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UNCERTAINTY ESTIMATION OF THE EXPERIMENTAL ASSESSMENT OF THE VENTILATION RATE

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SUMMARY

In the aim of the project GERIA (Geriatric Study of the Health Effects of Indoor Air Quality in Elderly Care Centres) measurements were carried out to assess the concentration of CO_2 inside of elderly care centres bedrooms. In previous works, a methodology was developed to determine the ventilation rate from these values when CO_2 emissions have only human origin. In this paper, we proceed to the estimation of measurement uncertainty associated with this method of determining the ventilation rate using a Monte Carlo method.

Keywords: CO_2 concentration / Ventilation rate / Uncertainty estimation

1. INTRODUCTION

Under the aim of the Project GERIA (Geriatric Study of Health Effects in Interior Quality Air at Elderly Care Centres in Portugal) continuous measurements of CO_2 concentration were carried out during the night in the bedroom of elderly care centres (ECC) In the case of these rooms, CO_2 is released exclusively due to the metabolism of the occupants and it is harmless due to its low concentration. However, it may be used as a surrogate marker of the human pollution released to the indoor environment and of the indoor air quality (IAQ).

Several methods may be used for the estimation of the ventilation rate of buildings (Ogink et al.; 2013; McWilliams, 2002). Tracer gas methods are commonly used for that purpose and several studies have been carried out using CO_2 emitted by the metabolic activity of humans and cattle (Ogink et al.; 2013). Usually the ventilation rate is assessed considering the CO_2 mass balance in the compartment, assuming that the indoor CO_2 concentration reached the steady state. In this method the rigorous assessment of the CO_2 release rate is required (Pedersen et al., 2008; Zhang et al; 2005; Calvet et al., 2011). Constant emission method was also used for the assessment of ventilation rate of cavities using unsteady state but, again the dosing rate must be known (Marques da Silva, 2015; Oliveira, 2001). Calvet et al. (2013) reviewed the origin and magnitude of errors associated with emissions from naturally ventilated buildings as compared to those typically found in mechanical ventilation. They found that the emission standard uncertainty in mechanical ventilation is at best 10% or more of the measured value, whereas in natural ventilation it may be considerably higher and there may also be significant unquantifiable biases. This uncertainty affects the estimate of the ventilation rate.

In the CO_2 measurements carried out at ECC bedrooms it was found that a significant part of them (about 30%) agree well with the theoretical curve obtained when considering a CO_2 constant emission rate and a constant rate of ventilation. Thus, a method was developed which consists in fitting the theoretical curve to the experimental results with two degrees of freedom by the method of least squares, allowing an estimated average emission rate and the average ventilation rate (Cerqueira et al., 2014). The quality of this fitting was assessed by the Kolmogorov-Smirnov test, allowing having an objective criterion for acceptance of the adjustment (Cerqueira, 2015). In order to know the accuracy of the method and to carry out the validation of the results obtained, considering the application of a non-linear mathematical model, this paper develops the estimation of the uncertainty of measurement by applying a numerical simulation method (Monte Carlo).

2. METHODS

2.1. Monitoring the indoor environment

In the framework of GERIA Project, 33 ECC in Lisbon were randomly selected in the preliminary phase (but only 18 were studied for IAQ). In the framework of ventilation, analysis and IAQ a survey of the characteristics of building stock was made and the measurement of CO_2 concentration, temperature and relative humidity in several sleeping rooms and in the outdoor environment was carried out.

In this study the level of CO_2 was used as surrogate marker of the pollution in the indoor air caused by human breathing. The measurement campaign was conducted between November 2013 and March 2014 and between April 2014 and July 2014. The recording of the measurements in sleeping rooms was carried out overnight about 12 hours on average. The measuring devices have the following expanded uncertainty estimates: (i) for CO_2 of U_{CO2}=62ppm for one measurement of 1000ppm and $U\,(C_{CO_2})$=175 ppm for one measurement of 3000 ppm and (ii) for temperature of $U(T)$=1,16^{o}C. The final goal was to find any association between air quality and respiratory health conditions.

2.2. Assessment of ventilation rates

To evaluate the ventilation rates the constant emission method was used. To minimize the impact on routines of users, CO_2 originating from the human breath was used as a tracer gas and it is assumed that the CO_2 release rate was constant.

As the source is constituted by the emissions of the occupants, the reliability of these measurements depends on the regular activity of the occupants, (uninterrupted) presence of the occupants during the measurements, permanence of the windows and doors closed and regularity of the weather during the measurement period. The measurement starts when the occupants enter the sleeping rooms and can be performed all night if the registry of CO_2 concentration does not show irregularities (i.e. changes in the pattern of emissions).

Assuming that the indoor temperature and outside temperature of air are approximately constant and uniform (this implies that the respective densities do not change in time), the mass balance can be expressed in terms of volumetric flow rates by equation (1), where the solution is given by the equation (2).

$$V\frac{\mathrm{d}c}{\mathrm{d}t} = G + \dot{V}(c_\mathrm{e} - c) \qquad (1)$$

$$c(t) = \left[\frac{\dot{V}.c_e + G}{\dot{V} + G}\right] . \left\{1 - e^{\frac{-(\dot{V}+G).t}{V}}\right\} + c_0 . e^{\frac{-(\dot{V}+G).t}{V}} \quad (2)$$

Where V is the effective volume of enclosure [m^3], $\dot{V}$ is outdoor air supply rate [$m^3.s^{-1}$], c_e is the outdoor concentration of pollutant [ppm], c_0 internal concentration of initial pollutant [ppm], $c(t)$ is the volumetric concentration of indoor pollutant at the time t [ppm] and G is the volume of pollutant generated [$m^3.s^{-1}$] (Awbi, 2003).

In the application of the constant emission technique it is assumed that starting form equation 2, the production of CO_2 is constant, yielding to the equation 3, which characterize the constant emission phase of CO_2 in the sleeping room:

$$C = \frac{(\dot{V}.C_e + G)}{(\dot{V} + G)} + \left[C_0 - \frac{(\dot{V}.C_e + G)}{(\dot{V} + G)}\right] . e^{-\left(\frac{\dot{V}+G}{V}\right).t} \quad (3)$$

To determine the ventilation rates the least squares regression method was used. The adjustment was made for two variables ($\dot{V}$ and G). Finally the ventilation rate ($\dot{V}/V$) was obtained from the adjusted volume flow rate ($\dot{V}$). Figure 1 shows an example of the experimental results (black line) and of the curve fitting (red line). The problem envisaged in this paper is: how to determine the uncertainty of the experimental ventilation rate?

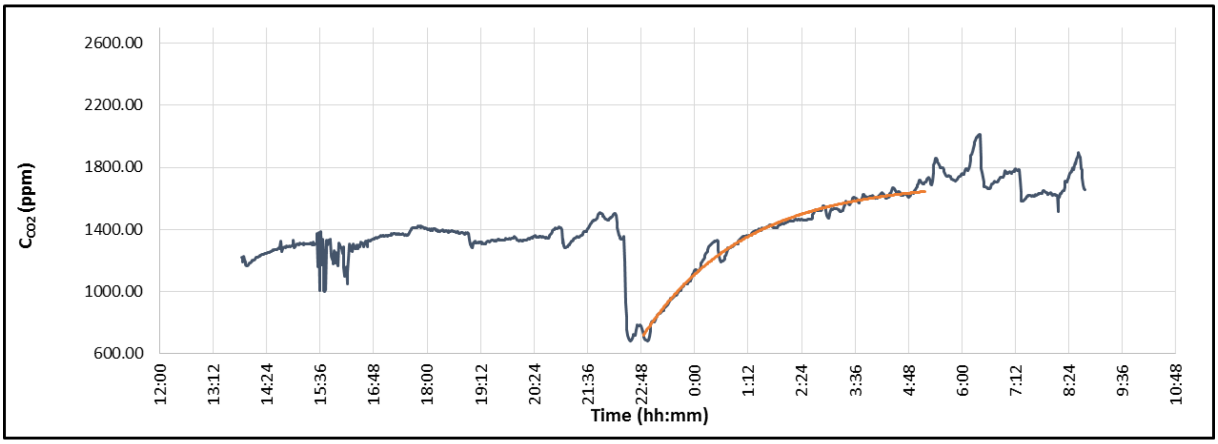

Fig. 1 – Experimental results and curve fitting example

2.3. Assessment of measurement uncertainty

The expression of measurement results obtained from experimental stochastic processes are considered today as complete if they include a best estimate and its measurement uncertainty, being the second parameter necessary to express the variability of random effects that affect the realization of the measurement.

In 1993, following the establishment of working groups by ISO, IEC, IUPAC, IUPAC, OIML and other organizations, ISO published an international guidance document called ISO-GUM (BIPM, JCGM:100, 2008) containing a method for the evaluation of the measurement uncertainties, including the widespread Law of Propagation of Uncertainties (LPU). This probabilistic approach of measurement considers that the values of the input quantities are represented by probability distribution functions (PDF) whose convolution yields the PDF of the output quantity, which contains the information necessary to express the accuracy of the result of measurement.

The approach proposed in ISO-GUM has as its starting point a formulation consisting of establishing a functional relationship (linear, explicit and univariate) between *N* input quantities, X_1, ..., X_N, collectively expressed by the vector $\boldsymbol{X}=(X_1, ..., X_N)^T$ (meaning T the transpose vector) and an output quantity, *Y.*

$$\boldsymbol{Y} = f(\boldsymbol{X}) = f(X_1, \cdots, X_N) \tag{4}$$

From equation (4), the next step of the method is to identify the sources of uncertainty and quantify their contributions. As a rule, these contributions are related to the parameters that express the variability of the PDF established, i.e., the estimators of standard deviation of these functions.

According to ISO-GUM, the LPU function (5) allows to combine input measurement uncertainties to calculate the output combined measurement uncertainty as follows (assuming that there is no correlation between the quantities, in which case there is a more complex expression that can get the ISO-GUM).

$$\boldsymbol{u_C^2(y)} = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 \cdot \boldsymbol{u^2(x_i)} \tag{5}$$

Tho apply this function, the terms that correspond to partial derivatives must be known (which implies that the functional relationship must be differentiable), as well as the several contributions to the uncertainty associated with each of the input quantities $u(x_i)$. Furthermore, based on the assumption that the Central Limit Theorem applies, it's also allowed to consider that the PDF of the output quantity is Gaussian and, because of that, the measurement uncertainty expanded expressed to a 95% confidence interval is achievable multiplying the combined uncertainty by the coverage factor of 2.00 (obtained for a representative sample of the quantity to be measured).

As mentioned earlier, this general approach is exact assuming that the functional relation is linear (or close to linear) and explicit. The spread of the ISO-GUM and its LPU method quickly showed that there were several categories of problems that could not be exactly solved using this approach. To overcome this difficulty, alternative approaches were studied, including the application of Monte Carlo method in the evaluation of measurement uncertainty (Ribeiro, 2007) and was published the Supplement 1 of the ISO-GUM (BIPM, JCGM:100, 2008) describing how to implement this numerical simulation approach able to promote numerical convolution of PDF of mathematical models. This approach applies to classes of problems like this, which requires the numerical optimization of an implicit relation of the type:

$$\boldsymbol{h}(\boldsymbol{Y},\boldsymbol{X})=0 \tag{6}$$

As the ventilation rate is estimated by a numerical fitting process using the least squares method, it is not possible to establish a differentiable function that relates the input variables (measurements of CO_2 concentration over time) and the output variables (particularly the rate of ventilation). Thus, it was necessary to use of Monte Carlo method.

In equation (3), a relation between the outdoor air supply rate and the effective volume of the enclosure is used, establishing a new parameter called frequency of the ventilation system, R_{ph}, given by:

$$\dot{V} = R_{ph} \cdot V \tag{7}$$

To perform the evaluation of uncertainty is required to obtain the measurement uncertainties related to the input quantities, c_e, c_o, V and t, being the values used from experimental data. The values of combined standard uncertainties considered for the measurement of concentration were 0,031 ppm, for lenght measurements of 1 mm and for time measurements of 0,1 s.

The numerical process of optimization was developed for the studied case developing a Matlab algorithm to solve the following conditional mathematical model:

$$\text{Min}(C, R\text{ph}, G)=0 \tag{8}$$

With two variables (R_{ph} and G) being considered as arguments of optimization of the function.

The use of Monte Carlo Method (MCM) to evaluate the measurement uncertainties using Matlab was based on the generation of pseudo random number sequences supported in Mersenne-Twister algorithm (Matsumoto and Nishimura, 1993), providing random data vectors with 10^5 draws, and applied the intrinsic function of Matlab “fminsearch" which determines the minimum of a scalar function of several input variables, given initial estimates for the optimization variables mentioned above. A schematic diagram of the functional relations can be found in Figure 2.

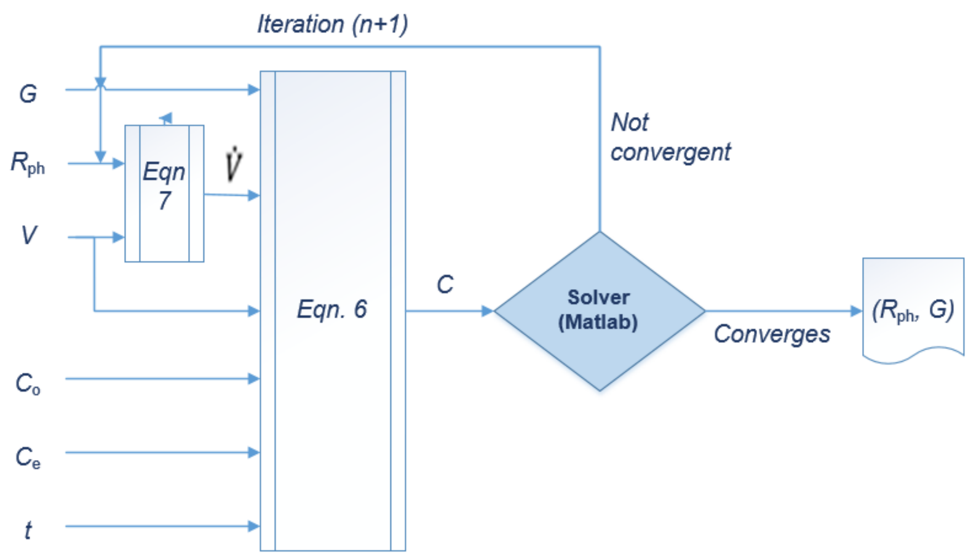

Figure 2 – Schematic diagram of the functional relations and optimization process developed

The MCM approach to evaluate measurement uncertainties of output quantities (see Fig. 2) was developed generating numerical sequences of each input quantity in accordance with its specific PDF, introducing the initial values for the optimization variables R_{ph} and G and defining a convergence criterion. The obtained values of optimized parameters defining output PDFs were ordered to allow to identify the limits of the 95% confidence intervals, whose magnitude indicates the extended uncertainty of measurement of these quantities.

The case selected to be studied is described in "Study CO_2 night, fall," having been used to excel spreadsheet labeled "File L19-D.Q1" corresponding to a room with id. 4399001 and occupation of two people. The input data are as follows: height = 3,3 m compartment, compartment area = 20,7 m^2, volume = 67,4 m^3, c_o (ppm) = 872 and c_e (ppm) = 553. Experimental data used was obtained for a time interval of 08:30 hours corresponding to 601 measurements at intervals of 1 min (see Fig. 1). Two other cases have been selected, one from the excel spreadsheet labeled “L17-B.Q24-(…)” (compartment id. 4101042 and occupation of three persons) and another from the excel spreadsheet labeled “L05-Eq.C” (compartment id. 2999114 and occupation of one person).

3. ANALYSIS OF THE RESULTS

Using the experimental data, it was possible to use the MCM to estimate uncertainties associated with measuring function of optimization variables, R_{ph} and G, being presented two output PDF´s of these quantities obtained through the run of 10^5 draws including the optimization process.

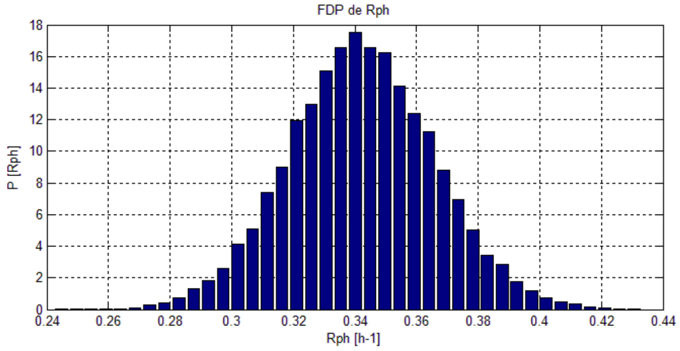

Figure 3 – PDF of the output quantity R_{ph}

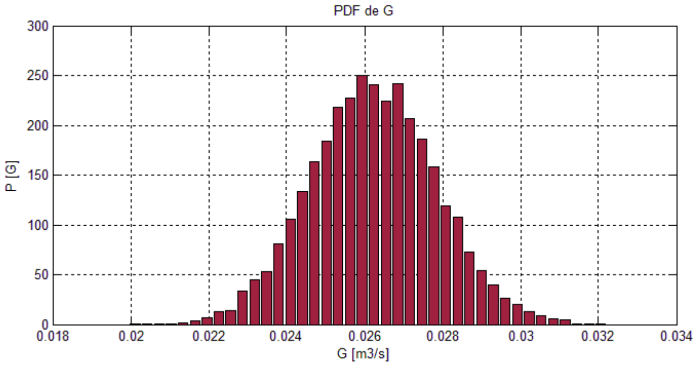

Figure 4 – PDF of the output quantity *G*

The estimates of the expanded uncertainties are presented in the Table 1, being additionally presented the skewness and kurtosis coefficients which express the deviation from the Gaussian PDF (reference values 0 and 3, respectively). In both cases, the results show that the PDF obtained can be considered to have Gaussian shape.

Quantity	Estimate	Expanded uncertainty (95%)	Relative uncertainty (95%)	Numerical accuracy	Skewness coefficient	Kurtosis coefficient
G (m^3/s)	0,026 23	0,003 2	12 %	0,000 2	0,02	2,96
R_{ph} calc. (h^{-1})	0,342 0	0,048	14 %	0,002 6	0,01	2,97

Table 1 – Results obtained for the output quantities using the case study ref. L19-D.Q1

Quantity	Estimate	Expanded uncertainty (95%)	Relative uncertainty (95%)	Numerical accuracy	Skewness coefficient	Kurtosis coefficient
G (m^3/s)	0,024 52	0,004 7	19 %	0,000 2	0,00	3,01
R_{ph} calc. (h^{-1})	0,200	0,043	21 %	0,002 7	0,02	2,99

Table 2 – Results obtained for the output quantities using the case study ref. L17-B.Q24

Quantity	Estimate	Expanded uncertainty (95%)	Relative uncertainty (95%)	Numerical accuracy	Skewness coefficient	Kurtosis coefficient
G (m^3/s)	0,007 29	0,001 1	15 %	0,000 2	0,01	2,98
R_{ph} calc. (h^{-1})	0,436	0,056	13 %	0,002 1	0,02	2,97

Table 3 – Results obtained for the output quantities using the case study ref. L05-Eq.C

Table 1 also indicates the level of accuracy (Cox and Harris, 2010), (Cox et al., 2012) obtained in the simulation, showing that its magnitude is in conformity with the expression of the uncertainty interval, allowing to validate these results.

The study carried out also considered two other experimental sets obtained for higher and lower values of input quantities (namely, the concentrations and outdoor air supply rate), aiming to evaluate the effect of these input quantities into the measurement uncertainties of the output quantities estimates (see tables 2 and 3). The experimental study showed that the relative expanded uncertainties found could reach higher values up to 21%, being the numerical accuracy and related coefficients (as presented in Table 1) of similar magnitude.

These CO_2 measurements were not carried out with the purpose of the assessment of the ventilation rate; they were carried out with the purpose of recording of the indoor air quality conditions that occur during the night in these bedrooms. The uncertainties of 14% (for the case study ref. L19-D.Q1) and 21% (for the case study ref. L17-B.Q24), although apparently high, are small enough to show that this measurement is below the recommended level for housing in Portuguese regulation (RDEEH, that points to the minimum value of 0,4 h^{-1}) thus allowing to validate the method as suitable for this intended purpose. Despite the uncertainty for the case study ref. L05-Eq.C being the smallest (just 13%), the estimated value of the ventilation rate (0,436 h^{-1}) is too close to the limit of 0,4 h^{-1}, thus not allowing to state that the ventilation rate of this room is above the threshold limit.

Another interesting result to point out is that the estimate of the CO_2 human metabolic emission and its uncertainty, for the case study ref. L19-D.Q1, is correctly laying between the extreme values of 0,0229 m^3/h (2 people 70 kg weight, 1,60 m tall and metabolic rate 46 W/m^2) and 0,0302 m^3/h (2 people 70 kg weight, 1,70 m tall and metabolic rate 58 W/m^2) (Awbi, 2003). This shows that the results of this assessment are consistent with the number of occupants in the room. However, for the other two case studies, they are pointing out to the estimation of the CO_2 human metabolic emission (for one person) laying between the extreme values of 0,0062 m^3/h and 0,0097 m^3/h. These values are very low and are not compatible with the metabolic rate of 46 W/m^2, corresponding to a reclined person (Awbi, 2003), and are pointing out to lower metabolic rates.

4. CONCLUSIONS

Records of the CO_2 human metabolic emissions have been carried out in bedrooms of elderly care centres. The uncertainty assessment, using Monte Carlo Method, showed that the expanded uncertainty of the average ventilation rate is laying between 13% and 21% for these case studies, and that the uncertainty for the CO_2 human metabolic emission is laying between 12% and 19%.

The results show that this approach has potential to be used in estimating average rates of ventilation with an acceptable uncertainty for this type of phenomena, being able to validate the method and to establish a conformity assessment procedure to accept experimental data.

5. ACKNOWLEDGEMENT

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