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About the use of CO₂ as tracer gas for identification of air renewal; combination with co-heating test

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Abstract

Three types of tracer gas test are, until now, mentioned in international standards: Injection at constant indoor concentration, injection at constant flow rate and transient injection followed by a recording of the decontamination curve.

A fourth method is proposed in this paper: it is based on the same scenario as the third method, but with weighting of the mass of tracer gas (CO₂) injected and integration of the curve of indoor concentration on the whole testing period.

The concentration peak is used to identify the “effective” volume of the building zone considered; this volume, associated to the final concentration, is used to calculate the amount of CO₂ remaining inside the zone at the end of the test.

The total mass of renovation air is then deduced from the corresponding CO₂ mass balance. The CO₂ can be injected from a bottle or directly produced by combustion on site. In the latter case, the tracer gas method is combined with a co-heating test.

It can be done, for example, with a current camping butane cooker:

From the weighting of this device and continuous recording of air temperature, CO₂ concentration and humidity ratio, three significant (energy, CO₂ and water) balances are established in such a way to verify and tune a reference simulation model of the building zone.

Keywords: *air renewal, tracer gas,co-heating*

1. Introduction

Three types of tracer gas tests are, until now, mentioned in international standards [1]:

- 1) Controlled injection at constant indoor concentration;

- 2) Injection at constant flow rate on time long enough to reach a constant concentration
- 3) Transient injection, just until reaching a high enough indoor concentration and recording of the decontamination curve (linear in semi-logarithmic scale).

The main difficulty met with the *first method* is related to a correct control of gas injection.

The main inconvenient of the *second method* is the requirement of long enough test duration (proportional to the zone volume) in order to reach a steady state regime.

And the *third method* doesn't give a direct identification of the flow rate. It requires the identification of an "effective" volume of the zone considered and this volume is related to the actual air mixing inside the zone.

Also the slope of the semi-logarithmic decontamination law is not always easy to identify...

In the two first methods, the identification of the air flow rate is based on a stationary tracer gas mass balance: the amount of tracer gas injected inside the zone is removed by the ventilation.

A fourth method is proposed here: it is based on the same scenario as the third method, but with careful weighting of the mass of tracer gas injected and on the integration of the curve of indoor concentration on the whole testing period.

CO₂ appears today as a very good candidate: it is almost free, non-toxic and cheap and reliable CO₂ sensors are now currently available.

2. Description of the new method

A schema of the measuring equipment is shown in Figure 1.

The controlled CO₂ injection is realized with a system associating one or several bottles, a balance, a re-heater, one or several expansion valves and one or several capillary tubes.

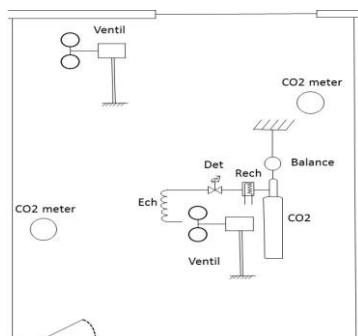


Figure 1: The measuring equipment

The test must include three consecutive periods:

- 1) Recording of all relevant variables *before* any injection, in order to identify as well as possible the initial conditions and to verify that the system considered is actually in steady state regime;
- 2) CO₂ *injection* until reaching a tolerable peak of indoor concentration (according to occupants and/or sensors tolerances), for example of the order of 5000 ppm;
- 3) *Decontamination* with continuous recording of the indoor concentration until reaching a much lower level (if possible below 2000 or even 1000 ppm).

The total mass of renovation air is deduced from the corresponding CO₂ mass balance, with consideration to the CO₂ emitted by the occupants as well as to the CO₂ injected, for example from some bottles:

$$\dot{M}_{\text{CO}_2;\text{peroccupant};\text{gh}} = 40 \text{ [g/h]} \quad (1)$$

$$\dot{M}_{\text{CO}_2;\text{occupants}} = n_{\text{occ}} \cdot \frac{\dot{M}_{\text{CO}_2;\text{peroccupant};\text{gh}}}{\text{s/h} \cdot \text{g/kg}} \quad (2)$$

$$M_{\text{CO}_2;\text{occupants}} = \dot{M}_{\text{CO}_2;\text{occupants}} \cdot (t_1 - t_0) \quad (3)$$

$$M_{\text{CO}_2;\text{injected}} = M_{\text{balance};0} - M_{\text{balance};1} \quad (4)$$

$$M_{\text{CO}_2;\text{su}} = M_{\text{CO}_2;\text{occupants}} + M_{\text{CO}_2;\text{injected}} \quad (5)$$

$$DM_{\text{CO}_2;\text{in}} = C_{\text{CO}_2;\text{in}} \cdot (X_{\text{CO}_2;\text{in}} - X_{\text{CO}_2;\text{in};0}) \quad (6)$$

$$C_{\text{CO}_2;\text{in}} = MM_{\text{CO}_2} \cdot \frac{V}{V_a \cdot MM_{\text{dry};\text{air}}} \quad (7)$$

The global CO₂ balance is used to identify the average fresh air mass having crossed the zone on the selected time period:

$$M_{\text{CO}_2;\text{ex}} = M_{\text{CO}_2;\text{su}} - DM_{\text{CO}_2;\text{in}} \quad (8)$$

$$M_{\text{freshair}} = \frac{M_{\text{CO}_2;\text{ex}}}{\overline{DX}_{\text{CO}_2;\text{in};\text{out}}} \cdot \frac{MM_{\text{CO}_2}}{MM_{\text{dry air}}} \quad (9)$$

$$(10)$$

$$\overline{DX_{CO_2;in;out}} = \frac{\int_{t_0}^{t_1} (X_{CO_2;in} - X_{CO_2;out}) dt}{t_1 - t_0} \quad (11)$$

$$\dot{M}_{f_{reshair}} = \frac{M_{f_{reshair}}}{t_1 - t_0} \quad (12)$$

$$\dot{M}_{f_{reshair}} = \dot{V}_{f_{reshair};m3/h} \cdot \frac{r}{s/h} \quad (13)$$

A simulation is then performed with above-identified air flow rate and CO₂ flow rate as input variables:

$$\dot{M}_{CO_2;ex;simulated} = \dot{M}_{CO_2;su;simulated} - \frac{dM_{CO_2in}}{d\tau_{simulated}} \quad (14)$$

$$\dot{M}_{CO_2;ex;simulated} = \dot{M}_{f_{reshair;simulated}} \cdot (X_{CO_2;in;simulated} - X_{CO_2;out}) \cdot \frac{MM_{CO_2}}{MM_{dry\ air}} \quad (15)$$

$$\dot{M}_{CO_2;su;simulated} = \dot{M}_{CO_2;occupants} + \dot{M}_{CO_2;injected;simulated} \quad (16)$$

$$DM_{CO_2;in;simulated} = \int_{t_0}^{t_1} \left[\frac{dM_{CO_2in}}{d\tau_{simulated}} \right] dt \quad (17)$$

$$DM_{CO_2;in;simulated} = C_{CO_2;in} \cdot (X_{CO_2;in;simulated} - X_{CO_2;in;0}) \quad (18)$$

The concentration peak is used to identify (by comparison between simulation and measure) the “effective” volume of the building zone considered; this volume, associated to the final concentration, is used to calculate the amount of CO₂ remaining inside the zone at the end of the test.

This peak is only little influenced by the actual air flow rate, in such a way that only a small number of iterations is actually required.

A comparison between “*effective*” and “*geometrical*” volumes can be used to assess the air mixing effectiveness.

3. Experimental validation

The use of CO₂ alone was tested, first in a large laboratory building and then in a real office building where the actual ventilation flow rate was directly measurable.

3.1 In laboratory

A typical curve recorded by the balance is shown in Figure 2.

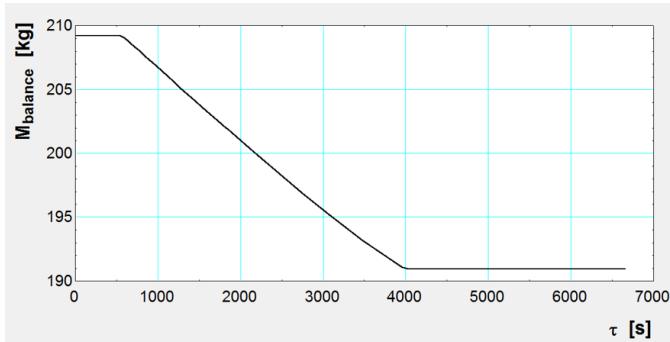


Figure2: Weight of the CO₂ bottles

A comparison between recorded and simulated indoor CO₂ concentrations is presented in Figure 3.

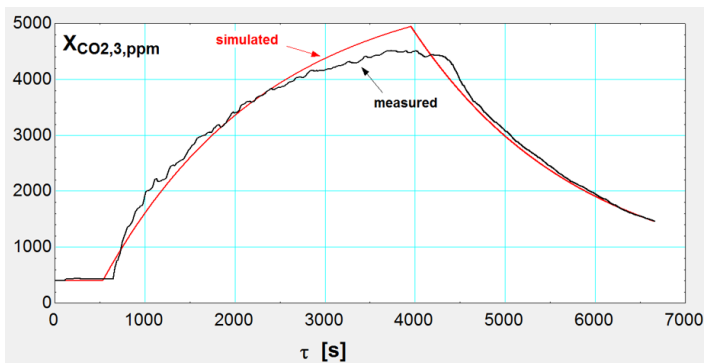


Figure 3: Recorded and simulated CO₂ concentrations inside the zone

The difference is explained by (still remaining) uncontrolled infiltrations and also by some remaining non-homogeneity in internal contamination (non-perfect mixing).

3.2 In an office room

The building considered is equipped with a centralized HVAC system.

One of the air terminal unit has been calibrated in laboratory in order to identify a relationship between the air flow rate supplied to the room and the terminal pressure drop. Such relationship is plotted in Figure 4.

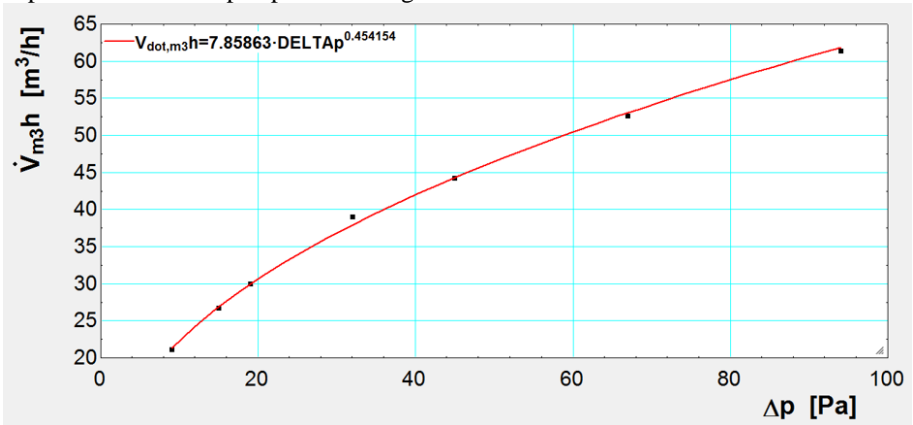


Figure 4: Calibration of one terminal unit

The tracer gas equipment used in this office room is presented in Figure 5.



Figure 5 : Tracer gas equipment

Recorded and simulated indoor air CO₂ concentrations are compared in Figure 6. Several iterations are required to identify a satisfactory value of the effective volume. The best result (coincidence between the recorded and simulated peaks) is obtained with an effective volume of 33 m³.

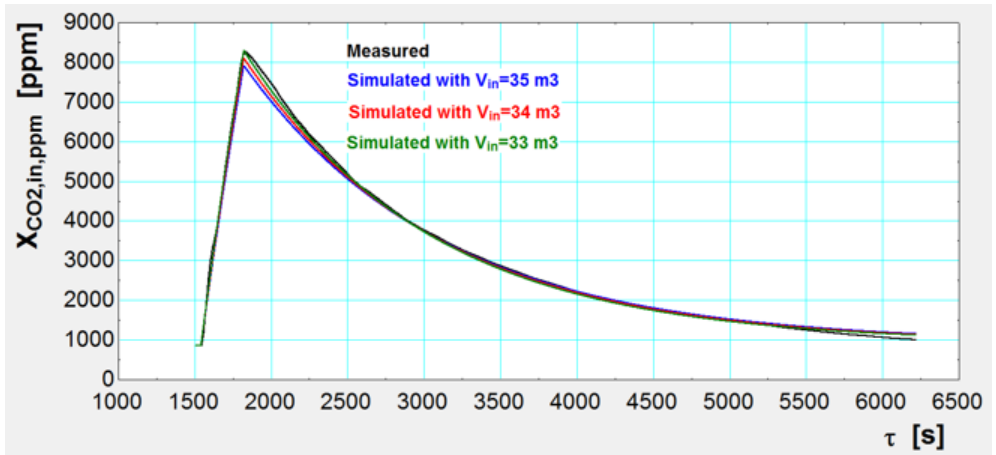


Figure 6: measured and simulated CO2 concentrations inside the zone

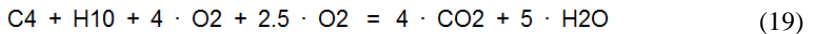
4. Possibility of combination with a co-heating test

4.1 The principle

An attractive solution consists in using a small butane burner to produce heat and CO₂ during a limited time and recording temperatures, CO₂ and also water vapor concentrations.

The source can be, for example, a small camping cooker is equipped with a bottle of 190 g of Butane.

The total combustion of this amount of butane is producing the following emissions:



$$M_{CO_2} = \frac{M_{C_4H_{10}}}{MM_{C_4H_{10}}} \cdot 4 \cdot MM_{CO_2} \quad (20)$$

$$M_{H_2O} = \frac{M_{C_4H_{10}}}{MM_{C_4H_{10}}} \cdot 5 \cdot MM_{H_2O} \quad (21)$$

This corresponds to 0.5711 kg of carbon dioxide and 0.292 kg of water. The amount of energy liberated by this combustion is defined as follows:

$$LHV_{\text{liquidbutane}} = -4.5344 \times 10^7 \text{ [J/kg]} \quad (22)$$

$$Q = M_{C_4H_{10}} \cdot LHV_{\text{liquidbutane}} \quad (23)$$

Which gives 8.534 MJ or 2.371 kWh. The combustion can be tuned in such a way to produce almost constant emissions of CO₂ and heat on a pre-fixed time period. The system can be pre-calibrated by continuous weighting in such a way to define the actual emission curves to be used as inputs in the simulation.

4.2 Prospective

A first evaluation of this new approach consists in simulating the response of a real building zone. The example considered is the living room of a house which has been extensively studied in the frame of the IEA-ECB annex 58 project [2][3]. All solar protections are closed. All internal heat gains other than the butane combustion are eliminated.

Just in order to provide a better visualization of the phenomena, the cellar and the attic are supposed to be maintained at outdoor temperature.

Simulations are performed on a dozen of hours with different combustion rates, but consuming the same amount of butane (190 g).

The burner is supposed to provide constant emissions (rectangular signals).

Heat and CO₂ balances are established by simulations with the model previously used [2]. In this model, the occupancy emissions are replaced by the corresponding emissions of the burner.

CO₂ balance:

The simulated contamination of is presented in Figure 7. The two cases considered correspond to a total combustion of the C₄H₁₀ available in 2 and 4 hours respectively.

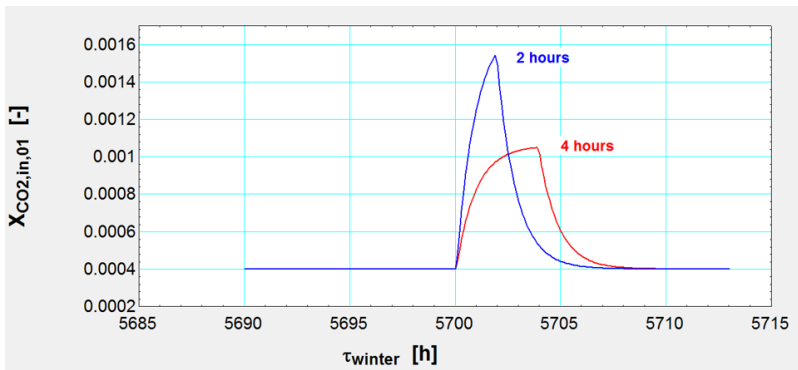


Figure 7: Simulation of the CO₂ contamination

If neglecting again the transient component (initial and final contaminations are the same on the time period considered), the combination of two integrations (CO₂ supply

and corresponding contamination) allows calculating the (average) ventilation flow rate:

$$\dot{M}_{01,out} = \frac{M_{CO2,burner}}{DX_{CO2;01,out,mean} \cdot [t_2 - t_1] \cdot \frac{MM_{CO2}}{MM_{dryair}}} \quad (24)$$

$$M_{CO2,burner} = 0.5766 \text{ [kg]} \quad (25)$$

$$DX_{CO2;01,out,mean} = \frac{\int_{t_1}^{t_2} (X_{CO2;01,in} - X_{CO2;out}) dt}{t_2 - t_1} \quad (26)$$

In the case considered, the air flow rate is estimated to 14.07 and 14.02 m³/h with 2 and 4 hours of combustion time, respectively.

Heat balance:

The simulated indoor air temperatures of the two cases considered as plotted in Figure 8.

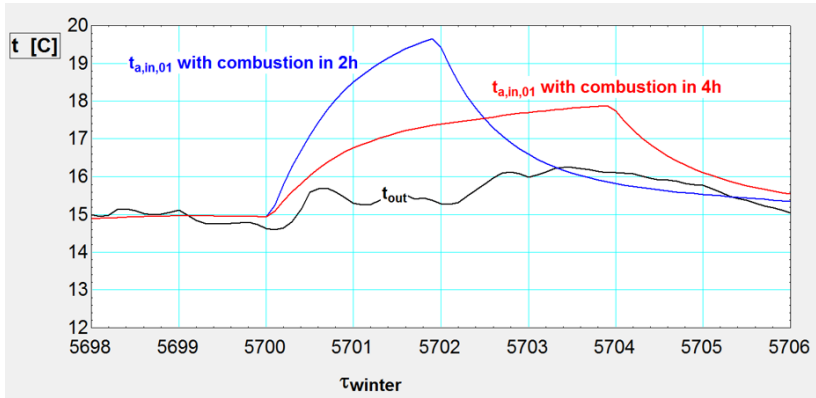


Figure 8: Living room and outdoor temperatures

Average temperatures are calculated on the period of time considered (from tau1=5695 to tau2=5715h).

If neglecting the energy storage, the global heat transfer coefficient between the living room and the outside environment (through all the internal and external walls, including the windows and through the ventilation) can be defined as follows:

$$K_{01;out} = \frac{Q_{burner}}{Dt_{01;out;mean} \cdot (t_2 - t_1)} \quad (27)$$

$$Q_{burner} = 8,615 \times 10^6 \text{ [J]} \quad (28)$$

$$Dt_{01;out;mean} = \frac{\int_{t_1}^{t_2} (t_{a;in;01} - t_{out}) dt}{t_2 - t_1} \quad (29)$$

Which gives almost the same values, 61.01 and 60.75 W/K, with 2 and 4 hours of combustion durations respectively.

But much more should be learned by comparing simulated and measured response factors (i.e. comparing the curves of Figure 8 with measured values)...

4.3 Test in climatic room

This new method has been tested in a climatic room. Examples of results are presented in Figures 9 to 11. The three recorded “responses” of the climate room are compared to simulations. The two first comparisons (on CO₂ and water vapor concentrations) are used to identify the actual air renewal. Then, the third comparison (on temperatures) can be used to tune the thermal simulation model of the room.

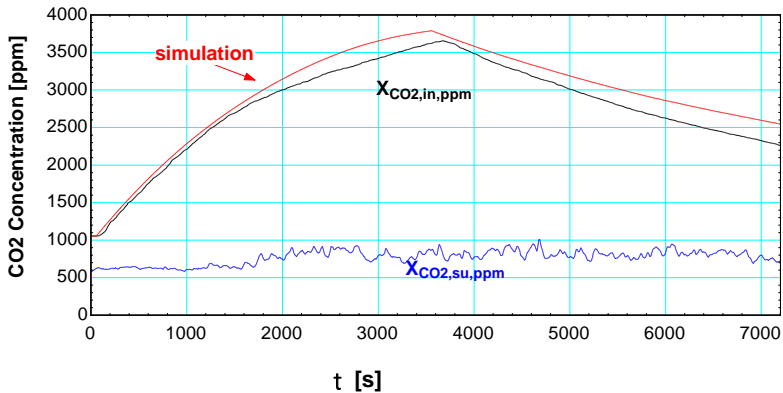


Figure 9: Response of the climate room to the emission of CO₂ produced by the butane burner

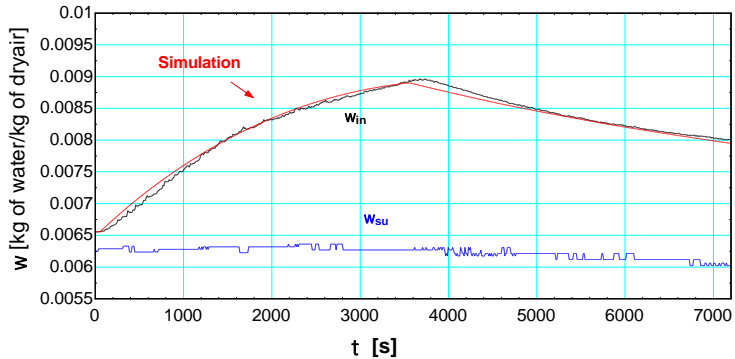


Figure 10: Response of the climate room to the emission of water vapor produced by the butane burner

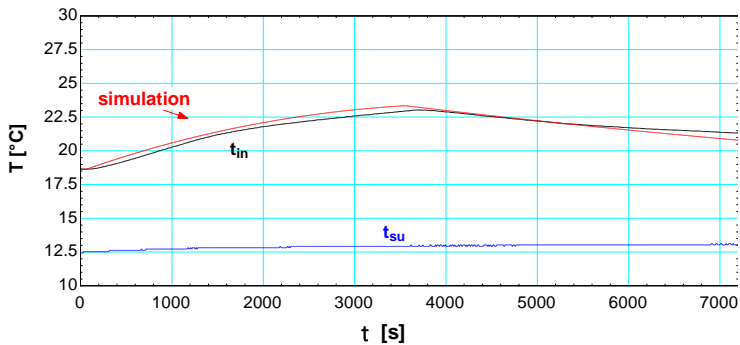


Figure 11: Response of the climate room to the sensible heat emission produced by the butane burner

5. Conclusion

The method consisting in contaminating a building zone by direct combustion should allow identifying, not only the actual air renovation, but also the actual thermal response of this zone. It appears as a very expedient way to combine both tracer gas and co-heating procedures.

Acknowledgements

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