

A Low-Cost Calibration Method for Temperature, Relative Humidity, and Carbon Dioxide Sensors Used in Air Quality Monitoring Systems

Rosa Amalia González Rivero, Luis Ernesto Morera Hernández, Olivier Schalm, Erik Hernández Rodríguez, Daniellys Alejo Sánchez, Mayra C. Morales Pérez, Vladimir Nuñez Caraballo, Werner Jacobs and Alain Martínez Laguardia

1. Introduction

If the reader wants to use the low-cost calibration methods as described in the article, one needs to perform several straightforward calculations. The calculations rely on several well-known formula. However, the combination of formulas come from several publications or disciplines and it is possible that one will need some time to collect the required background information. To simplify that work, an overview of the most important formulas is given in the Supplementary Material. This section will give an insight in (1) the calculation of the amount of produced gas in a syringe expressed in mole, (2) the calculation of the relative humidity (RH) in a closed box caused by a beaker containing a glycerol-water mixture, and (3) the calculation of the air exchange rate of the closed box to determine how well it is sealed from its environment. Table S1 gives an overview of all the symbols used in the formulas.

Table S1. Overview of the symbols used in the equations.

Symbol	Description	Unit
P_{gas}	Pressure of the gas inside the syringe	1 Pa = 1 N m ⁻²
P_{atm}	Atmospheric pressure	Pa
Δp	Pressure difference between the atmosphere and the syringe as measured by the water column in the hose	Pa
p_{vapour}	Pressure in the syringe caused by the saturated vapour	Pa
ρ	Density of the liquid (i.e., deionized water) in the hose	g mL ⁻¹
g	Gravity acceleration	9.81 m s ⁻²
Δh	Height of the water column	m
c	Constant in the empirical formula of Magnus and Tetens	611 Pa
a	Constant in the empirical formula of Magnus and Tetens	7.5
b	Constant in the empirical formula of Magnus and Tetens	237.3
t	Temperature	°C
V	Volume of the gas inside the syringe	m ³
R	Gas constant	8.3144 J K ⁻¹ mole ⁻¹
T	Temperature of the room	T[K] = t[°C] + 273.15
n	Amount of gas molecules in the syringe	mole

ρ_{sol}	Density of the glycerol-water solution used to control the RH in the calibration box.	g mL ⁻¹
$w_{glycerol}$	Weight fraction of the glycerol in the solution	
N	Airtightness expressed as air change (or exchange) rate	h ⁻¹
C_{start}	Internal concentration of tracer gas at the test onset	ppm
C_{end}	Internal concentration of tracer gas at the test end	ppm
$C_{background}$	External (room) concentration of tracer gas	ppm
Δt	Duration between measurements of C	hour

2. Calculation of the amount of gas generated in a syringe

The syringe in which the gas is produced contains a certain amount of gas molecules. In addition, it is also saturated by water vapour. To calculate the total amount of gas molecules inside the syringe expressed in mole the ideal gas law can be used (i.e., eq. S1). Since all solutions are at room temperature, the generated gas will also be at room temperature as well. The temperature of the room can be measured with a glass thermometer. The volume of generated gas can be measured from the scale on the syringe. The only remaining quantity that requires more attention is the calculation of the gas pressure inside the syringe.

$$p_{gas}V = nRT \Leftrightarrow n = \frac{p_{gas}V}{RT} \quad (S1)$$

The total pressure of an ideal gas mixture in the syringe is the sum of the partial pressures of the individual gases in the mixture (Dalton's Law). The syringe is largely filled by the generated gas but it is also saturated by water vapour. This means that the total pressure in the syringe $p_{syringe}$ is equal to $p_{gas} + p_{vapour}$ (eq. S2). The saturation vapour pressure of water p_{vapour} can be calculated with the empirical formula of Magnus and Tetens (eq. S3) and can be determined when the room temperature t [°C] is known (see also Fig. S-1a). The water column in the hose in the setup shown in Fig. S1 does not only close the connection with the atmosphere, it also gives the pressure difference between atmosphere and syringe (eq. S4). The water column also shows that the pressure of the gas in the syringe is higher than the atmospheric pressure (see Fig. S1). From the room temperature t and the difference in height Δh , it is possible to calculate the pressure of the gas.

$$p_{syringe} = p_{gas} + p_{vapour} \quad (S2)$$

$$p_{vapour} = ce^{at/(b+t)} \quad (S3)$$

$$\Delta p = \rho g \Delta h \quad (S4)$$

$$p_{syringe} = p_{atm} + \Delta p \Leftrightarrow p_{gas} = p_{atm} + \Delta p - p_{vapour} \quad (S5)$$

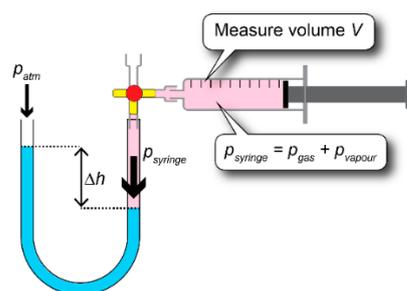


Figure S1. Schematic overview illustrating the pressure difference between the atmosphere and syringe.

The barometric pressure at sea level can be approximated by the average pressure at sea level, which is defined as 1013 hPa. In reality, the atmospheric pressure inside the room fluctuates with the weather. These fluctuations are considered when using publicly available pressures from local meteorological services. This imperfect way of measuring the barometric pressure can introduce errors in the calculation of the amount of gas inside the syringe. In addition, a small amount of gas between the water level in the hose and the three-way valve B in Fig. 4 is lost.

3. Calculation of the relative humidity from glycerol-water solution

The RH in a closed box can be controlled either by salt solutions or by glycerol solutions. The disadvantage of controlling RH with saturated salt solutions is that for each value of a series of RH, a different salt is needed. It also means that several products need to be purchased. In addition, salts in solutions undergo creeping where crystals precipitate far from an evaporating salt solution boundary. As a result, salts cover the surfaces of the glass beaker. Glycerol solutions have the advantage that the RH can be set continuously by adjusting the dilution of glycerol. The RH inside the closed plastic box set by the glycerol solution can be calculated in a quantitative way using eq. S6. To determine the RH, the density of the solution is determined with a calibrated pycnometer of 10 mL.

$$RH = -\frac{\rho_{sol}^{12.4} - 19.9}{0.189} \quad (S6)$$

The largest error in the determination of the RH using a glycerol-water mixture is the variation of the room temperature and its effect on the density of the solution. The formulas are determined for room temperature (24–25°C). In a laboratory located in a tropical country, the temperature in the room is about 25–30°C.

4. Calculation of the airtightness of the calibration box

The airtightness (N) or air exchange rate is defined as the number of times that air is replaced in an enclosure every hour, thus, is expressed in air change per hour (h^{-1}). The value is typically determined by injecting a tracer gas (e.g., CO_2) in the box so that its concentration is higher than its natural concentration in the atmosphere. Then, the exponential decay of the tracer gas in the box is monitored. An airtightness of one per hour (eq. S7) means that the entire volume leaves the box in 1 hour and that external air enters with the same speed.

$$N = \frac{\ln(C_{\text{start}} - C_{\text{background}}) - \ln(C_{\text{end}} - C_{\text{background}})}{\Delta t} \quad (S7)$$

Low-cost sensors are used to determine the air exchange rate in the box. This means that the air exchange rate is measured with a sensor that is in the process of being calibrated. In case the sensor makes a constant error in measuring CO₂ concentrations, then that constant is neutralized in the difference between the concentration in the box and the environment ($C_{start} + \Delta C - C_{background} - \Delta C$). Constant calibration errors will have no impact on the determination of air tightness.