An Attempt to Model Ventilation Rate in Classrooms Based on the Measurement of Relative Humidity

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Abstract

Indirect CO_2-based measurement of the ventilation rate is a well-established method based upon a balance equation of the CO_2 generated by people and dispersed by infiltration and ventilation. In principle, ventilation rate can also be estimated by water vapour mass balance when storage terms are properly modelled. This work aims to benchmark the CO_2-based model and the water vapour-based model to estimate of ventilation rate in classrooms. The case study is a secondary school in Morlupo, Rome. Here, four naturally ventilated classrooms and the adjacent spaces were monitored for a two-week period (indoor temperature and relative humidity RH, CO_2 concentration, occupancy, outdoor temperature and RH). The ventilation rate for each classroom was estimated using the indirect CO_2-based method and then fed to an energy model developed in TRNSYS. Buffer effects for moisture were estimated using a single-layer Equivalent Penetration Depth Model. The simulated humidity ratio was compared to the measured one and input parameters for the storage models were tweaked until convergence using an optimization algorithm. Such process was repeated for 2 of the 4 classrooms. Then, the tuned parameters identified for the storage model were used as input on the remaining 2 classrooms and the ventilation rate obtained using the water-vapour based method was compared to the results of the CO_2-based method. Results show that the water vapour-based method significantly underestimates the air changes per hour, calling for an in-depth analysis of storage buffer terms.

1. Introduction

Several school buildings in Italy are not equipped with mechanical ventilation systems, as ventilation is guaranteed by window operation. In those cases, an accurate estimate of ventilation rate is relevant to allow for a proper energy modelling. Among the most used methods to estimate ventilation rate, indirect CO2-based measurement is a well-established approach based upon a balance equation of the CO2 generated by people and dispersed by infiltration and ventilation. CO2 sensors are largely available on the market, but their cost is not as low. Therefore, in the present work, alternative methods are explored to model ventilation rates in naturally ventilated environments.

1.1 Methods for Estimating Ventilation Rates

Ventilation rate is often indirectly measured using the indirect method based on the monitoring of CO_2 levels (Batterman, 2017). The governing balance equation is (Lu et al., 2011):

$$V\frac{dC_{in}}{dt} = G_{CO2} + Q \cdot (C_{out} - C_{in}) \tag{1}$$

where C denotes the CO_2 concentration measured indoors (C_{in}) and outdoors (C_{out}), G_{CO2} the CO_2 generation rate, V the room volume, and Q the ventilation rate. Integrating by parts and assuming constant boundary conditions, which can be acceptable for short reference time, the equation can be written in a form that allows for a straightforward implementation:

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$$C_{in}(t) = C_{out} + \frac{G_{CO2}}{Q} \cdot \left(1 - e^{-\frac{Q}{V}t}\right) + +(C_0 - C_{out}) \cdot e^{-\frac{Q}{V}t} \quad (2)$$

If the CO_2 concentration is measured indoors and the room characteristics are known, the only unknown is represented by the ventilation rate. Eq. 2 can then be solved by iteration.

Another method to estimate ventilation rate is based on the EN 16798-7 standard (CEN, 2017), which requires knowledge of the net open surface towards outdoors and climate data.

The ventilation rate could be in principle also recovered from a water vapour (WV) mass balance. The governing mass balance equation is (Lu, 2003):

$$M_{air}\frac{dc_{in}}{dt} = \dot{m}_{wv} + \dot{m} \cdot (c_{out} - c_{in}) + \sum \dot{M}_\iota \quad (3)$$

where, besides the quantities seen before, c is the humidity ratio, $\dot{m}_{wv}$ is the indoor generation mass rate of water vapour and $\sum \dot{M}_i$ is the sum of moisture transfer rates between room surfaces and indoor air. This can be modeled as an additional storage effect. The moisture storage term can be represented according to different methods, characterized by different complexities (Glass and Tenwolde, 2009), for example, the estimate of the average of the outdoor water vapor pressure to approximate short-term buffering effects (TenWolde and Walkers, 2001), or the admittance model proposed by Jones (1993).

Besides solving the heat and mass transfer model using a finite-difference approach, the most common simplified methods used for considering short-term buffering effects are the Effective Capacitance Model and the Equivalent Penetration Depth Model (Janssen and Roels, 2009). In the Effective Capacitance Model, a multiplier is applied to the left-hand term of Eq. 3 to account for the added moisture capacity due to walls and internal objects. The empirical quantification of the multiplier and the diffculty to give it a physical meaning make this model slightly inaccurate (Woods, 2013). Regarding the Equivalent Penetration Depth (EPD) model, the main underlying hypothesis is that the moisture buffering process is determined by one thin layer of the surface that faces the room, which is subject to a cyclic variation of humidity. When short-term and long-term buffering phenomena have to be accounted for, the use of two layers is envisaged. The water vapour mass balance according to the EPD model is presented in equation 4. In addition to the terms described above, m_d describes exchange coefficients relative to adjacent airnodes, β_{surf} is the exchange coefficient for airnode-surface buffer and c_{surf} is the humidity ratio of the surface storage.

$$M_{air}\frac{dc_{in}}{dt} = \dot{m}_{wv} + \dot{m} \cdot (c_{out} - c_{in}) + \sum_j \dot{m}_d \cdot (c_{in,j} - c_{in}) + \beta_{surf} \cdot (c_{surf} - c_{in}) \quad (4)$$

The dynamics of the water content in the surface buffer layer is presented in Eq. 5, where k_{surf} is the gradient of the sorptive isotherm and M_{surf} is the mass of the buffer layer. β_{surf} (β in the following) can be determined based on the equivalent penetration depth, the surface size of the buffer material and the diffusion resistance μ of the buffer material. The mass of the surface buffer can be estimated by multiplying the equivalent penetration depth and the density of the buffer material.

$$M_{surf}k_{surf}\frac{dc_{surf}}{dt} = \beta_{surf} \cdot (c_i - c_{surf}) \quad (5)$$

The EPD model is a compromise between the simple, inaccurate, effective capacitance approach and the complex, yet accurate, finite-difference approach.

1.2 Aim of the Research

The aim of this research is to test the accuracy that the water vapour-based model can achieve in estimating the ventilation rate compared to the standard CO_2-based method. To do this, monitored indoor parameters in a high school were used to implement an CO_2-based model for the calculation of natural ventilation rates in two classrooms which were then used to calibrate the buffer properties to be used in the water vapour-based method. Finally data collected in two other classrooms were used to compare the results obtained from the two methods. The relevance of the application stems from the consideration that the cost of T/RH sensors is significantly lower than that of CO_2 concentration sensors with comparable accuracy. Moreover, naturally ventilated classrooms offer an interest case study as generation rate is only determined by number of occupants, so as per carbon dioxide generation.

2. Method

The case study is a secondary school in Morlupo, Rome, dating back to the 1990s. The building is made of reinforced concrete and non-load bearing brick walls, with no insulation. A two-week measurement campaign was conducted in four classrooms (Figure 1). Air temperature, CO_2 concentration and relative humidity were monitored with a time resolution of 10 min, while temperature and relative humidity were monitored in the adjacent environments and outdoors. Occupancy information was collected by the students with an hourly time resolution.

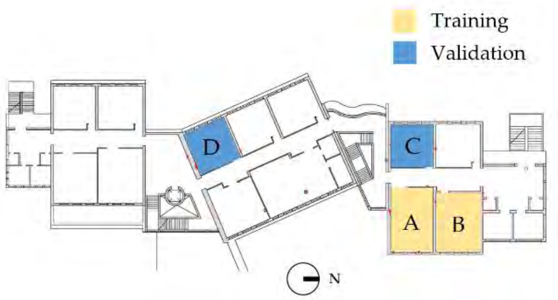

Fig. 1 – Second floor plan of the IIS Margherita Hack in Morlupo, Rome; classrooms used for training and testing

Data were processed as follows:

1. **Estimation of ventilation rate**. Ventilation rate was estimated by iteration based on CO_2 measurements and occupancy data. Outdoor CO_2 concentration was assumed to be 400 ppm, while CO_2 generation rate G_{CO2} was assumed equal to 0.216 l/min, after Johnson et al. (2018). Results from the solution of Eq. 2 were affected by implementation artifacts, partly due to weekly automatic calibration procedure. Therefore, data were smoothed, and outliers were identified as values exceeding the 95th percentile and excluded from the dataset. Missing values were replaced by linear interpolation.
2. **Optimization of Building Energy Simulations.** The energy models of classrooms A and B were implemented in TRNSYS (see Figure 1) and they were optimized using meta models (Prada et al., 2018) to determine parameters of moisture storage models. In detail, the target parameters to optimize were the mass of the buffer material (M), the gradient of the sorptive isotherm (k) and the exchange coefficient for air-node-surface buffer (β) for the EPD model. The assumed generation rate of water vapour was 55 g/h, which is the reference value associated to an "active" person according to BS 5250 (BSI, 2011).
3. **Model validation**. The Equivalent Penetration Depth determined from step 3 was used as input value to estimate (β, M) of classrooms C and D (see Figure 1) and validate the model. Ventilation rate is estimated from the water vapour mass balance through an iterative procedure and compared to the results of the CO_2-based method.

3. Results

By specifying the input parameters for the storage model, the assumption was made that the buffer was mostly generated by the plastered surface of the classrooms used to run the optimization (141 m^2 for classroom A, 150 m^2 for classroom B). Other parameters were set as follows: equivalent penetration depth d = 1 mm, ϱ = 900 kg/m^3, μ = 8, k = 0.015 (kg_w/kg_m/%). These hypotheses translate into β-values of 891 kg/h and 947 kg/h and M-values of 127 kg and 135 kg respectively for classrooms A and B.

Table 1 – Optimized input parameters for the EPD model

Cl.	k (kg_w/kg_m/%)	β (kg/h)	M (kg)	CVRMSE
A	0.38	371	127	0.086
B	0.43	371	137	0.083

The optimization algorithm returned the values reported in Table 1. While the mass of the buffer layer closely matches the original assumptions, the optimized values of k and β display much larger values, which go beyond physical representativeness of such quantities. This could be related to the buffer effect of other elements, such as the clothing of the students, that has limited impact on the overall mass (around 10 kg considering average fabric density, and an occupancy of 20 students), but whose buffer contribution has different time constants, which might become relevant considering the occupancy patterns of classrooms. The coefficient of variation of the root mean squared error (CVRMSE) displays a good performance of the model.

By equating the original β parameter accounting for plaster only and the effective β parameter derived by the optimization process, it was possible to identify the equivalent penetration depth that better characterized the moisture storage effect. For classroom A, this returned a thickness 0.0038 m, while for classroom B this returned a value of 0.0041 m.

Such input values were used for validation in the two remaining classrooms, C and D. The gradient of the sorptive isotherm was assumed to be 0.405 (kg_w/kg_m/%), i.e., the average of the optimized value. Likewise, the equivalent penetration depth was set to 0.004 m. The β and M parameters were calculated from such starting data and energy simulations were run on classrooms C and D for validation. The input parameters and the mean bias error of the models built for validation are displayed in Table 2. The mean bias error expressing the difference between the air changes per hour estimated using the CO_2-based method and the WV-based method is relatively high – 0.35 1/h (ACH) for classroom C and 0.41 1/h for classroom D.

Table 2 – Input parameters and Mean Bias Error (MBE) of the simulations run on classrooms C and D

Cl.	β (kg/h)	M (kg)	MBE (1/h)
C	317	454	0.35
D	321	460	0.41

The difference between the number of ACH calculated from the CO_2 method and the WV method is displayed in Figure 2. The ACH calculated from the CO_2-based method is in most cases higher than the one retrieved from WV-based method, with an interquartile range of approximately 0.7 1/h.

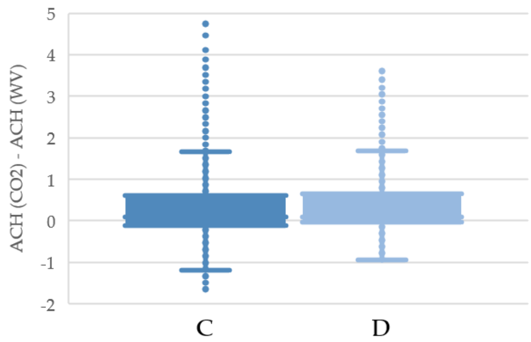

Fig. 2 – Difference between ACH calculated from CO_2-based method and WV-based method for classrooms C and D

4. Discussion

Estimating ventilation rate from water vapour balance finds an interesting application in naturally ventilated classrooms as the moisture loads due to typical living activities (cooking, having a shower, etc.) can be disregarded and occupancy has specific patterns, potentially easing the modelling of buffer phenomena. Nevertheless, results showed a large discrepancy between ventilation rates estimated from water vapour and CO_2 concentration mass balance.

These differences might be ascribed to several factors. First, the experimental data might bias the results in relation to (i) sensors' position in the classroom, which might have affected the readings of temperature, relative humidity and CO_2 concentration, (ii) sensors' accuracy, propagating calculation uncertainties (iii) data processing noise, as for instance the numerical artifacts introduced by the automatic calibration procedure of CO_2 sensors.

Errors related to the building energy simulation sum up to simplifications introduced by the EPD model; specifically, it should be considered that, in the current study, a single buffer layer was used as the observation period lasted 16 days and it was assumed that seasonal fluctuations were not relevant. The training performed on South-East facing classrooms, facing a closed parking lot, and testing performed on North-West facing classrooms, facing the hills, might have affected results as outdoor conditions might have been slightly different.

Finally, the optimization algorithm which returned effective values of β and M in a comprehensive way accounts also for the buffer storage represented by clothing of subjects in the room and the related temporal variability – contributions that could have been modelled separately.

5. Conclusion

This paper aimed at testing the accuracy that can be achieved by estimating ventilation rate from water vapour balance compared to estimates performed using the CO_2-based method in naturally ventilated classrooms. The environmental conditions in four classrooms, adjacent spaces and outdoors were monitored for 16 days. Two classrooms were used to train a buffer storage model by providing ventilation rates from CO_2-based models and adjusting the model relevant parameters by minimizing the difference between simulated and measured humidity ratio. This allowed us to tune input parameters for the equivalent penetration depth model, which were then used to model ventilation according to water-vapour based model in the two remaining classrooms, testing the quality of the model against the CO_2-based model prediction. Water-vapour based ventilation rate was largely underestimated, highlighting the need to provide more accurate estimate of the buffer storage term and its variation over time. Future work will include the analysis of a long-term dataset (7 months) and the implementation of analytical models for specific contributions of the moisture buffer.

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