Numerical Assessment of Seven Ventilation Systems for Social Residential Buildings based on Indoor Air Quality and Energy Consumption

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Abstract. This work presents a modelling approach for evaluating ventilation systems for their ability to provide good indoor air quality in dwellings. Infiltration and ventilation rates are defined by the conventional French 3CL-DPE standard. The case study is a two-bedroom apartment with a shared or separate kitchen and living room. Three natural ventilation options and four mechanical ventilation systems are compared with respect to exposure to PM2.5, NO2 and formaldehyde. Pollutant concentration levels are assessed in each room based on a scenario of daily occupancy, average annual outdoor concentrations and internal sources. The daily exposure of the occupants to the targeted substances allows the comparison of ventilation systems on the basis of the ULR-QAI index developed at LaSIE laboratory from La Rochelle University. For this case study, it results that controlled mechanical systems are much more efficient than natural ventilation systems, especially in the case of an open-plan kitchen.

1. Introduction

The energy retrofit of buildings and groupings of social housing is a key to fighting energy poverty and promoting sustainable rehabilitation, energy efficiency and health. The Interreg Sudoe ARCAS project aims to develop an evaluation and design methodology based on the integration and research of the optimal relationship between three axes: autonomy/energy efficiency, social quality/energy poverty and air quality/health. The present study is part of the search for a methodology, simple enough to be applied by non-expert users, allowing the classification of ventilation systems with respect to the indoor air quality (IAQ) of collective housing in the Sudoe zone and more particularly in the French Aquitaine Region.

Although it is currently easy to classify the different ventilation systems from energy point of view, the evaluation of their performance with respect to air quality is always a challenge. Langer et al [1] analyzed data from the National Housing Campaign carried out by the IAQ Observatory [2] and found no significant differences between the presence or absence of a natural/mechanical ventilation system, confirming in situ studies carried out in Denmark or Sweden [3; 4]. The difficulty of in situ analyses is the strong dependence on the activity of the occupants, especially concerning the windows opening. Therefore, it seems preferable to use numerical simulation in order to control the boundary conditions of the problem. Cony [5], by studying the parameters of influence of the IAQ of a single-family house with a multi-zone energy and IAQ dynamic simulation (TRNSYS and CONTAM software coupling), concludes that the balanced ventilation system is statistically more powerful than pressure and humidity self-regulating extraction systems, which show approximately the same performances with
respect to the IAQ. However, it should be noted that this type of modelling is complicated to implement and requires a high level of expertise.

We present here a simplified modeling approach of the sanitary performance of ventilation systems encountered in French collective housing. In the methodological part, the studied dwelling, the evaluated ventilation systems as well as the modelling principles and data are described. The results are presented and discussed in the last part of this paper.

2. Methodology

2.1. Studied case

The case studied here was chosen to be representative of French social housing. It is a 54.5 m² apartment of type 3 (3 main rooms i.e. 2 bedrooms and 1 living-room), which is the typology representing 33% of the French collective housing stock [6] ahead of types 2 (26%) or 4 (20%). The internal spatial distribution of the rooms is shown in Figure 1. A variant of this layout where the kitchen is completely open to the living room was also studied.

The bedrooms, the living room and the kitchen have a wall in contact with the outside allowing infiltrations and the presence, as the case may be, of air inlets for ventilation. Three natural ventilation systems and four mechanical ventilation systems were studied. These systems are presented in Table 1. They can be grouped according to the ventilation strategy to which they respond, i.e. whether each room is ventilated separately or whether the ventilation is said to be a whole-apartment ventilation, i.e. the air enters through the living rooms (bedrooms and living room) and is extracted through the service rooms (kitchen, bathroom and toilets). These two strategies are also illustrated in Figure 1.

![Figure 1. Schematic representation of the different airflows in the separated rooms ventilation case (left) and in the whole-apartment ventilation case (right).](image-url)
Table 1. Ventilation systems evaluated in the analysis

| Ventilation systems evaluated in the analysis | Q_{4P_a\_conv} (m^3.h^{-1}.m^{-2}) | Q_{varep\_conv} (m^3.h^{-1}.m^{-2}) |
|-----------------------------------------------|----------------------------------|----------------------------------|
| Natural (NV) or Mechanical (MV)               |                                  |                                  |
| Separated rooms ventilation                   | 2.0                              | 1.2                              |
| Inlets (NV-INLET)                             | 2.0                              | 2.145                            |
| Whole-apartment ventilation                  | 1.7                              | 2.145                            |
| Duct (NV-DUCT)                                | 1.7                              | 2.0625                           |
| Hybrid (MV-HYB)                               | 1.7                              | 2.2425                           |
| Constant Air Volume (MV-CAV)                 | 1.7                              | 1.65                             |
| Pressure-controlled (MV-PRESS)               | 1.7                              |                                  |
| Humidity-controlled (MV-HUM)                 | 1.7                              | 1.0725                           |

2.2. Infiltration and ventilation airflow rates

2.2.1. Whole apartment infiltration and ventilation airflows. The total exhaust air flow rates \(Q_{tot}\) are the sum of the total infiltration \(Q_{inf}\) and ventilation \(Q_{vent}\) flow rates of the dwelling, which are calculated using the French conventional 3CL-DPE method [7] that is based on NF EN 15242 [8]. According to this method that only accounts for stack effect, the air flow rate due to infiltration is evaluated by equation (1):

\[
Q_{inf} = 0.0146 \times Q_{4P_a\_conv} \times S_{env} \times (0.7 \times (19 - T_{out}))^{0.667}
\]

where \(Q_{inf}\) is the infiltration airflow rate \((m^3.h^{-1})\), \(Q_{4P_a\_conv}\) is the conventional leakage airflow rate per envelope surface area for an indoor to outdoor pressure difference of 4 Pascals \((m^3.h^{-1}.m^{-2})\), \(S_{env}\) is the selected envelope surface area \((28.8 \ m^2)\) and \(T_{out}\) is the conventional winter-averaged outdoor temperature for the French Aquitaine climatic zone \((8.08 \ ^{\circ}C)\). The selected values for \(Q_{4P_a\_conv}\) are presented in Table 1 and correspond to airtight envelope for the newest ventilation systems using the whole-building ventilation principle.

The airflow rate extracted by the ventilation system is evaluated according to equation (2):

\[
Q_{vent} = Q_{varep\_conv} \times S_{floor}
\]

where \(Q_{vent}\) is the ventilation airflow rate \((m^3.h^{-1})\), \(Q_{varep\_conv}\) is the conventional ventilation airflow rate per floor area \((m^3.h^{-1}.m^{-2})\) et \(S_{floor}\) is the floor surface area \((54.5 \ m^2)\). The 3CL-DPE method gives the \(Q_{varep\_conv}\) values; they are presented in Table 1.

2.2.2. Airflow rates between rooms. In the case of a separated rooms ventilation strategy, it is assumed that each room is ventilated independently of the others. Thus, the distribution of infiltration rates in each of the rooms is proportional to the surface area of the exterior walls and the ventilation rates are proportional to the floor area of these rooms.

In the case of whole-apartment ventilation, the distribution of infiltration rates is achieved in the same way but the calculation of the ventilation rate entering each room is done in accordance with the technical specifications of the ventilation system and the regulatory requirements, as detailed below.

For natural ventilation by ducts (NV-DUCT) and mechanical ventilation systems (MV-CAV, MV-PRESS and MV-HYB), the air inlets have been selected to allow a nominal flow rate of 30 m³.h⁻¹ in each bedroom and 50 m³.h⁻¹ for the living room, i.e. 27.3% of the total ventilation flow rate entering through each bedroom and 45.4% through the living room. This distribution is then applied to the \(Q_{vent}\) flow rate previously calculated to determine the actual flow rate entering each room due to the ventilation system. In the same way, the minimum extract flow rates imposed by the regulations (decrees of March 24, 1982 and October 28, 1983 relating to the ventilation of dwellings) for this type of housing \((75 \ m³.h^{-1} \ in \ kitchen, \ 30 \ m³.h^{-1} \ in \ bathroom \ and \ 15 \ m³.h^{-1} \ in \ toilets)\) define the proportions of extract.
flow rates (62.5% in kitchen, 25% in bathroom and 12.5% in toilets) to calculate the actual extract flow rate in each room from the total flow rate of extract air \( Q_{\text{tot}} \).

Regarding the humidity sensitive ventilation (MV-HUM), since the air inlets are dependent on the presence of the occupant (through its influence on the relative humidity of the room), the ventilation flow rates can vary from 4 to 30 m³.h⁻¹ in the bedrooms and the living room, and the extract flow rates from 10 to 50 m³.h⁻¹ in the kitchen, from 5 to 45 m³.h⁻¹ in the bathroom and from 5 to 30 m³.h⁻¹ in the toilets. It is thus necessary to dissociate two scenarios: at night when the occupants are in their bedrooms, the airflow rates are at their maximum at the air inlets to the bedrooms and at the extraction in the bathroom (close to the bedrooms), and at their minimum at the air inlet to the living room and at the extraction from the toilets; and conversely during daytime when the occupants are in the living room.

In addition to this operation under normal conditions, there is a period of increased ventilation in the kitchen for half an hour during cooking activity for all mechanical systems (except for constant flow ventilation). During this period the \( Q_{\text{vent}} \) and \( Q_{\text{tot}} \) flow rates are not used to calculate the actual ventilation and extraction flow rates in each room, which are directly equal to their nominal values, and the kitchen extraction flow rate is increased to 105 m³.h⁻¹. In order to satisfy the equality of the flow rates into and out of the dwelling, the infiltration rate \( Q_{\text{inf}} \) must be adjusted. This is achieved by the relation linking the infiltration flow rates to the pressure difference on either side of the envelope:

\[
Q_{\text{inf}}(\Delta p) = Q_{\text{inf}}(\Delta p = 1) \times \Delta p^{0.67}
\]

where \( Q_{\text{inf}}(\Delta p = 1) \) is the infiltration airflow rate for 1 Pa pressure difference (m³.h⁻¹.Pa⁻¹). A value of 5.37 m³.h⁻¹.Pa⁻¹.67 is given by the French DTU 68.3 [9] for a T3 apartment.

Once these flows exchanged between the exterior and interior of the dwelling are evaluated, we can then, in the case of whole-apartment ventilation system, determine by differentiation the interzone flows exchanged between each room, knowing the direction of airflow through the dwelling (Figure 1).

### 2.3. Indoor Air Quality

#### 2.3.1. Pollutant concentrations in rooms

The calculation of the average pollutant concentrations is carried out in each room by considering a perfect homogeneity of the concentrations (one calculation node per room). The resolution of the equations of conservation of the mass of each pollutant is carried out in steady-state with however a new resolution each time the ventilation flow rates are modified (when the flow rate increases during cooking or by humidity-controlled system when an occupant is present in the room...) or that a new emitting activity of one of the studied pollutants is in progress. The balance considers the transport by air of the pollutants from one room to another or from outside, the emission of pollutants by building materials and occupants’ activities and the deposition or sorption of these pollutants by reaction on the surface of the walls.

The pollutants considered in this study are fine particles (PM2.5), nitrogen dioxide (NO2) and formaldehyde because these pollutants are known to have a significant impact on the air quality of homes [5; 10]. Formaldehyde is a well-known tracer of indoor air quality because it is ubiquitous in the indoor environment, emitted by furniture and building materials. Sources of particulate matter and NO2 can be outdoor sources, mainly from road traffic, or indoor sources from human activities such as cooking or incense burning. The outdoor concentrations used in these simulations are annual average outdoor concentrations measured by regional air monitoring agencies in the cities of La Rochelle, Poitiers, Bordeaux and Angoulême. They are 11.9 and 27.3 µg·m⁻³ for PM2.5 and NO2 respectively and the outdoor concentration of formaldehyde is considered to be zero. Two types of indoor sources were considered here: formaldehyde emissions from building materials, and PM2.5 and NO2 emissions from human activities. Formaldehyde emission rates from materials were set at the limit value between categories A+ and A of the French labelling system for building and decorative materials for their emissions of gaseous pollutants [11], i.e. 12.5 µg·m⁻²·h⁻¹ for the floor and ceiling and 5 µg·m⁻²·h⁻¹ for the walls. The activities defined in this case study are the use of a vacuum cleaner and cooking. The PM2.5
emission rate is 0.07 mg.min\(^{-1}\) for 10 minutes per week for vacuuming and 1.6 mg.min\(^{-1}\) for 30 minutes per day for cooking [12]. Cooking activity also emits 3.1 mg.min\(^{-1}\) of NO\(_2\) [13]. Deposition (or removal by reaction) rates on walls, floor and ceiling are based on the values proposed by [13], namely 1.8 × 10\(^{-4}\) m.s\(^{-1}\) for PM2.5 and 1.2 × 10\(^{-4}\) m.s\(^{-1}\) for NO\(_2\).

2.3.2. Risk assessment. The health risk due to exposure to substances present in the air is assessed using the ULR-IAQ index developed by [5]. This index ranges from 0 for a very good IAQ to 10 for a very bad IAQ and relates the concentrations of pollutants in the air to the Indoor Air Guide Values (IAGV) promulgated by the National Agency for Food, Environmental and Occupational Health Safety (ANSES):

\[
I_{ULR-IAQ,p} = 10 \times \frac{C_{p}^{exo} - IAGV_{LT,p}}{IAGV_{ST,p} - IAGV_{LT,p}}
\]

where \(IAGV_{LT,p}\) et \(IAGV_{ST,p}\) are the IAGV for long and short-term exposure, respectively. The average daily exposure concentration \(C_{p}^{exo}\) of an occupant to a pollutant (p) is the average of the concentrations calculated during the presence of the occupant, weighted by the corresponding occupation durations. In the case studied here, the occupant is assumed to spend 9 hours in bedroom 1, 3 hours in the living room and 0.5 hours in the kitchen. To calculate the 24-hour exposure, it is also assumed that during the 11.5 hours spent outside the dwelling, the person is exposed to a concentration equal to that in bedroom 1 (which is similar to an office-type pollution). The \(IAGV_{LT,p}\) et \(IAGV_{ST,p}\) are respectively 10 and 25 \(\mu g/m^3\) for PM2.5, 40 and 200 \(\mu g/m^3\) for NO\(_2\) and 10 and 100 \(\mu g/m^3\) for formaldehyde.

ULR-IAQ sub-indices are calculated for the three selected pollutants and then, the multi-pollutant ULR-IAQ index is defined as the maximal value of those three sub-indices [5].

3. Results

For each studied ventilation system, the simulations were carried out considering on the one hand the case where the kitchen is separated from the living room (with the communicating door always closed) and on the other hand the case where it is completely open to the living room. The results expressed by the attribution of a ULR-IAQ score for each ventilation system in each of the two configurations are presented in Figure 2. In both cases and for all systems, the index is always highest for PM2.5 exposure and therefore corresponds to the multi-pollutant ULR-QAI index. The numerical work of [5] showed that this index was due to PM2.5 for 65% of the 2334 cases treated and formaldehyde for the other cases (NO\(_2\) had not been simulated). The main difference lies in the single and low source of formaldehyde in our study, based on the emission of the main walls according to an A+/A label. Those simulations also considered the emission from furniture and other occupant activities with emissions up to 4 times higher.

In the configuration where the kitchen and living room are separated, there is a cleavage between natural ventilation solutions, which all show an index of 10 (NV-WINDOW) or almost 10 (9.2 for NV-INLET and 9.6 for NV-DUCT), and controlled mechanical systems with about 3 points less (7.1 for MV-HYB, 7 for MV-HUM and 6.7 for MV-PRESS). Whilst the absence of ventilation rate modulation for the MV-CAV system generates a higher daily ventilation volume than other mechanical systems, this system (and also the natural ventilation ones) suffers from a higher ULR-IAQ index due to the impossibility of activating the increased ventilation mode in the kitchen during cooking activity.

In the case where the kitchen is completely open to the living room, the results are more differentiated and the levels are lower (in particular due to the dilution of the kitchen emissions in a larger volume). Separated rooms NV-WINDOW is still unable to ensure good air quality. On the other hand, natural inlet and duct ventilation in this configuration is much more efficient than when the kitchen and living room are separated, with an ULR-IAQ rating of 5.4 (compared to 9.6 in the previous case), however still less efficient than mechanical systems. Within the latter, the MV-CAV system has an efficiency closer to the other systems than in the previous configuration, this time equivalent to the MV-
HUM system (ULR-IAQ = 4.4 and 4.5 respectively), the best solution being the MV-PRESS system with an index of 3.8.

Figure 2. Comparison of the ULR-IAQ indexes of each pollutant for the studied ventilation systems and the cases where the kitchen is separated from the living room (upper graph) or not (lower graph).

These latter results are compared in Figure 3 with two other modeling approaches: a single zone approach and a more sophisticated approach based on TRNSYS-CONTAM coupling [5]. First, the multi-pollutant ULR-IAQ indices were recalculated by considering the dwelling as a single volume (noted as "Single zone"). We notice that this approach predicts roughly equivalent system performances with respect to IAQ, with in particular the humidity sensitive system as the least performing, which is in contradiction with the results of our approach ("Multizone - 24h") and that obtained from TRNSYS-CONTAM [5]. The multizone approach developed in this study thus appears to greatly improve the systems performances prediction regarding single zone approach, while keeping simple to use compared to more complicated approaches.
Figure 3. Comparison of ventilation systems according to different modeling approaches.

Figure 4 presents the results as a function of the share of heat losses due to air renewal compared to the total heating needs (calculations performed according to the French RT2012 Standard [14]). We observe that mechanical systems minimize the heating needs while providing comparable IAQ. Humidity-controlled ventilation gives the lowest heating needs of all ventilation systems.

4. Conclusion
In this study, we propose a simple methodology to evaluate an IAQ index for dwellings and to compare the performance of ventilation systems on this criterion. This approach has been compared at different levels of modeling and appears to yield results similar to the most refined approach, and sufficiently discriminating to distinguish differences in the performance of ventilation systems with respect to IAQ. The results show that for the most common configuration (kitchen open to living room or kitchen and living room separated but with the separating door open most of the time), the ducted natural ventilation system provides an air quality relatively close to what could be achieved with mechanical systems, but generates higher volumes of renewed air, i.e. higher energy consumption than controlled mechanical ventilation. The humidity-controlled system can be considered as a good compromise in this respect since it limits the extracted air flows when the rooms are unoccupied while ensuring a good indoor air quality. Moreover, it appears that the hybrid ventilation system, particularly advantageous for its low installation cost in rehabilitation, is also effective to significantly improve the air quality in the...
dwellings. It should also be noted that this analysis does not consider the presence of a kitchen hood, since it is not strictly speaking a ventilation system. However, the systematic use of such additional equipment is a key element in reducing exposure to cooking products.

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