Influence of multizone airleakage on IAQ performance in residential buildings

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ABSTRACT

This article proposes to study the impact of envelope and internal partition walls airleakage distributions, on the indoor air quality (IAQ) performance. It is based on a preliminary performance-based approach using formaldehyde with three emission levels (low, medium, high). This multizone modelling (CONTAM) approach uses as performance indicators, the average concentration per room as well as the percentage of time of exceeding the limit value (ELV) of 9 $\mu g.m^{-3}$. This work allowed to highlight that the ELV was largely exceeded for the high and medium emission scenarios, whether for balanced ventilation or exhaust-only ventilation, complying with the regulatory flow rates. And this, respectively in 100% and 90% of the time for balanced ventilation, and 100% for exhaust-only ventilation. Impacts on concentrations of detailed external and internal airleakage distributions are higher with exhaust-only ventilation than with balanced ventilation (52% and 18% of maximal variation between the different distributions, respectively).

KEYWORDS

multizone modelling, indoor air quality, airleakage

1. INTRODUCTION

Adequate air change rates are necessary in order to ensure a good indoor air quality, including a proper humidity level in buildings. On the other side, building energy performance requires to rethink the ventilation and the air change rates, because of their impact on thermal losses. In this context, envelope airtightness treatment becomes crucial, especially for low energy dwellings. Indeed, envelope air leakage entails thermal losses, but also modifies theoretical voluntary airflows circuits in building.

The present paper is a part of a PhD thesis developing a performance-based approach for ventilation in low-energy dwellings, integrating indoor air quality. Such an approach implies a more precise quantification of airflows in the dwellings, and between the rooms, in order to avoid global and/or local situations with high pollutant or humidity levels. As airtightness is recognized as an essential issue for low energy dwellings, it is nowadays often included in energy-performance (EP) calculations, often through single zone models with uniform air leakage. Because more consideration is often given to energy performance than to indoor air quality issues, air leakage through internal partitions is often disregarded. Thus, additional studies are needed to check these current assumptions. Therefore, in the present study impact of air leakage through building envelope and through internal partitions on inside formaldehyde concentrations has been investigated.

2. METHODS

2.1. Studied House

The studied building is a 2 stories-low-energy brick house equipped with a balanced ventilation system, located near Chambéry, France. A measurement campaign was conducted in order to quantify and finely describe envelope and internal partitions airleakage (Guyot et al. 2016). Envelope airtightness is n_{50}=1.5 h^{-1} (Eq. 1) and internal partitions were measured as rather airtight, with a median value of q_{50}=0.8 $m^3.h^{-1}.m^{-2}$, (Eq. 2). The house has four bedrooms (called BR1, BR2, BR3, BR4), two bathrooms (Bath 1 and 2), two toilets (WC 1 and 2), a mezzanine (Mezz), a kitchen open on the living room (K+LR) and a hall, as shown on Figure 1.

$$n_{50} = \frac{C_L * (50)^n}{V} \quad \textbf{(1)}$$

$$q_{50} = \frac{C_L * (50)^n}{A} \quad \textbf{(2)}$$

Where C_L is the airleakage coefficient [$m^3.h^{-1}.Pa^{-n}$] ; n is the airflow exponent [-] ; A is the area of the measured wall [m²] ; 50 is a 50Pa reference pressure difference across the building envelope or across the measured wall, V is the building heated volume [m^3].

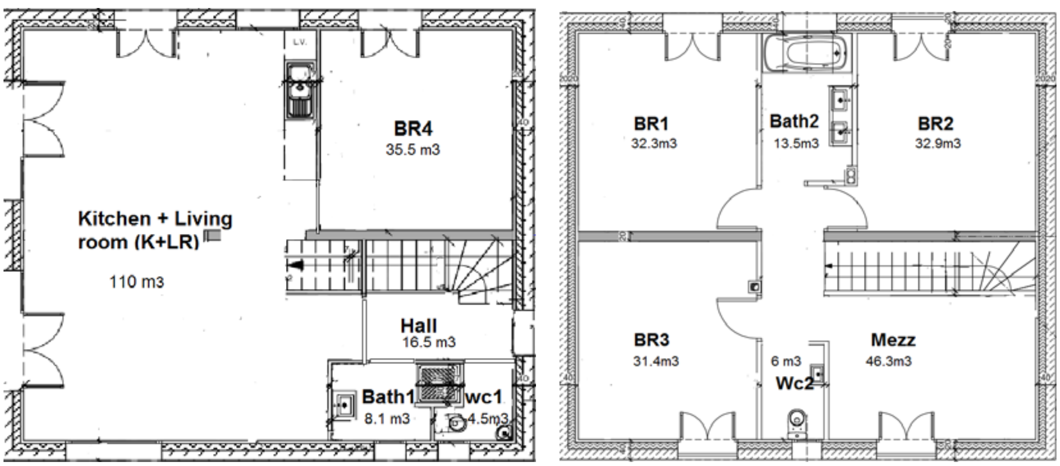

Figure 1. Plan of the house studied: (a) ground floor (b) first floor.

2.2. Modelling study

Formaldehyde concentrations were investigated using numerical modelling with CONTAM software (Walton et Emmerich 1994). We used a multizone model for the dwelling (each room is one zone), with a 10 minutes' time step over the heating period, with meteorological data of a typical year in Lyon (ASHRAE IWEC Weather file, 2001). The wind at the building is calculated from the weather data using a 0.3287 modifier factor, resulting from a power law used with factors from a suburban area and a 8.5 m-elevation of the house.

The pressure coefficients from the EN 15242 (CEN 2007) are used, supposing no barrier, i.e +0.5 on the upwind facades and -0.7 on the downwind facades. The inside temperature is supposed to be 20°C during the heating period.

2.3. Airleakage distributions

Four cases of detail in modelling airleakage were simulated and compared: airtight envelope (case a), evenly distributed envelope airleakage (case b), unevenly envelope airleakage (case c) and unevenly external and internal airleakage (case d). With case a, we calculate airflows due to mechanical ventilation only. Cases b, c and d use experimental data on airleakage performed on this low energy house.

In order to further study, the impact of internal partition airleakage, we defined and compared four other cases taking into account measured values and input values proposed in (Guyot el al., 2016) for heavy and wood structures.

Table 1: Description of airleakage distributions cases, from Guyot et al., 2016.

Cases	Envelope airtightness	Internal partition walls airleakage
Case a (theoretical)	without	without
Case b	Evenly distributed	without
Case c	Unevenly distributed	without
Case d	Unevenly distributed (measured on the heavy structure house)	Unevenly distributed (measured on the heavy structure house)
Case d2	Unevenly distributed (measured on the heavy structure house)	Unevenly distributed (Input values from Guyot et al 2016) for a heavy structure: $q_{50,\ median}$ = 1,2 $m^3.m^{-2}.h^{-1}$ Inter quartile range (q_{50}) = 3 $m^3.m^{-2}.h^{-1}$
Case d3	Unevenly distributed (measured on the heavy structure house)	Unevenly distributed (measured on a wood structure house)
Case d4	Unevenly distributed (measured on the heavy structure house)	Unevenly distributed (Input values from Guyot et al 2016) for a wood structure: q_{50}, median = 6 $m^3.m^{-2}.h^{-1}$ Inter quartile range (q_{50}) = 12 $m^3.m^{-2}.h^{-1}$

2.4. Ventilation systems

The ventilation system is supposed to provide regulatory airflows: 135 m^3/h for a 6 rooms-house, with 2 bathrooms (30 m^3/h) and 2 toilets (15 m^3/h). This accounts for a dwelling air change rate (ACR) of 0.4 h^{-1}. Regulation requires that kitchen exhaust should be able to switch from a base speed of 45 m^3/h to a peak speed of 135 m^3/h. We studied two types of constant airflow ventilation: exhaust-only and balanced ventilation. Extract airflows are the same in both cases. With balanced ventilation, each bedroom is equipped with a supply vent providing 19,3 m^3/h, the living room with two. With exhaust-only ventilation, this seven supply vents are replaced by self-regulating trickle vents with a 22 $m^3.h^{-1}$ module.

2.5. Occupation scenarii

We used data from the French national campaign on IAQ of dwellings from 2005 (Zeghnoun, Dor, et Grégoire 2010). In the present study, we used the following occupation scenarii for the 5 occupants.

Table 2: Occupancy schedules.

Occupant	In living-room + open kitchen	In bathroom	In bedroom
N°1 and 2 (bedroom 1)	7h-8h30 12h-14h 19h-21h (5h30-duration)	6h20-7h (bathroom n°2)	21h-6h20 (9h20 duration)
N°3 (bedroom 2)	6h20-8h30 12h-14h 19h-20h20 (5h30-duration)	20h20-21h (bathroom n°2)	21h-6h20 (9h20 duration)
N°4 (bedroom 3)	6h20-8h30 12h-14h 19h-19h40 20h20-21h (5h30-duration)	19h40-20h20 (bathroom n°2)	21h-6h20 (9h20 duration)
N°5 (bedroom 4)	6h20-8h30 12h-14h 19h-20h20 (5h30-duration)	20h20-21h (bathroom n°1)	21h-6h20 (9h20 duration)

2.6. Formaldehyde emission scenarii

Formaldehyde (HCHO) is a common VOC interesting to survey in dwellings for many reasons. Firstly, this pollutant is nearly always measured in homes (100% of the French dwellings), and it’s also a quasi-only inside production (until 10 times superior than the outside) due to huge quantity of indoor emitting materials, furniture and products (Kirchner et al. 2006). Secondly, this substance is recognized as having a large range of health impacts, depending on the concentration and the acute and chronic exposures (AFSSET 2007; CIRC 2006; INERIS 2010). As a result, several studies identified formaldehyde among the pollutant of concerns in dwellings (Kirchner et al. 2007; Koistinen et al. 2008; WHO 2010; Logue et al. 2011a; Borsboom et al. 2016).

Emission rates measured directly at the dwelling scale are rarely found in the literature (Hodgson et al., 2000; Sherman and Hodgson, 2002), and especially in low-energy dwellings considered as representative of the French dwellings. We proposed to use a simplified method, based on a mass balance to calculate formaldehyde average emission rates adapted from (Hodgson et al. 2000; Sherman et Hodgson 2002), using measurements campaign from the (Guyot et al. 2017). We defined a low-emission class: 4,5 $\mu g.h^{-1}.m^{-2}$; a middle-emission class: 12,0 µg.h^{-1}.m^{-2}; and a high-emission class: 23,6 µg.h^{-1}.m^{-2}. Then, we used a continuously emitting model for formaldehyde emission.

2.7. IAQ metrics using formaldehyde

In this study, we focused on long-term exposure, because of the lack of data at the building scale on rates for short-term emissions. We decided to use the reference exposure limit value (ELV) set to the minimum one used through the world, i.e. 9 µg/m^3 for formaldehyde (USA-California) as proposed by (Cony Renaud Salis et al. 2017). We selected also as performance metrics related to formaldehyde calculated in each zone of the dwelling over the heating period: average concentration, ratio between average concentration and ELV, percentage of time with concentration over the ELV. We used also the maximum total cumulative exposure of the five occupants: E_{max}, (Eq. 3), which will be compared to the total cumulative exposure to the ELV during the whole heating period (4366 h), E_{ELV}=39294 µg.m^{-3}.h^{-1}:

$$E_{max} = \max_{j}\left(\sum_{i} C_j(t_i) * t_i\right) \tag{3}$$

where $C_j(t_i)$ is the exposure concentration for occupant j at the time step t_i.

3. RESULTS

3.1. Exhaust-only ventilation

On Figure 2, we plotted the average formaldehyde concentration in each zone of the house obtained with the highest formaldehyde emission rate, for the seven airleakage cases. We also plotted the exposure ratio for the seven cases and three levels of emissions (Figure 3).

Whatever the case, with the high-emission scenario the concentration stays in the range 17.3–36.6 µg.m^{-3}, thus 1.9–4.1 times higher than the ELV, exceeding it more than 99.9% of the time. Ignoring envelope airleakage accounts for a maximum difference of −33.3% on the average concentration (case a, BR4). Taking into account unevenly distributed airleakage accounts for a maximum 27.3% difference (case c, BR2). Taking into account internal partition wall airleakage can reach an impact of 38.8% (case d3, BR1).

For the medium formaldehyde emission, average concentrations are in the range 10.2–19.9 µg.m^{-3}, i.e. between 1.1 and 2.2 times the ELV, exceeding it more than 99% of the time.

For the low formaldehyde emission (not shown here), average concentrations are in the range 5.6–9.25 µg.m^{-3}, 0.6–1.0 times the ELV. This average exceeding concentration occurs only in WC2 in the d2 case and in BR1 in the d3 case. Depending the cases studied, Bath2, WC2, BR1 and Mezz are zones with concentrations over the ELV more than 30% of the time, even if their average concentration is below the ELV. It can be noted that only in d3, one bedroom (BR1) concentration is higher than the ELV, but 70% of the time, due to a threshold effect. For cases d, d2 and d4, the average concentration in BR1 is 8.4 µg.m^{-3}, with an exceeding time of 0.04, 0.24 and 3.6% respectively.

Studying the maximum formaldehyde exposure (Figure 3), we can first note that the exposure clearly depends on the emission level (high/medium/low). It should be added that Figure 3 shows only the case of the most exposed occupant, which differs depending on the case: occupants 1 and 2 (cases c, d3, d4), occupant 3 (cases d, d2) and occupant 5 (cases a, b). This maximum exposure can be compared to the ELV limit exposure, and the resulting ratio is in the range [1.6–2.1] for the high emission scenario, [0.9–1.2] for the medium emission scenario, [0.5–0.6] for the low emission scenario.

Ignoring envelope airleakage always underestimates the exposure (case a), −24.7% for the high-emission scenario. Taking into account unevenly distributed envelope airleakage distribution slightly overestimates the exposure, −5.4% for the high-emission scenario. Depending on the internal partition wall airleakage distribution selected, impacts on the exposure are in the range [−9% to +0.4%].

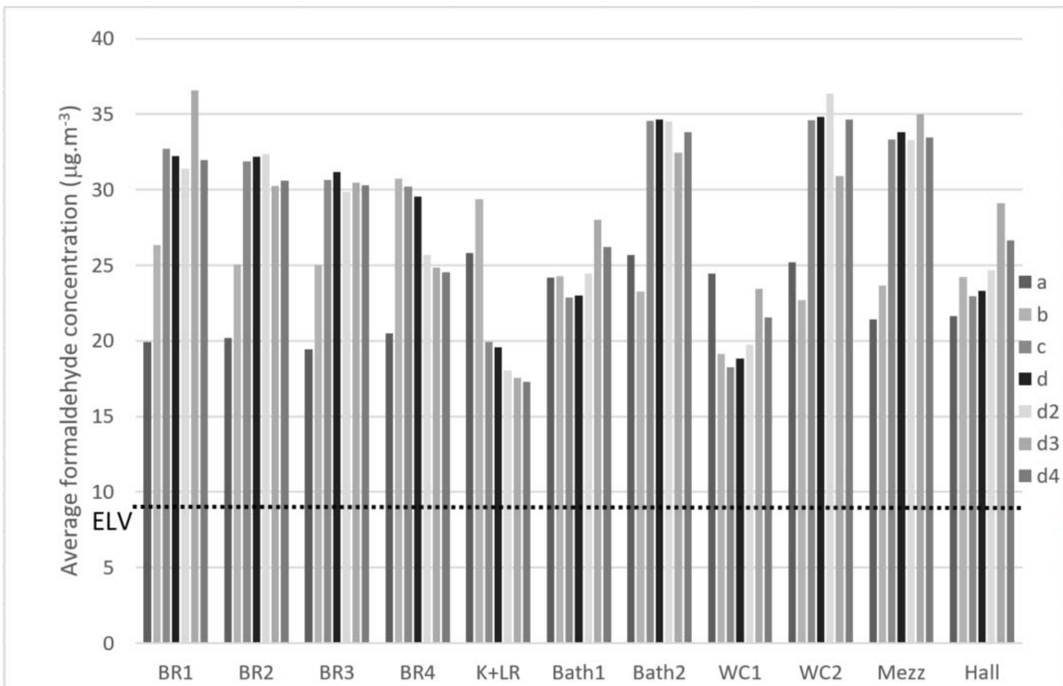

Figure 2: Impact of detailed airleakage data on average formaldehyde concentration; high-emission scenario, exhaust-only ventilation.

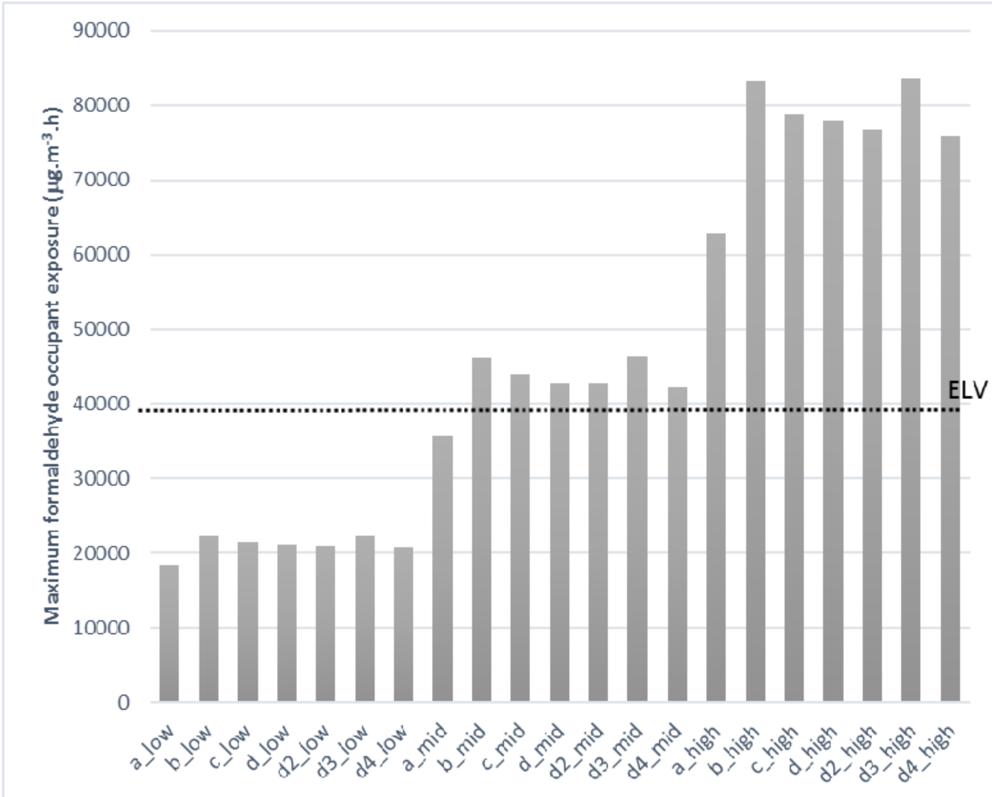

Figure 3 : Impact of airleakage distribution on maximum exposed occupant to formaldehyde; three levels of emissions, exhaust-only ventilation.

3.2. Balanced ventilation

All the cases (a to d4) were also simulated with balanced ventilation. However, all indicators show lower dispersion than with exhaust-only ventilation and are not shown in detail.

For the high-emission scenario, the concentration is in the range 17.1–26.9 µg.m^{-3}, 1.9–3.0 higher than the ELV, more than 99.9% of the time. In the seven cases, we observed no impact on average bedroom concentrations (maximum difference, −1.7%, BR4, d4).

For the medium formaldehyde emission, average concentrations are in the range 10.1–15.0 µg.m^{-3}, 1.1–1.7 higher than the ELV, exceeding it more than 90% of the time. For the low formaldehyde emission scenario, average concentrations are in the range 5.5–7.4 µg.m^{-3}, 0.6–0.8 times the ELV. The concentration stays under the ELV in each room 100% of the time.

In the seven cases, we also obtained low impacts of airleakage cases on the ratio between maximum formaldehyde exposure and ELV limit exposure (maximum difference, 6.4%, case a). The exposure ratio is lower than with the exhaust-only ventilation system, staying in the range [1.4–1.5] for the high-emission scenario, [0.8–0.9] for the medium-emission scenario and in the range [0.4–0.5] for the low-emission scenario.

4. DISCUSSION

Results analysis shows firstly than whatever the case and whatever the ventilation system, average formaldehyde concentrations are higher than the selected threshold of 9 $\mu g.m^{-3}$, except for the lower emission rate of 4,5 $\mu g.h^{-1}.m^{-2}$. We must here specify than the French regulatory threshold is higher: 30 $\mu g.m^{-3}$ since January 2015, but should become 10 $\mu g.m^{-3}$ in 2023. Moreover, emission rates have been here estimated on a little sample including only 10 houses. Performing the calculation on a larger sample could led to different emission rates and thus different results.

We also observe that balanced ventilation gives lower concentrations than the equivalent exhaust-only ventilation providing the same exhaust airflow of 135 $m^3.h^{-1}$. For instance, for the lower emission rate, ELV is never exceeded with the balanced ventilation whereas it is exceeded in four zones more than 30% of the time with the exhaust-only ventilation, including a room for 70% of the time. We can outline here than such a ventilation system is never used on new French low-energy house. Instead, humidity demand-controlled exhaust-only ventilation is used, performing around 30% lower ventilation rates.

In this studied house, we can also observe that using an unevenly distributed envelope airtightness can have a strong impact (up to 52%) on formaldehyde concentrations with an exhaust-only ventilation but also an impact (up to 18%) with balanced ventilation. With an exhaust-only ventilation system, impacts of using internal partitions airleakage can reach 20%. With a balanced ventilation impact is very light (up to 3%), because of the lower pressure differences between zones. This suggests also that impact of modelling doors undercut might be light with such a ventilation system, since we can get the same order of magnitude in size of the path between an undercut and a leak on internal partition (Guyot et al. 2016).

5. CONCLUSION AND PERSPECTIVES

We studied impacts of a detailed envelope airleakage distribution and of internal partition airleakage data on the ventilation performance of a low-energy house. We used a multizone modelling approach performed with three levels of emissions (4,5-12,0 and 23,6 9 $\mu g.m^{-3}$), to calculate IAQ metrics based on formaldehyde. The selected metrics are average concentration in each zone, ratio with the limit value (ELV) of 9 $\mu g.m^{-3}$, and time of exceeding concentration. We studied two types of ventilation: exhaust-only and balanced ventilation, providing the total regulatory airflow of 135 $m^3.h^{-1}$ required for this house.

We showed that formaldehyde concentrations were rarely under the ELV, except for the lower emission scenario with the balanced ventilation system.

This seems relevant to use detailed data on envelope airtightness. Indeed, gaps on average formaldehyde concentrations can reach 52% with exhaust-only ventilation and 18% with the equivalent balanced ventilation. Taking into account detailed data on internal partitions airleakage seems worthwhile with an exhaust-only ventilation system but non useful with balanced ventilation systems.

Such results must be confirmed with the on-going modelling study on other metrics based on other parameters ($PM_{2,5}$, humidity, CO_2).

As a general perspective, we need to get more emission rates in the literature on formaldehyde but also on other pollutants of concern as particle matter, at a house scale.

6. ACKNOWLEDGEMENTS

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