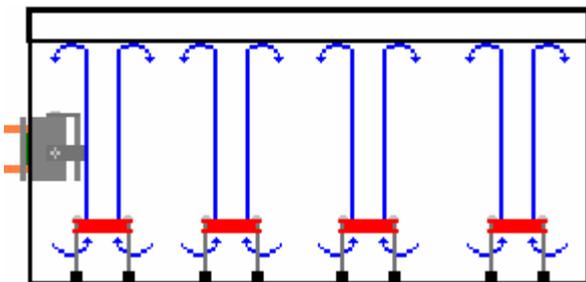


Fig. 7 – Fan in different positions.

### 3.2.5 Operating Characteristics

All control devices in the DERE have been installed on a bench, where it is possible to activate the opening system, control pressure, concentration, luminosity, temperature and fan speed.

The acquisition of the response sign can be done using the serial out interface of the transducer's electronics, and/or by means of its analogical out interface, with the aid of an oscilloscope. Figure 8 shows an overview of the bench, with certain highlights.

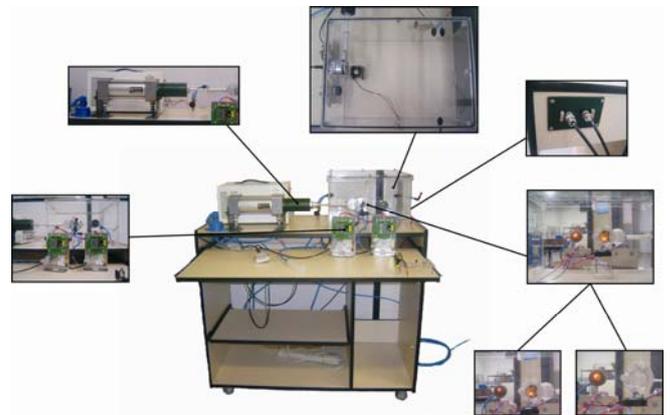


Fig. 8- DERE and bench.

### 3.2.6 Modeling of the Physical Process in the DERE

To model the pure diffusion mass movement to inside the DERE, a 2-D numeric simulation of the process was performed. The simulation employs the method of finite elements of Characteristic-Based Split. Figure 9 show the mesh generated to the DERE, and figure 10 shows the simulation results.

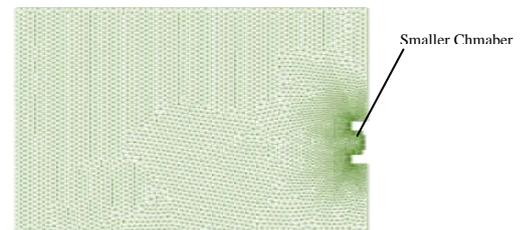


Fig. 9 – 2-D mesh used in the numeric simulation.

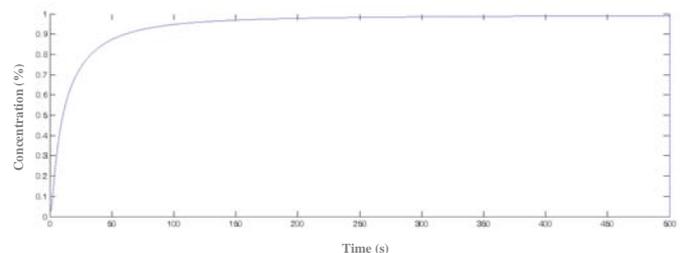


Fig. 10 – Numeric simulation results for a node located at the bottom of the smaller chamber (Concentration X Time).

The results shown in figure 10 were used to calculate the transference function for pure diffusion cases.

## 4. RESULTS WITH THE DERE

### 4.1 DERE Characterization

Aiming at characterizing the concentration degree generated, and to ensure the metrological quality needed for calibration, 144 tests were carried out. Tests were performed with the fan in different positions in the larger chamber, simultaneously varying velocity. As such, it was attempted to establish the best position so that the transducer's performance was not jeopardized, as its electronics have proven

to be very sensitive to direct and strong discharges, freezing the acquisition.

It has been noticed that as the fan was brought away from the smaller chamber, the rise time increased, and that after a certain point the rise time remained constant. In such case, the fan would just have the function of keeping the mixture homogeneous, i.e., the discharge wouldn't contribute for the mixture's mass movement. With that, pure diffusion tests were performed, which average value for 4 tests is presented in figure 9.

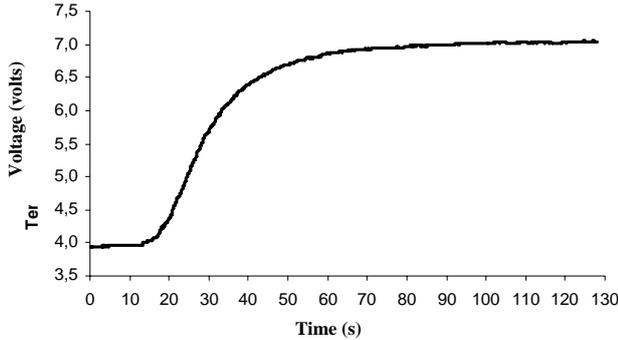


Fig. 9 – Pure Diffusion.

By Eq. 5, it can be verified that to subject the transducer to a concentration degree it is necessary to increase the mixture's mass velocity, in a way that the diffusive term can be ignored. To perform such process, the fan was brought closer to the smaller chamber up to a point at which the discharge would not freeze the mixture, and the speed was increased. It was noticed that up to a certain speed the rise time was reduced, and at the next level of speed the time turned to increase and the electronics turned to freeze acquisition. As such, the best speed to perform tests was determined.

To increase the speed without freezing the transducer, vacuum was established in the smaller chamber, prior to the activation of the opening system. A small change was noticed in the rise time, but increasing the vacuum has not reduced such time. It indicates that the transducer's limit was reached. As such, for the calculation of the transference function, it was assumed that the transducer has been subjected to one degree. Figure 10 shows the average of 4 tests performed with the best assembly for position, fan and vacuum.

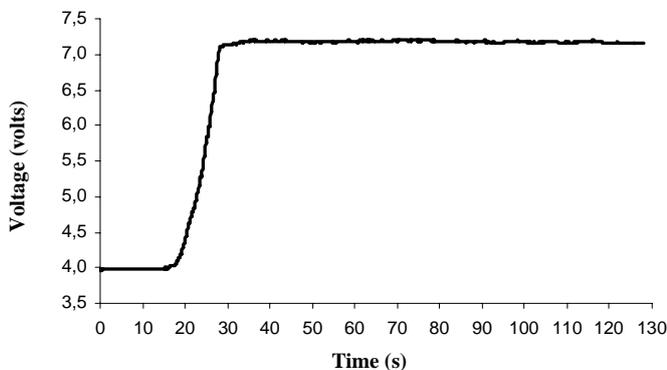


Fig. 10 – Dynamic response of the CO2 transducer.

The rise time for the answer shown in figure 10 was 8 s, representing a significant improvement vis-à-vis the tests performed in FOD. The values of other dynamic characteristics are: time constant is 26 s, and the response time is 28 s.

#### 4.2 Dynamics

The transducer's transference function was calculated using the RFreq system, developed by the Dynamic Metrology Laboratory of the University of Brasília – LMD/UnB [12]. The method employed by the system is Derivation. It was assumed that the combination of vacuum and fan was sufficient to ensure that the assumption made for pure convection has been satisfied, i.e., one concentration degree occurs. Figure 11 shows the transference function and phase of the CO<sub>2</sub> transducer.

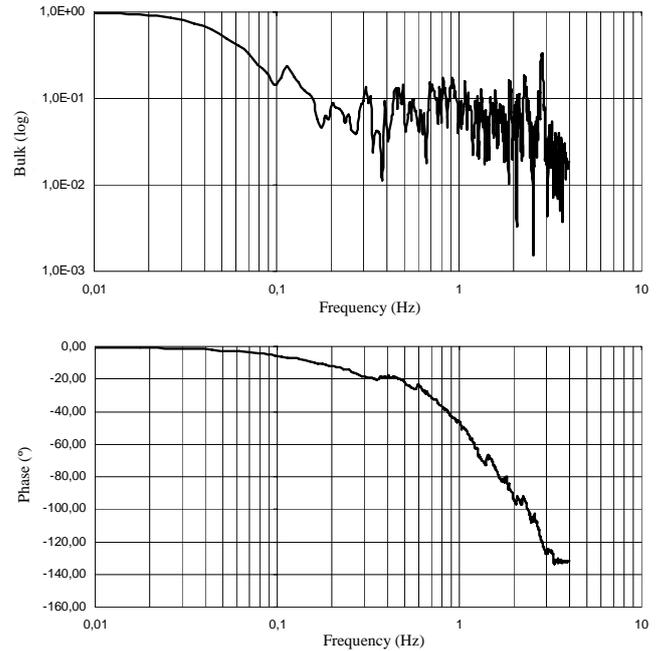


Fig. 11 – Transference function and phase.

#### 4.3 Influence Quantities

The assessed influence quantities were: temperature, pressure and luminosity. These variables are analyzed as the photo-detectors depend on light and dark moments of the IR source. As such, changes in luminosity may alter sensitivity. And variations in pressure and temperature alter density, and CO<sub>2</sub> diffusiveness coefficient.

To assess the effect of such variables, tests were performed in which one of the quantities varied and the others (as well as the measured object) were kept constant.

The transducer used in the study has a thermistor that offsets the temperature effects, reason why there was no need to assess such variable. Pressured was varied from  $p = atm$  up to  $p = atm + 150 mbar$  (tab. 1). Luminosity was varied from 0 lux to 317 lux (tab. 2). Tests with pressure and luminosity were performed with concentration value equal to zero, as in this manner it is possible to check if these quantities are interfering inputs, i.e., those that modify the transducer's zero.

Tab.1 – Test with Pressure variation

Pressure (bar)	Temp. (°C)	Luminosity (lux)	Transducer Sign
0.89	20.04	320	3.9698
0.91	19.91	318	3.9681
0.94	20.00	320	3.9677
0.97	20.00	320	3.9678
1.00	20.30	320	3.9676
1.03	20.30	320	3.9583
1.06	20.30	320	3.9647

Tab.2 – Test with luminosity variation.

Pressure (bar)	Temp. (°C)	Luminosity (lux)	Transducer Sign
0.89	20.16	0	3.9512
0.89	20.14	15	3.9511
0.89	20.11	64	3.9516
0.89	20.06	96	3.9517
0.89	20.01	130	3.9524
0.89	20.01	179	3.9524
0.89	20.04	251	3.9524
0.89	20.04	264	3.9527
0.89	20.06	317	3.9535

It can be seen that both pressure and luminosity did not materially alter the transducer's performance. As the photo-detectors are encapsulated in the optical cavity, the luminosity effect is offset. In this case, the conclusion is that such influence quantities are not interfering inputs.

In the test to assess if the influence quantities are modifying inputs, i.e., those that modify the transducer's sensitivity, pressure altered performance (of the transducer) but it cannot be measured due to the acquisition freezing made by the electronics. The test to check whether an influence quantity is a modifying input consists in keeping concentration at the middle of the transducer's range, vary the influence quantity and check if it causes any change.

## 5. CONCLUSIONS

Though the methodological aspects are undergoing a development process (and as such are subject to discussions and considerations that can lead to its improvement), we can conclude that:

a) the diffusion theoretical model properly represents the physical process that takes place in the calibration device DERE;

b) the mass movement in the DERE can be modeled using Equations (4) and (5), allowing calculating the transference function having as input the analytical solving of the equations;

c) the experiments' results show that the developed device properly characterizes the dynamic performance of the CO<sub>2</sub> transducer, providing characteristic information for analysis in the time and frequency domains, as well as allowing to control influence quantities that usually can cause uncertainties in processes of environmental measurements.

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