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Indoor air quality and comfort in seven newly built, energy-efficient houses in France

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1. Introduction

Because of the global warming, many governments have taken action to reduce anthropogenic greenhouse-gas emissions, to promote energy efficiency and to support for renewable energy. In France, the residential and commercial building sector is responsible of 23% of national greenhouse-gas emissions and is the largest energy consumer, accounting for 43% of energy consumption in the country in 2007 [1]. In 2011, the average unit energy intensity of the residential sector was 190 kWh/m², higher than that of the commercial sector [2]. In this context, France has pledged to reduce greenhouse-gas emissions by 75% by 2050 and to reduce building energy consumption by 38% by 2020 [3]. Existing structures are being refurbished to increase energy efficiency at an accelerating rate, and as of 2013, all newly constructed buildings must meet the French 2012 thermal-regulation standards (RT 2012) for buildings. Although these new airtight buildings must have a primary conventional-energy consumption not exceeding 50 kWh/m² per year, there are no requirements directly protecting the health and wellbeing of occupants. Moreover, the only literature review on indoor air quality (IAQ) in highly energy-efficient houses [4] concludes that "with regard to indoor air quality, there is a dearth of information relating to highly efficient structures". The authors note that it is difficult to extrapolate the results of studies of the construction of airtight buildings in colder climates (Canada, Central Europe and northern USA) to other countries because of differences in climate, construction practices, indoor sources depending of what people purchase on their homes and the social and economic conditions of the occupants. Finally, a small number of studies have investigated indicators of IAQ [5,6,7,8,9,10,11], but none has conducted an IAQ longitudinal survey and compare their results with those of standard buildings.

The objective of the present study, which was funded by the French Observatory of Indoor Air Quality (OQAI in French), is to evaluate the IAQ and the occupants' comfort in seven low-energy, newly built houses in France. The survey was conducted during the pre-occupancy stage and during occupancy in summer and winter. The concentrations of several IAQ indicators and the indoor environmental parameters were measured during occupation. These results were compared to the IAQ of standard

French houses [12], to the results of previous studies conducted in new dwellings and to the IAQ guideline values currently used in France. The air changes per hour (ACH) from mechanical ventilation with heat recovery (MVHR) were measured and compared to those of standard French homes [13]. The air-exhaust rates were compared to the French standards [14] for minimal airflow for dwellings according to the number of habitable rooms. The noise levels were measured, and the occupants' perceptions were evaluated with a questionnaire.

2. Materials and methods

A recently developed method for assessing IAQ, occupant comfort and energy consumption was applied in this study. A detailed description of sampling and measurement techniques has been presented elsewhere [15]. A short overview of the analytical procedures and the sampling strategy is given below.

2.1. Description of the seven single-family detached houses

Seven newly built, single-family detached houses in four regions of France (Centre, Pays-de-la-Loire, Ile-de-France and Rhône-Alpes) were investigated in this study (Table 1).

Table 1 - Main characteristics of the seven new single-family detached houses investigated in this study in terms of construction, equipment and occupancy

The buildings had one or two stories, and one had an attached garage (A). All houses were constructed in accordance with an energy-efficient building certification such as the French BBC-Effinergie certification or the German Passivhaus certification. Three houses were certified (A: BBC-Effinergie; C and D: Passivhaus); house B's certification process was on-going, and the builders or owners of the other houses are not pursuing certification. Houses F and G satisfied the requirements of all 14 targets of the French High Environmental Quality Programme (HQE). The airtightness of all buildings was measured with a

blower-door test between 0.29 and 3.33 vol/h under 50 Pascal pressure (0.06 and 0.41 m³/h.m² under 4 Pascal pressure). The houses' annual consumption of conventional primary energy (heating, cooling, ventilation, auxiliaries, hot water production, lighting facilities) was between 46 and 79 kWh/m²/year. These houses were well within the requirements of the French 2005 thermal regulations (RT 2005) for buildings (airtightness less than 0.8 m³/h.m² under 4 Pa and annual consumption of conventional primary energy less than 150 kWh/m²/year). The houses also qualified as highly energy-efficient houses as defined by the French 2012 thermal regulation (RT 2012) because of their high airtightness (under 0.6 m³/h.m² under 4 Pa) and their theoretical low energy consumption (an annual consumption of conventional primary energy equal or less than 50 kWh/m²/year). All of the houses were wood frame except for house A (stone) and used mineral (A, F and G) or vegetable (B, C, D and E) insulating material. All of the houses were equipped with an MVHR system with two, three or four normal fan speeds and occasionally one boost setting. The heating systems were mostly heat pumps (A, C, D, F and G) or wood stoves (B and E). House D had a wood stove for enjoyment rather than function. Hot water was mainly provided by solar panels with electric boosters (B, C, D, F and G) except in two houses (thermodynamic in house A and electric in house E). All of the houses but A had products and materials described by the manufacturers as low volatile-organic-compound-emitting. The inhabitants were families of 2-4 non-smokers, except for house G, which remained unoccupied during this study. The occupation rates were often lower than the median occupation rate (0.8) of the standard French houses [13] suggesting that these houses were under-occupied or were larger than an average French home.

2.2. Measurement protocol

The IAQ and indoor environmental parameters was monitored between February 2009 and July 2010 (Figure 1) just after the houses' completion (except for house A, completed in March 2008) for less than one year each. The IAQ was monitored in the main bedroom and in the living room and kitchen

(collectively called “living room”) for three weeks in each building in the pre-occupancy stage and during occupancy (summer: Sum; winter: Win) except in houses F and G. The ACH, the air exhaust rates and the level of noise were determined simultaneously in the pre-occupancy stage. The temperature, the relative humidity and the concentration of radon were measured only in occupied houses. The MVHR systems were switched on during these investigations at the medium normal fan speed during the pre-occupancy stage (except for houses E and G, where the MVHR systems were turned off) and in manual or automatic mode during occupancy.

Figure 1 - Weekly investigation and moving dates of the seven new single-family detached houses between February 2009 and July 2010

The strategy of sampling / measurement and the accuracy/uncertainty of the indoor air quality parameters are presented in Table 2.

Table 2 – Strategy of sampling/measurement and accuracy of indoor air quality parameters

Every ten minutes during the investigation, total volatile organic compounds (TVOC in toluene equivalent in $\mu\text{g}/\text{m}^3$) were measured with a photoionisation detector (PID) (PGM 7240 - RAE Systems) in the living room and carbon dioxide (CO_2 in ppm) was measured by a non-dispersive infra-red probe (TSI Q-Trak 8552) in the main bedroom. Individual volatile organic compounds (VOC) and aldehydes were collected over seven days in the main bedroom by a passive sampler (Radiello®, and Fondazione Salvatore Maugeri – IRCCS, Italy) with stainless steel net cartridges filled, respectively, with Carbograph 4 adsorbents and with 2,4-dinitrophenylhydrazine (2,4-DNPH)-coated Florisil. Sixteen VOC (1,2,4-trimethylbenzene, 1,4-dichlorobenzene, 1-methoxy-2-propanol and its acetate, 2-butoxyethanol and its acetate, benzene, ethylbenzene, m-/p-xylenes, n-decane, n-undecane, o-xylene, styrene, tetrachloroethylene, toluene, trichloroethylene) and four aldehydes (acetaldehyde, acrolein, formaldehyde, hexaldehyde) were quantified in $\mu\text{g}/\text{m}^3$ by, respectively, gas chromatography, mass spectrometry and flame ionisation and high-performance liquid chromatography and detection by UV absorption. These

compounds were measured during the national survey of IAQ in French dwellings [12], and the analytical method and the detection limit for each compound were previously detailed by [16]. Then, all other organic compounds whose concentrations exceeded $1 \mu\text{g}/\text{m}^3$ were identified and quantified in $\mu\text{g}/\text{m}^3$ toluene equivalent. Carbon monoxide (CO in ppm) was monitored only in winter every five minutes during seven days with an electrochemical sensor (Drager Pac III) in each room that contained combustion equipment. The mass concentration of suspended particulate matter with an aerodynamic diameter less than $2.5 \mu\text{m}$ ($\text{PM}_{2.5}$) was measured in the living room with a sampling system (Chempass, Model. 3400, Thermo Fisher Scientific) coupled to an air sampler (Microvol 1100, Ecotech) operating at $1.8 \text{ l}/\text{min}$ from 5 pm to 8 am on weekdays and for 24 hours a day on weekends. The filters (37-mm-diameter PTFE membrane, 2- μm porosity, Gelman Sciences) were weighed before and after sampling according to NF EN 14907 [17], and mass concentrations are given in $\mu\text{g}/\text{m}^3$. During both investigations during occupancy, room temperatures (T in $^{\circ}\text{C}$) and relative humidity (RH in %) were monitored every ten minutes with Hydrolog sensors (Rotronic) in the main bedroom and the living room at different heights. Radon concentrations (Bq/m^3) were measured over more than two months using two Kodalpha LR 115 detectors (Dosirad, and France), one in the living room and the other in the bedroom, after the inhabitants moved in. The radon measurement was made principally during fall months for houses A, C, E, during spring months for houses D and F and during fall/winter months for house B. During the pre-occupancy stage and for normal fan speeds (low, medium, high and sometimes very high) of the MVHR, the ACH (in h^{-1}) in the main bedroom and living room, the air exhaust rate (l/s) and the mean noise level (in $\text{dB}(\text{A})$) were measured, respectively, by SF6 tracer gas (B & K Multigas Monitor type 1302 with a B & K multipoint sampler and doser type 1303), by an array of hot wires (Swemaflow 233, Admi Industries) and by a type-II sonometer (Centre 322). The ACH was measured under the same outdoor conditions. No ACH measurements were made under the MVHR boost fan speed, which was activated for only a short period. The average ACH of each building was estimated, taking into account the ACH measurements of both rooms, the volume of those rooms and the total volume of the house. Because doors were opened very often during our investigations and thus homogenous zone of concentration

created, we supposed that air removal measured in 2 rooms could be translated to the air removal of the whole house. Because the MVHR systems are not very often checked during/after the completion of the building, we decided to evaluate its performance in terms of ACH, air exhaust rate and noise level.

Concurrent with sampling and measuring, survey questionnaires were developed based on the national survey on indoor air quality in French dwellings [18] to collect general information on newly constructed houses, their equipment, their occupancy and the activities and perceptions of the inhabitants during each investigation.

2.3. Graphical representation and statistical analysis

A histogram representation with vertical error bars was used for measurements of T, RH, PM_{2.5}, radon, air exhaust rates and mean noise levels.

The software package SAS 9.1 was used for statistical analysis. To characterise the distribution of the raw data, the following parameters were calculated for the concentrations of CO₂ and for the measurements of T and RH: minimum, arithmetic mean, median, maximum and 25th and 75th percentile. For VOC and aldehyde values below the limit of quantification (LQ), the calculated value of the LQ divided by two was used in the statistical calculation (arithmetic mean, median, geometric mean). The differences in indoor environmental parameters (CO₂, T and HR) between occupancy in summer and in winter for each house were assessed using the Kruskal Wallis rank-sum test. A two-sided test was used because the sign of the difference was not known *a priori*. Spearman's rank correlation (r_s) was used to express correlations between the indoor PM_{2.5} levels and outdoor PM_{2.5} levels. P-values < 0.05 were considered statistically significant.

3. Results

3.1. Performance of MVHR

The performance of MVHR was evaluated for six houses during the pre-occupancy stage after inspection and their adjustment by the installers; in houses D and E, the systems of ventilation were adjusted after measurement.

3.1.1. Air exchange per hour (ACH)

Table 3 presents the measurement of ACH (in h^{-1}) for the living room and the main bedroom and the average ACH for the house.

Table 3 - Measured ACH per room and estimation of average ACH (h^{-1}) by house depending on the fan speed of the MVHR system in six houses (confidence interval). n.m.: not measured; n.e.: not estimated

When the MVHR systems were switched off, the ACH of both rooms induced by air leakage did not exceed 0.05 h^{-1} , except in house F, where it reached 0.1 h^{-1} . When the MVHR systems were turned on, the ACH values increased with increasing fan speed (in houses A, B, D and F). The ACH values ranged between $0.4\text{-}0.8 \text{ h}^{-1}$ in house A, $0.2\text{-}1.2 \text{ h}^{-1}$ in house B, $0.1\text{-}1.3 \text{ h}^{-1}$ in house C, $0.2\text{-}0.7 \text{ h}^{-1}$ in house D, $0.2\text{-}0.6 \text{ h}^{-1}$ in house E and $0.5\text{-}0.6 \text{ h}^{-1}$ in house F. Shortcomings appeared at the highest fan speed, where ACH values were in some cases equal to the ACH value at the medium fan speed (house C) or even lower (bedroom of house E). The average ACH values for MVHR systems without a boost fan speed were between 0.1 and 0.3 h^{-1} at the lower fan speed, 0.3 and 0.5 h^{-1} at the medium speed and up to 1 h^{-1} at the highest speed. For the MVHR systems with a boost fan speed (houses A and F), the minimum average ACH values were 0.6 h^{-1} and 0.5 h^{-1} , respectively.

3.1.2. Air exhaust rates

Air exhaust rates (l/s) were measured for each outlet and for each fan speed of the MVHR system. For technical reasons (e.g., height, size, geometry of the outlets, presence of furniture fixed to the wall near the outlets), not all measurements were recorded. Figure 2 shows that the air exhaust rates increased with the increasing fan speed of the ventilation systems for the majority of houses, though deviations appear in

houses A and F. The air exhaust rates were the same for the lower as for the medium fan speed in house A (WC and bathroom 1) and house F (WC and bathroom 2). Finally, for both houses and considering only WC and bathroom outlets, the difference in the air exhaust rates between the lower and the higher fan speeds was smaller (less than 1.7 l/s) than in the other houses (between 3.3 and 8.6 l/s).

Figure 2 – Measured air exhaust rate (l/s) per room by the fan speed of the MVHR system in six houses

3.1.3. Average noise level

The average noise level (dB(A)) was measured for each MVHR fan speed. The results are presented in Figure 3, and all measured values less than or equal to 30 dB(A) (under the range value of the sonometer used) were replaced by the symbol *. The average noise level increased with increasing MVHR fan speed, except in a few rooms in house F. The utility room where the MVHR system was located was the noisiest (value ranged between 33 and 59 dB(A)), except in house D. The bedrooms (and occasionally office rooms) were generally the quietest (less than 30 to 33 dB(A)), except in houses B and D (up to 48 and 36 dB(A), respectively). The average noise levels in house E were markedly lower. Overall, indoor noise levels were rated between “quite pleasant” and “extremely pleasant” by the inhabitants. Noises coming from inside the house, especially those from the MVHR ventilator and those that were noticeable at bedtime (B), during the night (A, D) or during quiet parts of the day were rated as more bothersome than noises from outside.

Figure 3 – Measured average noise level (dB(A)) per room depending on the MVHR fan speed in six houses (* average noise level value \leq 30 dB(A)) (BAT: bathroom; BED: bedroom; LR: living room; OFF: office room; UR: utility room)

3.1.4. Use of the MVHR system

During occupancy, several technical improvements were made to the MVHR systems in response to complaints from the inhabitants regarding the poor adjustment of the air-flow rate (houses A and E), disturbance of the air-flow rate during occupancy (houses A and C) or after cleaning the inlets/outlets (house B), noise disturbance (house A and C) and the need to replace components of the ventilation system (houses A and F). The inhabitants reported that the MVHR systems were difficult to use and that the user manual was complex; the majority used only the manual mode rather the program mode. The inhabitants of house E used the program mode, but the available schedules did not match their lifestyle.

3.2. Indoor environment parameters

3.2.1. Air stuffiness and thermal comfort

The concentrations of CO₂ and the T and RH values measured in the main bedroom of each house during occupancy (Sum and Win) are presented in Table 4.

Table 4 - Descriptive statistics of CO₂ level (ppm), T (°C) and RH (%) measured weekly in the main bedrooms of six occupied houses by season. (Sum: summer; Win: winter; P25: 25th percentile; P75: 75th percentile; n.a.: not available)

The median CO₂ levels were always below 1000 ppm and ranged between 351 ppm (house B) and 811 ppm (house A). These levels were significantly lower in summer than in winter ($p < 0.0001$). The lowest levels were close to the measured outdoor level, and the highest levels were less than 2100 ppm. Houses C and D appeared to have less fresh air than the others because of their high interquartile temperature ranges. The median temperatures were between 20.3 and 25.7 °C in summer and 19.5 and 21.6 in winter. Larger variation in temperature was observed in winter (8 to 15 °C) than in summer (3 to 8 °C). The median RH values were between 45 and 58% in summer and between 29 and 34% in winter. As expected, the T and RH values were significantly higher in summer than in winter ($p < 0.0001$).

According to the inhabitants, the global thermal comfort of their houses ranged between "rather satisfactory" and "satisfactory" in the summer (T and RH were "comfortable") and between "somewhat dissatisfied" and "satisfied" in winter (T was "comfortable", but RH was fairly low). The most discomfort was experienced in winter.

3.2.2. Indoor air quality

Table 5 presents the median TVOC levels and the concentrations of the individual VOC and aldehydes measured weekly in the main bedrooms of the seven houses in the pre-occupancy stage and during occupancy.

Table 5– Indoor TVOC, VOC and aldehyde levels ($\mu\text{g}/\text{m}^3$) measured weekly in seven new low-energy houses at the pre-occupancy stage (Pre) and during occupancy (Sum: summer; Win: winter). LI: Limit of identification ($<1 \mu\text{g}/\text{m}^3$); LD: limit of detection; LQ: limit of quantification; n.a.: not available; n.m.: not measured; Q.F.: quantification frequency

In the pre-occupancy stage, the median TVOC levels were low in houses A and B (less than $150 \mu\text{g}/\text{m}^3$) and high in the other houses (between 500 and more than $3000 \mu\text{g}/\text{m}^3$). In houses C, D and E, the TVOC concentrations were higher in pre-occupancy than during occupancy.

Forty-four VOCs and seven aldehyde compounds in ten families were identified and quantified at least once. The number of these compounds varied between 20 and 35 per house. Seventeen of the 20 targeted compounds measured during the national survey of IAQ in dwellings in France were quantified, and three were never detected (2-butoxy ethyl acetate, 1-methoxy-2-propanol, 1-methoxy-2-propyl acetate). The compounds were split into two groups by quantification frequency: the most frequently detected (in at least 56% of samples; 14 VOCs: 1,2,4-trimethylbenzene, alkylbenzenes, alpha-pinene, benzene, camphene, n-decane, n-undecane, ethylbenzene, limonene, pentane, styrene, toluene, m- and p-xylene, and o-xylene; five aldehydes: acetaldehyde, acrolein, formaldehyde, hexaldehyde and isovaleraldehyde) and the least frequently detected (in at most 39% of samples; 30 VOCs and two aldehydes). For the most frequently detected compounds, high levels were measured in the pre-occupancy stage in houses C, E and

G and lower levels were measured in house A. During occupancy, eight compounds were always quantified. Hexaldehyde presented the highest concentrations in the majority of houses both before occupancy ($69.7\text{-}856\ \mu\text{g}/\text{m}^3$) and after ($36.1\text{-}104.9\ \mu\text{g}/\text{m}^3$ in summer and $14.6\text{-}96\ \mu\text{g}/\text{m}^3$ in winter). Formaldehyde was the only compound whose concentrations were systematically higher in summer than winter. Acetaldehyde, n-decane, n-undecane, alpha-pinene, 1,2,4-trimethylbenzene and o-xylene were also always measured. For the less frequently measured compounds, high levels were detected in the pre-occupancy stage in houses C and E. N-butyl acetate was quantified at high concentrations in only two buildings ($548.1\ \mu\text{g}/\text{m}^3$ in occupied house B in winter and $108.2\ \mu\text{g}/\text{m}^3$ in unoccupied house E). This compound is mainly used as a solvent or diluent in the cosmetics, clothing, automotive, food and pharmaceutical industries and in the production of liquid floor wax, photographic film and plastics [19]. Here, this compound may be related to the use of perfume and/or cosmetics such as nail polish and nail-polish remover [20] because VOC sampling was carried out in the main bedrooms opening onto a private bathroom. In house B, the inhabitants declared daily use of perfume and hairspray during the week of measurement in winter. In house E, the inhabitants lived in the house during the two first days of the pre-occupancy stage, when the MVHR system was switched off.

The mass concentrations of $\text{PM}_{2.5}$ were always below $30\ \mu\text{g}/\text{m}^3$ and ranged from 6 (house C) to $28\ \mu\text{g}/\text{m}^3$ (house B; Figure 4). The measured concentrations were higher in winter than in summer in houses A, B, C and E but not in house F. This exception can be linked to the proximity of a construction site to house F during the summer. For all houses, the pre-occupancy concentrations of $\text{PM}_{2.5}$ remained under $15\ \mu\text{g}/\text{m}^3$ and never exceeded those levels during occupancy. The radon concentrations ranged between 7 and $66\ \text{Bq}/\text{m}^3$ and were highest in houses B and E and lowest in house D (Figure 5). In general, the radon concentrations were higher in the living room than in the main bedroom, except in house E. CO concentrations were measured during the winter in only three houses (B, D and E), all of which had wood stoves, and were near zero ppm, with a peak at 8 ppm measured immediately after lighting the wood stove in house D.

Figure 4 - Weekly mass concentrations of PM_{2.5} (µg/m³) measured in the living room for six houses during the pre-occupancy stage (Pre) and during occupancy (summer: Sum; winter: Win). n.a.: not available; n.m.: not measured

Figure 5 - Radon concentrations (Bq/m³) measured in the living room and in the main bedroom for six occupied houses. n.a.: not available

4. Discussion

4.1. Assessment of the performance and the use of MVHR

When the MVHR systems were switched off, the ACH of most of houses was less than 0.05 h⁻¹ (except for house F, at 0.12 h⁻¹), confirming that the buildings were highly airtight (as previously measured with a blower-door test). The average ACH generated by four adjusted MVHR systems before measurement (houses A, B, C and F) at the medium (most used) fan speed was compared to a rate of 0.5 h⁻¹. This value corresponds to the median ACH value of French dwellings [13] and is frequently used in national standards/regulation in Europe [21]. A value of 0.5 h⁻¹ was reached in houses B, C and F and exceeded in house A. The measured air exhaust rates for four adjusted MVHR systems before measurement (houses A, B, C and F) were compared to the French regulations concerning residential-building ventilation [14]. It appears that the achievable air exhaust rates and the minimum values of reduced rates were reached occasionally but not systematically for each house (Table 6). The average noise levels in the main bedrooms of the four houses were near 30 dB(A) for the low fan speed). For the other fan speeds, higher noise levels (between 35 and 48 dB(A)) caused the inhabitants to complain, as in house B. Our observations were consistent with those of eight passive houses [22] and in recently built Dutch homes equipped with MVHR systems and natural and mechanical-exhaust ventilation [23]. Shortcomings such as insufficient ventilation, high noise levels, unclean systems and insufficient maintenance were common [23]. The recurring problem in MVHR-ventilated airtight buildings is not a technical shortcoming of the ventilation system itself; installer expertise and solid installation-qualification procedures are

indispensable to MVHR success [24]. Finally, the inhabitants in our study found the ventilation system difficult to use, as previously shown in passive houses [25].

Table 6 - Comparison of the measured air exhaust rate (l/s) for four houses to the French regulations concerning residential-building ventilation [14].

4.2. Comparison of our IAQ results to those of previous studies

During the pre-occupancy stage, the instructions were as follows: absence of inhabitants, selection of the median fan speed for the MVHR system and no air-polluting activities such as painting, aerosol spraying and sanding. These instructions were followed in all but not for three houses: there was painting in house C, the presence of inhabitants during the first 24 hours and painting in house E and the MVHR systems were switched off in houses E and G. Thus, the highest concentrations of the most common VOCs and aldehydes were measured in those houses, although the mass concentrations of PM_{2.5} were unchanged. The lowest concentrations were observed in house A, for which the estimated average ACH for the medium MVHR fan speed was nearly double (0.9 h⁻¹) that of the other houses (approximately 0.5 h⁻¹). Moreover, this house was investigated 13 months after its completion versus one month for the other houses. The geometric concentrations of TVOC and of the most commonly quantified VOCs and aldehydes of three unoccupied houses for which the instructions were followed (houses A, B and D) were calculated. VOCs and aldehydes were compared to data from previous studies. Our TVOC values obtained with a PID instrument and providing information on a given mixture of VOC cannot be compared with TVOC values obtained in other studies by using sampling on a sorbent and subsequent separation by gas chromatography. Those studies were conducted in unoccupied and ventilated dwellings less than one year old, which can be energy efficient (EE) and/or built with low-emissions material (LE) (Table 7). It appears that the concentrations of TVOC and the majority of aromatic hydrocarbons measured in our study were consistently lower than those reported by authors from other countries. The concentrations of other organic compounds were also always lower than those reported [26,27,28].

However, the concentrations of aldehydes, terpenes, aliphatic hydrocarbons and 1,2,4-trimethylbenzene were sometimes higher than those measured [10,29,30,31,32,33]. The concentrations of organic compounds measured in non-ventilated houses (E and G) were higher than those reported in a new, unventilated Minergie home [8], except for alpha-pinene, formaldehyde and acetaldehyde.

Table 7 - Comparison of geometric concentrations of TVOC and of the most frequently quantified VOC and aldehydes in this study in three unoccupied houses (A, B and D) to the results of previous studies conducted in unoccupied and ventilated dwellings less than one year old. Some of these houses may have been energy-efficient and/or built with low-emitting material. n.m.: not measured

The arithmetic means of TVOC and the geometric means of the most frequently measured VOCs and aldehydes in occupied houses (A, B, C, D, E and F) in summer and in winter were compared (Table 8) to data from previous studies. Those studies were conducted in newly occupied homes and presented in a recent literature review [34]. Only studies conducted in occupied and ventilated dwellings less than one year old were selected, and a small number of studies in energy-efficient homes were added. ~~Our TVOC concentrations were lower than those reported in 24 R-2000 standard homes in Canada [35], in two Minergie apartments in Switzerland [8] and in 292 dwellings in Japan [36]. Our results were similar to those measured in six apartments built with low emissions material in Finland [30].~~ The decrease in TVOC levels over time observed in houses C, D and E was also reported by other authors [35]. In R-2000 standard homes, TVOC concentrations were higher during the first week after closure and then decreased with time and became relatively stable approximately 40 days after closure, at approximately one quarter of the maximum observed level [6]. A 50% decrease in TVOC levels was observed after seven days of strong ventilation [30]. All VOCs and aldehydes measured in our study presented concentrations lower than those reported by another authors [36,37]. The concentrations of ethylbenzene, styrene, toluene and limonene measured in our study were lower than those reported by any other study. For all other compounds, the concentrations were in the ranges of those measured in another studies [10,11,30,35].

Table 8 - Comparison of the mean concentration of TVOC and geometric mean concentrations of the most frequently VOC and aldehydes quantified in this study in six occupied houses (A, B, C, D, E and F) in summer and winter with the results of previous studies conducted in newly occupied and ventilated

dwellings less than one year old. Some of these houses may have been energy-efficient and/or built with low-emissions material. n.m.: not measured

4.3. Comparison of our IAQ results to the standard French houses F and the indoor air-quality guideline values used in France

The values of CO₂, VOC, aldehyde compounds, PM_{2.5} mass, radon concentrations, temperature and relative humidity in the occupied houses (A, B, C, D, E and F) were compared to the IAQ of the standard French houses [12]. The standard French houses have an ACH of 0.5 h⁻¹ [13] but are older than the houses in our study (half built before 1968), are under-equipped with MVHR (only 1.1%), are built predominantly of masonry (only 6% wood frame), have higher occupation rates (0.8) and allow smoking (34% of homes have at least one smoker).

The median CO₂ concentrations measured in summer and in winter in our study were lower than the national median CO₂ level (756 ppm) for three houses (B, E and F) and between 756 ppm and 1000 ppm for the other houses (A, C and D). The seasonal variation in CO₂ levels (lower in summer than in winter) is most likely related to the increased rate of air exchange in these houses in summer due to the opening of windows, as observed in another studies [38,39]. The occupants of our houses reported opening the windows more than one half hour per day in summer and rarely or almost never in winter, as in standard French houses [13], suggesting that the occupants of low-energy houses do not drastically change their usual ventilation behaviours. The comparison between the median temperatures and relative humidities measured in these houses and the median values of French dwellings are shown in Figure 6. Houses A, B and F, but not houses C, D and E, exceeded the national median temperature. In contrast, only house E reached the national median relative humidity, specifically in winter.

Figure 6 - Comparison of weekly median T (°C) and RH (%) measured in the bedroom for six occupied houses (Sum: summer; Win: winter) to the seasonal values measured in standard French dwellings (CNL). n.a.: not available

The median ratios of the average concentrations of VOC, aldehydes, PM_{2.5} and radon measured in all occupied houses to the national median concentration in standard French dwellings are presented in Figure 7. Compared to the median concentration of indoor air pollutants in standard French dwellings, the average concentrations of PM_{2.5}, radon and two aromatic hydrocarbons compounds (benzene and toluene) were lower, whereas the concentration of formaldehyde was not significantly different. The concentrations of three aromatic hydrocarbon compounds (ethylbenzene, m- and p-xylene and 1,2,4-trimethylbenzene), one aldehyde (acrolein) and one aliphatic hydrocarbon compound (n-decane) were less than 1.5 times higher than the national levels. Other compounds were more markedly elevated in concentration, including hexaldehyde (up to 4.7 times higher) and n-decane (up to two times higher) and (to a lesser extent) styrene, o-xylene and acetaldehyde (between 1.7 and 1.5 times higher).

Figure 7 – Median ratio of the average concentrations of VOC, aldehydes, PM_{2.5} and radon measured in six occupied houses to the national median concentration in French dwellings

Although it is difficult to explain these differences, the high levels of hexaldehyde may be associated with the use of wood as the main construction material [27]. The degradation of the wood (composite wood products and lumber) or its secondary metabolites is most likely responsible for the presence of the aldehydes [40]. High aldehyde levels may also be related to the use of paints and varnishes for wood [41,42,43], the presence of new materials (less than one year old) such as particle-board furniture [44] and the surface coverings of walls [45], floors and ceilings [46]. The recent use of products containing solvents (paint, adhesives, etc.) may cause elevated concentrations of n-undecane and n-decane [47]. Formaldehyde was present in homes in our study at levels comparable to other French homes, although higher levels were expected because of the age of the buildings and materials (less than one year) and the high use of wood. The low concentration of radon and the low mass concentration of PM_{2.5} may be associated with the very high airtightness of these buildings compared to average French homes. Based on the living room's radon measurement (on ground level), the mean concentration reaches 16 Bq/m³ for measurement period in spring, 35 Bq/m³ for measurement period in fall. The only one measure available for measurement period in fall/winter is equal to 43 Bq/m³ (for house B). According this observation,

occupants' window opening behaviour depending on season could have an impact on radon concentration but this hypothesis can't be validated because their behaviours haven't been recorded during the radon measurement period. Finally, the low concentrations of aromatic hydrocarbons may be related to the general absence of attached garages, which are known to be an important source of those compounds [48,49,50]. The high concentrations of benzene and toluene in house A, the only building with an attached garage, seem to reinforce this hypothesis. The drier air might be associated with better ventilation in houses equipped with MVHR systems [51] and with a lower production of water vapour because of the under-occupation of these buildings.

The concentrations of formaldehyde, benzene and radon did not exceed the indoor air-quality guideline values currently used in France (respectively 30 $\mu\text{g}/\text{m}^3$ long-term exposure, 1st January 2015, 5 $\mu\text{g}/\text{m}^3$ long-term exposure, 1st January 2013 [52] and 400 Bq/m^3 for a public building according [53]). The concentrations of acetaldehyde, xylenes, styrene and toluene were within the European guideline values [54] (respectively 200 $\mu\text{g}/\text{m}^3$, 200 $\mu\text{g}/\text{m}^3$, 250 $\mu\text{g}/\text{m}^3$ and 300 $\mu\text{g}/\text{m}^3$), but the level of $\text{PM}_{2.5}$ exceeded the WHO air-quality guidelines [55] (10 $\mu\text{g}/\text{m}^3$ annual mean).

4.4. Temporal variation of IAQ in occupied houses

The temporal variation in IAQ in the six occupied houses was calculated based on the concentration ratio between the measurements made during the first and second surveys for $\text{PM}_{2.5}$ and VOC and aldehyde compounds in at least four houses (Figure 8). For VOC and aldehydes, the ratios were calculated only for each compound measured in each survey. The first survey was conducted in summer and the second in winter, except for houses D and F. The interval between the surveys was three months for house D, four months for house C and six months for houses A, B, E and F. The median of the ratios for each of the six houses was calculated.

Figure 8 – Ratio of the concentrations of VOC, aldehydes and $\text{PM}_{2.5}$ measured during the second survey to those measured during the first survey for each of six occupied houses and ratio of the median concentrations for all houses

The majority of VOC and aldehydes exhibited lower concentrations in the second survey (median ratio less than 1), or similar in the case of 1,2,4-trimethylbenzene, whereas the opposite trend was observed for n-undecane and PM_{2.5} (median ratio greater than 1).

The concentrations of toluene, styrene, xylenes, ethylbenzene, terpenes (alpha-pinene and limonene) and acetaldehyde decreased for most of the houses, suggesting that these compounds were mainly emitted by building sources such as building material, insulation, decoration, surface coatings, furniture and other sources. The concentrations of these compounds decreased with the decreasing of emission-source strength over time. Those observations were consistent with another authors [35], which showed significantly reduced concentrations of styrene, p-xylene and alpha pinene over one year in new homes. Another authors [37] also observed over a period of one year in a wood detached house that concentrations of seven COV compounds, including toluene, alpha-pinene and limonene, exhibited a declining trend with time. Several authors have shown that aldehyde concentrations can be influenced by building materials and human activities [30,44]. In our study and because of the recent construction of the buildings, building materials appear to have been the principal source of high aldehyde concentrations [45,46]. The decreased hexaldehyde concentrations may be correlated with the increased age of the furniture and the ground/wall/ceiling coverings [46], but after more than one year, none of these materials has any influence on hexaldehyde levels [44]. In houses D and F, the higher levels of formaldehyde observed during the second survey (in summer) corroborated the observations of other authors [31,56,57]. This increase may be attributed principally to the influence of temperature on VOC emissions from materials [58] and secondarily to the reactions between organic compounds (especially terpenes) and ozone [59,60,61]. A study carried out in new single - family homes in California showed that as outdoor air exchange rates decrease or the indoor temperature increases, the indoor concentrations of formaldehyde increase [62].

The highest concentrations of benzene and toluene relative to national standards were observed in house A (ratios of 3.9 and 1.3, respectively) and seem to be linked to the presence of an attached garage. Several

authors [48,49,50] have shown that many pollutant sources, such as gasoline-fired engines (automobiles, gardening tools such as lawnmowers, etc.), fuel, paint and solvent are commonly stored or used in residential attached garages and may be an important source of monocyclic aromatic hydrocarbons.

The high ratios of n-undecane concentrations relative to national standards in houses A, B and E (1.9, 7.0 and 4.6, respectively; attributable to painting that occurred in houses B and E between the two surveys) explained the high median ratio level observed for all houses (median ratio = 1.3). The relatively high levels of n-decane in houses B and E (ratios of 4.7 and 2.1, respectively) support this hypothesis.

Increased concentrations of PM_{2.5} (median = 1.8) were observed in all buildings except house F and seem to be seasonal. The influence of season on the particulate-matter concentrations has previously been reported [63,64] and appears to be linked to different ventilation practices in summer and winter. According to a meta-analysis conducted in Europe [65], the highest particulate-matter infiltration was observed in summer, with the lowest infiltration in winter. Because of the increased ventilation in summer from the opening of windows, indoor PM levels were highly correlated with outdoor PM levels, whereas in winter, PM levels were more strongly influenced by human indoor activities. In our study, indoor and outdoor PM_{2.5} concentrations showed a strong positive correlation in summer ($r = 0.98$) and a weak positive correlation in winter ($r = 0.11$). Finally, the highest ratio of PM_{2.5} concentrations, observed in houses B and E (≥ 3), seems to be related to the use of wood for heating during the second survey (in winter). The impact of the wood heating system on indoor PM₁₀, PM_{2.5} and PM₁ concentrations has been shown previously [66].

5. Conclusions

Seven newly built, low-energy single-family detached houses in France conform to the highly airtight and energy-efficient standards set forth in RT2012 were investigated during the pre-occupancy stage and during occupancy in summer and winter. Because of the limited sample size, caution must be taken and

the findings can't be generalized. The following conclusions can be drawn from the present study but contribute significantly to knowledge about IAQ and occupant's comfort in energy efficient homes.

Several IAQ-indicator measurements show that the concentrations of aromatic hydrocarbons, terpenes, alkanes and aldehydes were higher in the pre-occupancy stage than during occupancy. The concentrations of some aromatic hydrocarbons (toluene, ethylbenzene, xylenes, styrene), terpenes (alpha-pinene, limonene) and acetaldehyde decreased with time, possibly in relation to the decrease in emissions from building materials over time. The concentrations of alkanes (n-decane and n-undecane), benzene and major aldehydes (formaldehyde and hexaldehyde) may increase temporarily in response to human activities. The PM_{2.5} levels increased during occupancy and appear to be related, in summer, to the outdoor PM_{2.5} levels via an increased infiltration level and with indoor human activities in winter. The air temperature and relative humidity were higher in summer than in winter (between 20 and 26 °C in summer, versus between 20 and 22 °C in winter between 45 and 58% RH versus 29 and 34% RH, respectively).

Compared to the IAQ of standard French houses, the median concentrations of PM_{2.5}, radon, benzene and toluene were lower in the houses studied. The air temperature and the formaldehyde concentrations were similar to those found in typical French houses, whereas the concentrations of ethylbenzene, m- and p-xylene, 1,2,4-trimethylbenzene and acrolein were slightly higher (less than 1.5-fold). In contrast, concentrations of hexaldehyde, acetaldehyde, styrene, o-xylene, n-decane and n-undecane exceeded the levels in typical French dwellings by more than 50%. The concentrations of these compounds seem to be related to new construction. The relative humidity of the study houses was lower than in French dwellings, possibly due to the constant and permanent ventilation occurred by the MVHR systems and due to limited water production linked to the under-occupancy of the study houses. The levels of indoor pollutants in the study houses were within the guideline values for indoor air quality used in France, but the PM_{2.5} level exceeded the levels set by WHO recommendations. The MVHR systems exhibited commonly reported shortcomings but provided sufficient ACH (≥ 0.5 h⁻¹). In summer, the inhabitants improved the houses' ventilation by opening windows, as in conventional dwellings. MVHR systems

seem to be difficult to use, and high noise levels can be produced at the highest fan speed. Finally, in airtight buildings, the mechanical ventilation systems must work constantly; if they shut down, without ventilation through open windows, indoor air quality can become poor and present a risk to human health.

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Indoor air quality and comfort in seven newly built, energy-efficient houses in France

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1. Introduction

Because of the global warming, many governments have taken action to reduce anthropogenic greenhouse-gas emissions, to promote energy efficiency and to support for renewable energy. In France, the residential and commercial building sector is responsible of 23% of national greenhouse-gas emissions and is the largest energy consumer, accounting for 43% of energy consumption in the country in 2007 [1]. In 2011, the average unit energy intensity of the residential sector was 190 kWh/m², higher than that of the commercial sector [2]. In this context, France has pledged to reduce greenhouse-gas emissions by 75% by 2050 and to reduce building energy consumption by 38% by 2020 [3]. Existing structures are being refurbished to increase energy efficiency at an accelerating rate, and as of 2013, all newly constructed buildings must meet the French 2012 thermal-regulation standards (RT 2012) for buildings. Although these new airtight buildings must have a primary conventional-energy consumption not exceeding 50 kWh/m² per year, there are no requirements directly protecting the health and wellbeing of occupants. Moreover, the only literature review on indoor air quality (IAQ) in highly energy-efficient houses [4] concludes that "with regard to indoor air quality, there is a dearth of information relating to highly efficient structures". The authors note that it is difficult to extrapolate the results of studies of the construction of airtight buildings in colder climates (Canada, Central Europe and northern USA) to other countries because of differences in climate, construction practices, indoor sources depending of what people purchase on their homes and the social and economic conditions of the occupants. Finally, a small number of studies have investigated indicators of IAQ [5,6,7,8,9,10,11], but none has conducted an IAQ longitudinal survey and compare their results with those of standard buildings.

The objective of the present study, which was funded by the French Observatory of Indoor Air Quality (OQAI in French), is to evaluate the IAQ and the occupants' comfort in seven low-energy, newly built houses in France. The survey was conducted during the pre-occupancy stage and during occupancy in summer and winter. The concentrations of several IAQ indicators and the indoor environmental parameters were measured during occupation. These results were compared to the IAQ of standard

French houses [12], to the results of previous studies conducted in new dwellings and to the IAQ guideline values currently used in France. The air changes per hour (ACH) from mechanical ventilation with heat recovery (MVHR) were measured and compared to those of standard French homes [13]. The air-exhaust rates were compared to the French standards [14] for minimal airflow for dwellings according to the number of habitable rooms. The noise levels were measured, and the occupants' perceptions were evaluated with a questionnaire.

2. Materials and methods

A recently developed method for assessing IAQ, occupant comfort and energy consumption was applied in this study. A detailed description of sampling and measurement techniques has been presented elsewhere [15]. A short overview of the analytical procedures and the sampling strategy is given below.

2.1. Description of the seven single-family detached houses

Seven newly built, single-family detached houses in four regions of France (Centre, Pays-de-la-Loire, Ile-de-France and Rhône-Alpes) were investigated in this study (Table 1).

Table 1 - Main characteristics of the seven new single-family detached houses investigated in this study in terms of construction, equipment and occupancy

The buildings had one or two stories, and one had an attached garage (A). All houses were constructed in accordance with an energy-efficient building certification such as the French BBC-Effinergie certification or the German Passivhaus certification. Three houses were certified (A: BBC-Effinergie; C and D: Passivhaus); house B's certification process was on-going, and the builders or owners of the other houses are not pursuing certification. Houses F and G satisfied the requirements of all 14 targets of the French High Environmental Quality Programme (HQE). The airtightness of all buildings was measured with a

blower-door test between 0.29 and 3.33 vol/h under 50 Pascal pressure (0.06 and 0.41 m³/h.m² under 4 Pascal pressure). The houses' annual consumption of conventional primary energy (heating, cooling, ventilation, auxiliaries, hot water production, lighting facilities) was between 46 and 79 kWh/m²/year. These houses were well within the requirements of the French 2005 thermal regulations (RT 2005) for buildings (airtightness less than 0.8 m³/h.m² under 4 Pa and annual consumption of conventional primary energy less than 150 kWh/m²/year). The houses also qualified as highly energy-efficient houses as defined by the French 2012 thermal regulation (RT 2012) because of their high airtightness (under 0.6 m³/h.m² under 4 Pa) and their theoretical low energy consumption (an annual consumption of conventional primary energy equal or less than 50 kWh/m²/year). All of the houses were wood frame except for house A (stone) and used mineral (A, F and G) or vegetable (B, C, D and E) insulating material. All of the houses were equipped with an MVHR system with two, three or four normal fan speeds and occasionally one boost setting. The heating systems were mostly heat pumps (A, C, D, F and G) or wood stoves (B and E). House D had a wood stove for enjoyment rather than function. Hot water was mainly provided by solar panels with electric boosters (B, C, D, F and G) except in two houses (thermodynamic in house A and electric in house E). All of the houses but A had products and materials described by the manufacturers as low volatile-organic-compound-emitting. The inhabitants were families of 2-4 non-smokers, except for house G, which remained unoccupied during this study. The occupation rates were often lower than the median occupation rate (0.8) of the standard French houses [13] suggesting that these houses were under-occupied or were larger than an average French home.

2.2. Measurement protocol

The IAQ and indoor environmental parameters was monitored between February 2009 and July 2010 (Figure 1) just after the houses' completion (except for house A, completed in March 2008) for less than one year each. The IAQ was monitored in the main bedroom and in the living room and kitchen

(collectively called “living room”) for three weeks in each building in the pre-occupancy stage and during occupancy (summer: Sum; winter: Win) except in houses F and G. The ACH, the air exhaust rates and the level of noise were determined simultaneously in the pre-occupancy stage. The temperature, the relative humidity and the concentration of radon were measured only in occupied houses. The MVHR systems were switched on during these investigations at the medium normal fan speed during the pre-occupancy stage (except for houses E and G, where the MVHR systems were turned off) and in manual or automatic mode during occupancy.

Figure 1 - Weekly investigation and moving dates of the seven new single-family detached houses between February 2009 and July 2010

The strategy of sampling / measurement and the accuracy/uncertainty of the indoor air quality parameters are presented in Table 2.

Table 2 – Strategy of sampling/measurement and accuracy of indoor air quality parameters

Every ten minutes during the investigation, total volatile organic compounds (TVOC in toluene equivalent in $\mu\text{g}/\text{m}^3$) were measured with a photoionisation detector (PID) (PGM 7240 - RAE Systems) in the living room and carbon dioxide (CO_2 in ppm) was measured by a non-dispersive infra-red probe (TSI Q-Trak 8552) in the main bedroom. Individual volatile organic compounds (VOC) and aldehydes were collected over seven days in the main bedroom by a passive sampler (Radiello®, and Fondazione Salvatore Maugeri – IRCCS, Italy) with stainless steel net cartridges filled, respectively, with Carbograph 4 adsorbents and with 2,4-dinitrophenylhydrazine (2,4-DNPH)-coated Florisil. Sixteen VOC (1,2,4-trimethylbenzene, 1,4-dichlorobenzene, 1-methoxy-2-propanol and its acetate, 2-butoxyethanol and its acetate, benzene, ethylbenzene, m-/p-xylenes, n-decane, n-undecane, o-xylene, styrene, tetrachloroethylene, toluene, trichloroethylene) and four aldehydes (acetaldehyde, acrolein, formaldehyde, hexaldehyde) were quantified in $\mu\text{g}/\text{m}^3$ by, respectively, gas chromatography, mass spectrometry and flame ionisation and high-performance liquid chromatography and detection by UV absorption. These

compounds were measured during the national survey of IAQ in French dwellings [12], and the analytical method and the detection limit for each compound were previously detailed by [16]. Then, all other organic compounds whose concentrations exceeded $1 \mu\text{g}/\text{m}^3$ were identified and quantified in $\mu\text{g}/\text{m}^3$ toluene equivalent. Carbon monoxide (CO in ppm) was monitored only in winter every five minutes during seven days with an electrochemical sensor (Dräger Pac III) in each room that contained combustion equipment. The mass concentration of suspended particulate matter with an aerodynamic diameter less than $2.5 \mu\text{m}$ ($\text{PM}_{2.5}$) was measured in the living room with a sampling system (Chempass, Model. 3400, Thermo Fisher Scientific) coupled to an air sampler (Microvol 1100, Ecotech) operating at $1.8 \text{ l}/\text{min}$ from 5 pm to 8 am on weekdays and for 24 hours a day on weekends. The filters (37-mm-diameter PTFE membrane, 2- μm porosity, Gelman Sciences) were weighed before and after sampling according to NF EN 14907 [17], and mass concentrations are given in $\mu\text{g}/\text{m}^3$. During both investigations during occupancy, room temperatures (T in $^{\circ}\text{C}$) and relative humidity (RH in %) were monitored every ten minutes with Hydrolog sensors (Rotronic) in the main bedroom and the living room at different heights. Radon concentrations (Bq/m^3) were measured over more than two months using two Kodalpha LR 115 detectors (Dosirad, and France), one in the living room and the other in the bedroom, after the inhabitants moved in. The radon measurement was made principally during fall months for houses A, C, E, during spring months for houses D and F and during fall/winter months for house B. During the pre-occupancy stage and for normal fan speeds (low, medium, high and sometimes very high) of the MVHR, the ACH (in h^{-1}) in the main bedroom and living room, the air exhaust rate (l/s) and the mean noise level (in $\text{dB}(\text{A})$) were measured, respectively, by SF₆ tracer gas (B & K Multigas Monitor type 1302 with a B & K multipoint sampler and doser type 1303), by an array of hot wires (Swemaflow 233, Admi Industries) and by a type-II sonometer (Centre 322). The ACH was measured under the same outdoor conditions. No ACH measurements were made under the MVHR boost fan speed, which was activated for only a short period. The average ACH of each building was estimated, taking into account the ACH measurements of both rooms, the volume of those rooms and the total volume of the house. Because doors were opened very often during our investigations and thus homogenous zone of concentration

created, we supposed that air removal measured in 2 rooms could be translated to the air removal of the whole house. Because the MVHR systems are not very often checked during/after the completion of the building, we decided to evaluate its performance in terms of ACH, air exhaust rate and noise level. Concurrent with sampling and measuring, survey questionnaires were developed based on the national survey on indoor air quality in French dwellings [18] to collect general information on newly constructed houses, their equipment, their occupancy and the activities and perceptions of the inhabitants during each investigation.

2.3. Graphical representation and statistical analysis

A histogram representation with vertical error bars was used for measurements of T, RH, PM_{2.5}, radon, air exhaust rates and mean noise levels.

The software package SAS 9.1 was used for statistical analysis. To characterise the distribution of the raw data, the following parameters were calculated for the concentrations of CO₂ and for the measurements of T and RH: minimum, arithmetic mean, median, maximum and 25th and 75th percentile. For VOC and aldehyde values below the limit of quantification (LQ), the calculated value of the LQ divided by two was used in the statistical calculation (arithmetic mean, median, geometric mean). The differences in indoor environmental parameters (CO₂, T and HR) between occupancy in summer and in winter for each house were assessed using the Kruskal Wallis rank-sum test. A two-sided test was used because the sign of the difference was not known *a priori*. Spearman's rank correlation (r_s) was used to express correlations between the indoor PM_{2.5} levels and outdoor PM_{2.5} levels. P-values < 0.05 were considered statistically significant.

3. Results

3.1. Performance of MVHR

The performance of MVHR was evaluated for six houses during the pre-occupancy stage after inspection and their adjustment by the installers; in houses D and E, the systems of ventilation were adjusted after measurement.

3.1.1. Air exchange per hour (ACH)

Table 3 presents the measurement of ACH (in h^{-1}) for the living room and the main bedroom and the average ACH for the house.

Table 3 - Measured ACH per room and estimation of average ACH (h^{-1}) by house depending on the fan speed of the MVHR system in six houses (confidence interval). n.m.: not measured; n.e.: not estimated

When the MVHR systems were switched off, the ACH of both rooms induced by air leakage did not exceed 0.05 h^{-1} , except in house F, where it reached 0.1 h^{-1} . When the MVHR systems were turned on, the ACH values increased with increasing fan speed (in houses A, B, D and F). The ACH values ranged between $0.4\text{-}0.8 \text{ h}^{-1}$ in house A, $0.2\text{-}1.2 \text{ h}^{-1}$ in house B, $0.1\text{-}1.3 \text{ h}^{-1}$ in house C, $0.2\text{-}0.7 \text{ h}^{-1}$ in house D, $0.2\text{-}0.6 \text{ h}^{-1}$ in house E and $0.5\text{-}0.6 \text{ h}^{-1}$ in house F. Shortcomings appeared at the highest fan speed, where ACH values were in some cases equal to the ACH value at the medium fan speed (house C) or even lower (bedroom of house E). The average ACH values for MVHR systems without a boost fan speed were between 0.1 and 0.3 h^{-1} at the lower fan speed, 0.3 and 0.5 h^{-1} at the medium speed and up to 1 h^{-1} at the highest speed. For the MVHR systems with a boost fan speed (houses A and F), the minimum average ACH values were 0.6 h^{-1} and 0.5 h^{-1} , respectively.

3.1.2. Air exhaust rates

Air exhaust rates (l/s) were measured for each outlet and for each fan speed of the MVHR system. For technical reasons (e.g., height, size, geometry of the outlets, presence of furniture fixed to the wall near the outlets), not all measurements were recorded. Figure 2 shows that the air exhaust rates increased with the increasing fan speed of the ventilation systems for the majority of houses, though deviations appear in

houses A and F. The air exhaust rates were the same for the lower as for the medium fan speed in house A (WC and bathroom 1) and house F (WC and bathroom 2). Finally, for both houses and considering only WC and bathroom outlets, the difference in the air exhaust rates between the lower and the higher fan speeds was smaller (less than 1.7 l/s) than in the other houses (between 3.3 and 8.6 l/s).

Figure 2 – Measured air exhaust rate (l/s) per room by the fan speed of the MVHR system in six houses

3.1.3. Average noise level

The average noise level (dB(A)) was measured for each MVHR fan speed. The results are presented in Figure 3, and all measured values less than or equal to 30 dB(A) (under the range value of the sonometer used) were replaced by the symbol *. The average noise level increased with increasing MVHR fan speed, except in a few rooms in house F. The utility room where the MVHR system was located was the noisiest (value ranged between 33 and 59 dB(A)), except in house D. The bedrooms (and occasionally office rooms) were generally the quietest (less than 30 to 33 dB(A)), except in houses B and D (up to 48 and 36 dB(A), respectively). The average noise levels in house E were markedly lower. Overall, indoor noise levels were rated between “quite pleasant” and “extremely pleasant” by the inhabitants. Noises coming from inside the house, especially those from the MVHR ventilator and those that were noticeable at bedtime (B), during the night (A, D) or during quiet parts of the day were rated as more bothersome than noises from outside.

Figure 3 – Measured average noise level (dB(A)) per room depending on the MVHR fan speed in six houses (* average noise level value \leq 30 dB(A)) (BAT: bathroom; BED: bedroom; LR: living room; OFF: office room; UR: utility room)

3.1.4. Use of the MVHR system

During occupancy, several technical improvements were made to the MVHR systems in response to complaints from the inhabitants regarding the poor adjustment of the air-flow rate (houses A and E), disturbance of the air-flow rate during occupancy (houses A and C) or after cleaning the inlets/outlets (house B), noise disturbance (house A and C) and the need to replace components of the ventilation system (houses A and F). The inhabitants reported that the MVHR systems were difficult to use and that the user manual was complex; the majority used only the manual mode rather the program mode. The inhabitants of house E used the program mode, but the available schedules did not match their lifestyle.

3.2. Indoor environment parameters

3.2.1. Air stuffiness and thermal comfort

The concentrations of CO₂ and the T and RH values measured in the main bedroom of each house during occupancy (Sum and Win) are presented in Table 4.

Table 4 - Descriptive statistics of CO₂ level (ppm), T (°C) and RH (%) measured weekly in the main bedrooms of six occupied houses by season. (Sum: summer; Win: winter; P25: 25th percentile; P75: 75th percentile; n.a.: not available)

The median CO₂ levels were always below 1000 ppm and ranged between 351 ppm (house B) and 811 ppm (house A). These levels were significantly lower in summer than in winter ($p < 0.0001$). The lowest levels were close to the measured outdoor level, and the highest levels were less than 2100 ppm. Houses C and D appeared to have less fresh air than the others because of their high interquartile temperature ranges. The median temperatures were between 20.3 and 25.7 °C in summer and 19.5 and 21.6 in winter. Larger variation in temperature was observed in winter (8 to 15 °C) than in summer (3 to 8 °C). The median RH values were between 45 and 58% in summer and between 29 and 34% in winter. As expected, the T and RH values were significantly higher in summer than in winter ($p < 0.0001$).

According to the inhabitants, the global thermal comfort of their houses ranged between "rather satisfactory" and "satisfactory" in the summer (T and RH were "comfortable") and between "somewhat dissatisfied" and "satisfied" in winter (T was "comfortable", but RH was fairly low). The most discomfort was experienced in winter.

3.2.2. Indoor air quality

Table 5 presents the median TVOC levels and the concentrations of the individual VOC and aldehydes measured weekly in the main bedrooms of the seven houses in the pre-occupancy stage and during occupancy.

Table 5– Indoor TVOC, VOC and aldehyde levels ($\mu\text{g}/\text{m}^3$) measured weekly in seven new low-energy houses at the pre-occupancy stage (Pre) and during occupancy (Sum: summer; Win: winter). LI: Limit of identification ($<1 \mu\text{g}/\text{m}^3$); LD: limit of detection; LQ: limit of quantification; n.a.: not available; n.m.: not measured; Q.F.: quantification frequency

In the pre-occupancy stage, the median TVOC levels were low in houses A and B (less than $150 \mu\text{g}/\text{m}^3$) and high in the other houses (between 500 and more than $3000 \mu\text{g}/\text{m}^3$). In houses C, D and E, the TVOC concentrations were higher in pre-occupancy than during occupancy.

Forty-four VOCs and seven aldehyde compounds in ten families were identified and quantified at least once. The number of these compounds varied between 20 and 35 per house. Seventeen of the 20 targeted compounds measured during the national survey of IAQ in dwellings in France were quantified, and three were never detected (2-butoxy ethyl acetate, 1-methoxy-2-propanol, 1-methoxy-2-propyl acetate). The compounds were split into two groups by quantification frequency: the most frequently detected (in at least 56% of samples; 14 VOCs: 1,2,4-trimethylbenzene, alkylbenzenes, alpha-pinene, benzene, camphene, n-decane, n-undecane, ethylbenzene, limonene, pentane, styrene, toluene, m- and p-xylene, and o-xylene; five aldehydes: acetaldehyde, acrolein, formaldehyde, hexaldehyde and isovaleraldehyde) and the least frequently detected (in at most 39% of samples; 30 VOCs and two aldehydes). For the most frequently detected compounds, high levels were measured in the pre-occupancy stage in houses C, E and

G and lower levels were measured in house A. During occupancy, eight compounds were always quantified. Hexaldehyde presented the highest concentrations in the majority of houses both before occupancy ($69.7\text{-}856\ \mu\text{g}/\text{m}^3$) and after ($36.1\text{-}104.9\ \mu\text{g}/\text{m}^3$ in summer and $14.6\text{-}96\ \mu\text{g}/\text{m}^3$ in winter). Formaldehyde was the only compound whose concentrations were systematically higher in summer than winter. Acetaldehyde, n-decane, n-undecane, alpha-pinene, 1,2,4-trimethylbenzene and o-xylene were also always measured. For the less frequently measured compounds, high levels were detected in the pre-occupancy stage in houses C and E. N-butyl acetate was quantified at high concentrations in only two buildings ($548.1\ \mu\text{g}/\text{m}^3$ in occupied house B in winter and $108.2\ \mu\text{g}/\text{m}^3$ in unoccupied house E). This compound is mainly used as a solvent or diluent in the cosmetics, clothing, automotive, food and pharmaceutical industries and in the production of liquid floor wax, photographic film and plastics [19]. Here, this compound may be related to the use of perfume and/or cosmetics such as nail polish and nail-polish remover [20] because VOC sampling was carried out in the main bedrooms opening onto a private bathroom. In house B, the inhabitants declared daily use of perfume and hairspray during the week of measurement in winter. In house E, the inhabitants lived in the house during the two first days of the pre-occupancy stage, when the MVHR system was switched off.

The mass concentrations of $\text{PM}_{2.5}$ were always below $30\ \mu\text{g}/\text{m}^3$ and ranged from 6 (house C) to $28\ \mu\text{g}/\text{m}^3$ (house B; Figure 4). The measured concentrations were higher in winter than in summer in houses A, B, C and E but not in house F. This exception can be linked to the proximity of a construction site to house F during the summer. For all houses, the pre-occupancy concentrations of $\text{PM}_{2.5}$ remained under $15\ \mu\text{g}/\text{m}^3$ and never exceeded those levels during occupancy. The radon concentrations ranged between 7 and $66\ \text{Bq}/\text{m}^3$ and were highest in houses B and E and lowest in house D (Figure 5). In general, the radon concentrations were higher in the living room than in the main bedroom, except in house E. CO concentrations were measured during the winter in only three houses (B, D and E), all of which had wood stoves, and were near zero ppm, with a peak at 8 ppm measured immediately after lighting the wood stove in house D.

Figure 4 - Weekly mass concentrations of PM_{2.5} (µg/m³) measured in the living room for six houses during the pre-occupancy stage (Pre) and during occupancy (summer: Sum; winter: Win). n.a.: not available; n.m.: not measured

Figure 5 - Radon concentrations (Bq/m³) measured in the living room and in the main bedroom for six occupied houses. n.a.: not available

4. Discussion

4.1. Assessment of the performance and the use of MVHR

When the MVHR systems were switched off, the ACH of most of houses was less than 0.05 h⁻¹ (except for house F, at 0.12 h⁻¹), confirming that the buildings were highly airtight (as previously measured with a blower-door test). The average ACH generated by four adjusted MVHR systems before measurement (houses A, B, C and F) at the medium (most used) fan speed was compared to a rate of 0.5 h⁻¹. This value corresponds to the median ACH value of French dwellings [13] and is frequently used in national standards/regulation in Europe [21]. A value of 0.5 h⁻¹ was reached in houses B, C and F and exceeded in house A. The measured air exhaust rates for four adjusted MVHR systems before measurement (houses A, B, C and F) were compared to the French regulations concerning residential-building ventilation [14]. It appears that the achievable air exhaust rates and the minimum values of reduced rates were reached occasionally but not systematically for each house (Table 6). The average noise levels in the main bedrooms of the four houses were near 30 dB(A) for the low fan speed). For the other fan speeds, higher noise levels (between 35 and 48 dB(A)) caused the inhabitants to complain, as in house B. Our observations were consistent with those of eight passive houses [22] and in recently built Dutch homes equipped with MVHR systems and natural and mechanical-exhaust ventilation [23]. Shortcomings such as insufficient ventilation, high noise levels, unclean systems and insufficient maintenance were common [23]. The recurring problem in MVHR-ventilated airtight buildings is not a technical shortcoming of the ventilation system itself; installer expertise and solid installation-qualification procedures are

indispensable to MVHR success [24]. Finally, the inhabitants in our study found the ventilation system difficult to use, as previously shown in passive houses [25].

Table 6 - Comparison of the measured air exhaust rate (l/s) for four houses to the French regulations concerning residential-building ventilation [14].

4.2. Comparison of our IAQ results to those of previous studies

During the pre-occupancy stage, the instructions were as follows: absence of inhabitants, selection of the median fan speed for the MVHR system and no air-polluting activities such as painting, aerosol spraying and sanding. These instructions were followed in all but not for three houses: there was painting in house C, the presence of inhabitants during the first 24 hours and painting in house E and the MVHR systems were switched off in houses E and G. Thus, the highest concentrations of the most common VOCs and aldehydes were measured in those houses, although the mass concentrations of PM_{2.5} were unchanged. The lowest concentrations were observed in house A, for which the estimated average ACH for the medium MVHR fan speed was nearly double (0.9 h^{-1}) that of the other houses (approximately 0.5 h^{-1}). Moreover, this house was investigated 13 months after its completion versus one month for the other houses. The geometric concentrations of TVOC and of the most commonly quantified VOCs and aldehydes of three unoccupied houses for which the instructions were followed (houses A, B and D) were calculated. VOCs and aldehydes were compared to data from previous studies. Our TVOC values obtained with a PID instrument and providing information on a given mixture of VOC cannot be compared with TVOC values obtained in other studies by using sampling on a sorbent and subsequent separation by gas chromatography. Those studies were conducted in unoccupied and ventilated dwellings less than one year old, which can be energy efficient (EE) and/or built with low-emissions material (LE) (Table 7). It appears ~~that the concentrations of TVOC and~~ the majority of aromatic hydrocarbons measured in our study were consistently lower than those reported by authors from other countries. The concentrations of other organic compounds were also always lower than those reported [26,27,28].

However, the concentrations of aldehydes, terpenes, aliphatic hydrocarbons and 1,2,4-trimethylbenzene were sometimes higher than those measured [10,29,30,31,32,33]. The concentrations of organic compounds measured in non-ventilated houses (E and G) were higher than those reported in a new, unventilated Minergie home [8], except for alpha-pinene, formaldehyde and acetaldehyde.

Table 7 - Comparison of geometric concentrations of TVOC and of the most frequently quantified VOC and aldehydes in this study in three unoccupied houses (A, B and D) to the results of previous studies conducted in unoccupied and ventilated dwellings less than one year old. Some of these houses may have been energy-efficient and/or built with low-emitting material. n.m.: not measured

The arithmetic means of TVOC and the geometric means of the most frequently measured VOCs and aldehydes in occupied houses (A, B, C, D, E and F) in summer and in winter were compared (Table 8) to data from previous studies. Those studies were conducted in newly occupied homes and presented in a recent literature review [34]. Only studies conducted in occupied and ventilated dwellings less than one year old were selected, and a small number of studies in energy-efficient homes were added. ~~Our TVOC concentrations were lower than those reported in 24 R-2000 standard homes in Canada [35], in two Minergie apartments in Switzerland [8] and in 292 dwellings in Japan [36]. Our results were similar to those measured in six apartments built with low emissions material in Finland [30].~~ The decrease in TVOC levels over time observed in houses C, D and E was also reported by other authors [35]. In R-2000 standard homes, TVOC concentrations were higher during the first week after closure and then decreased with time and became relatively stable approximately 40 days after closure, at approximately one quarter of the maximum observed level [6]. A 50% decrease in TVOC levels was observed after seven days of strong ventilation [30]. All VOCs and aldehydes measured in our study presented concentrations lower than those reported by another authors [36,37]. The concentrations of ethylbenzene, styrene, toluene and limonene measured in our study were lower than those reported by any other study. For all other compounds, the concentrations were in the ranges of those measured in another studies [10,11,30,35].

Table 8 - Comparison of the mean concentration of TVOC and geometric mean concentrations of the most frequently VOC and aldehydes quantified in this study in six occupied houses (A, B, C, D, E and F) in summer and winter with the results of previous studies conducted in newly occupied and ventilated

dwellings less than one year old. Some of these houses may have been energy-efficient and/or built with low-emissions material. n.m.: not measured

4.3. Comparison of our IAQ results to the standard French houses F and the indoor air-quality guideline values used in France

The values of CO₂, VOC, aldehyde compounds, PM_{2.5} mass, radon concentrations, temperature and relative humidity in the occupied houses (A, B, C, D, E and F) were compared to the IAQ of the standard French houses [12]. The standard French houses have an ACH of 0.5 h⁻¹ [13] but are older than the houses in our study (half built before 1968), are under-equipped with MVHR (only 1.1%), are built predominantly of masonry (only 6% wood frame), have higher occupation rates (0.8) and allow smoking (34% of homes have at least one smoker).

The median CO₂ concentrations measured in summer and in winter in our study were lower than the national median CO₂ level (756 ppm) for three houses (B, E and F) and between 756 ppm and 1000 ppm for the other houses (A, C and D). The seasonal variation in CO₂ levels (lower in summer than in winter) is most likely related to the increased rate of air exchange in these houses in summer due to the opening of windows, as observed in another studies [38,39]. The occupants of our houses reported opening the windows more than one half hour per day in summer and rarely or almost never in winter, as in standard French houses [13], suggesting that the occupants of low-energy houses do not drastically change their usual ventilation behaviours. The comparison between the median temperatures and relative humidities measured in these houses and the median values of French dwellings are shown in Figure 6. Houses A, B and F, but not houses C, D and E, exceeded the national median temperature. In contrast, only house E reached the national median relative humidity, specifically in winter.

Figure 6 - Comparison of weekly median T (°C) and RH (%) measured in the bedroom for six occupied houses (Sum: summer; Win: winter) to the seasonal values measured in standard French dwellings (CNL). n.a.: not available

The median ratios of the average concentrations of VOC, aldehydes, PM_{2.5} and radon measured in all occupied houses to the national median concentration in standard French dwellings are presented in Figure 7. Compared to the median concentration of indoor air pollutants in standard French dwellings, the average concentrations of PM_{2.5}, radon and two aromatic hydrocarbons compounds (benzene and toluene) were lower, whereas the concentration of formaldehyde was not significantly different. The concentrations of three aromatic hydrocarbon compounds (ethylbenzene, m- and p-xylene and 1,2,4-trimethylbenzene), one aldehyde (acrolein) and one aliphatic hydrocarbon compound (n-decane) were less than 1.5 times higher than the national levels. Other compounds were more markedly elevated in concentration, including hexaldehyde (up to 4.7 times higher) and n-decane (up to two times higher) and (to a lesser extent) styrene, o-xylene and acetaldehyde (between 1.7 and 1.5 times higher).

Figure 7 – Median ratio of the average concentrations of VOC, aldehydes, PM_{2.5} and radon measured in six occupied houses to the national median concentration in French dwellings

Although it is difficult to explain these differences, the high levels of hexaldehyde may be associated with the use of wood as the main construction material [27]. The degradation of the wood (composite wood products and lumber) or its secondary metabolites is most likely responsible for the presence of the aldehydes [40]. High aldehyde levels may also be related to the use of paints and varnishes for wood [41,42,43], the presence of new materials (less than one year old) such as particle-board furniture [44] and the surface coverings of walls [45], floors and ceilings [46]. The recent use of products containing solvents (paint, adhesives, etc.) may cause elevated concentrations of n-undecane and n-decane [47]. Formaldehyde was present in homes in our study at levels comparable to other French homes, although higher levels were expected because of the age of the buildings and materials (less than one year) and the high use of wood. The low concentration of radon and the low mass concentration of PM_{2.5} may be associated with the very high airtightness of these buildings compared to average French homes. Based on the living room's radon measurement (on ground level), the mean concentration reaches 16 Bq/m³ for measurement period in spring, 35 Bq/m³ for measurement period in fall. The only one measure available for measurement period in fall/winter is equal to 43 Bq/m³ (for house B). According this observation,

occupants' window opening behaviour depending on season could have an impact on radon concentration but this hypothesis can't be validated because their behaviours haven't been recorded during the radon measurement period. Finally, the low concentrations of aromatic hydrocarbons may be related to the general absence of attached garages, which are known to be an important source of those compounds [48,49,50]. The high concentrations of benzene and toluene in house A, the only building with an attached garage, seem to reinforce this hypothesis. The drier air might be associated with better ventilation in houses equipped with MVHR systems [51] and with a lower production of water vapour because of the under-occupation of these buildings.

The concentrations of formaldehyde, benzene and radon did not exceed the indoor air-quality guideline values currently used in France (respectively 30 $\mu\text{g}/\text{m}^3$ long-term exposure, 1st January 2015, 5 $\mu\text{g}/\text{m}^3$ long-term exposure, 1st January 2013 [52] and 400 Bq/m^3 for a public building according [53]). The concentrations of acetaldehyde, xylenes, styrene and toluene were within the European guideline values [54] (respectively 200 $\mu\text{g}/\text{m}^3$, 200 $\mu\text{g}/\text{m}^3$ 250 $\mu\text{g}/\text{m}^3$ and 300 $\mu\text{g}/\text{m}^3$), but the level of $\text{PM}_{2.5}$ exceeded the WHO air-quality guidelines [55] (10 $\mu\text{g}/\text{m}^3$ annual mean).

4.4. Temporal variation of IAQ in occupied houses

The temporal variation in IAQ in the six occupied houses was calculated based on the concentration ratio between the measurements made during the first and second surveys for $\text{PM}_{2.5}$ and VOC and aldehyde compounds in at least four houses (Figure 8). For VOC and aldehydes, the ratios were calculated only for each compound measured in each survey. The first survey was conducted in summer and the second in winter, except for houses D and F. The interval between the surveys was three months for house D, four months for house C and six months for houses A, B, E and F. The median of the ratios for each of the six houses was calculated.

Figure 8 – Ratio of the concentrations of VOC, aldehydes and $\text{PM}_{2.5}$ measured during the second survey to those measured during the first survey for each of six occupied houses and ratio of the median concentrations for all houses

The majority of VOC and aldehydes exhibited lower concentrations in the second survey (median ratio less than 1), or similar in the case of 1,2,4-trimethylbenzene, whereas the opposite trend was observed for n-undecane and PM_{2.5} (median ratio greater than 1).

The concentrations of toluene, styrene, xylenes, ethylbenzene, terpenes (alpha-pinene and limonene) and acetaldehyde decreased for most of the houses, suggesting that these compounds were mainly emitted by building sources such as building material, insulation, decoration, surface coatings, furniture and other sources. The concentrations of these compounds decreased with the decreasing of emission-source strength over time. Those observations were consistent with another authors [35], which showed significantly reduced concentrations of styrene, p-xylene and alpha pinene over one year in new homes. Another authors [37] also observed over a period of one year in a wood detached house that concentrations of seven COV compounds, including toluene, alpha-pinene and limonene, exhibited a declining trend with time. Several authors have shown that aldehyde concentrations can be influenced by building materials and human activities [30,44]. In our study and because of the recent construction of the buildings, building materials appear to have been the principal source of high aldehyde concentrations [45,46]. The decreased hexaldehyde concentrations may be correlated with the increased age of the furniture and the ground/wall/ceiling coverings [46], but after more than one year, none of these materials has any influence on hexaldehyde levels [44]. In houses D and F, the higher levels of formaldehyde observed during the second survey (in summer) corroborated the observations of other authors [31,56,57]. This increase may be attributed principally to the influence of temperature on VOC emissions from materials [58] and secondarily to the reactions between organic compounds (especially terpenes) and ozone [59,60,61]. A study carried out in new single - family homes in California showed that as outdoor air exchange rates decrease or the indoor temperature increases, the indoor concentrations of formaldehyde increase [62].

The highest concentrations of benzene and toluene relative to national standards were observed in house A (ratios of 3.9 and 1.3, respectively) and seem to be linked to the presence of an attached garage. Several

authors [48,49,50] have shown that many pollutant sources, such as gasoline-fired engines (automobiles, gardening tools such as lawnmowers, etc.), fuel, paint and solvent are commonly stored or used in residential attached garages and may be an important source of monocyclic aromatic hydrocarbons.

The high ratios of n-undecane concentrations relative to national standards in houses A, B and E (1.9, 7.0 and 4.6, respectively; attributable to painting that occurred in houses B and E between the two surveys) explained the high median ratio level observed for all houses (median ratio = 1.3). The relatively high levels of n-decane in houses B and E (ratios of 4.7 and 2.1, respectively) support this hypothesis.

Increased concentrations of PM_{2.5} (median = 1.8) were observed in all buildings except house F and seem to be seasonal. The influence of season on the particulate-matter concentrations has previously been reported [63,64] and appears to be linked to different ventilation practices in summer and winter. According to a meta-analysis conducted in Europe [65], the highest particulate-matter infiltration was observed in summer, with the lowest infiltration in winter. Because of the increased ventilation in summer from the opening of windows, indoor PM levels were highly correlated with outdoor PM levels, whereas in winter, PM levels were more strongly influenced by human indoor activities. In our study, indoor and outdoor PM_{2.5} concentrations showed a strong positive correlation in summer ($r = 0.98$) and a weak positive correlation in winter ($r = 0.11$). Finally, the highest ratio of PM_{2.5} concentrations, observed in houses B and E (≥ 3), seems to be related to the use of wood for heating during the second survey (in winter). The impact of the wood heating system on indoor PM₁₀, PM_{2.5} and PM₁ concentrations has been shown previously [66].

5. Conclusions

Seven newly built, low-energy single-family detached houses in France conform to the highly airtight and energy-efficient standards set forth in RT2012 were investigated during the pre-occupancy stage and during occupancy in summer and winter. Because of the limited sample size, caution must be taken and

the findings can't be generalized. The following conclusions can be drawn from the present study but contribute significantly to knowledge about IAQ and occupant's comfort in energy efficient homes.

Several IAQ-indicator measurements show that the concentrations of aromatic hydrocarbons, terpenes, alkanes and aldehydes were higher in the pre-occupancy stage than during occupancy. The concentrations of some aromatic hydrocarbons (toluene, ethylbenzene, xylenes, styrene), terpenes (alpha-pinene, limonene) and acetaldehyde decreased with time, possibly in relation to the decrease in emissions from building materials over time. The concentrations of alkanes (n-decane and n-undecane), benzene and major aldehydes (formaldehyde and hexaldehyde) may increase temporarily in response to human activities. The PM_{2.5} levels increased during occupancy and appear to be related, in summer, to the outdoor PM_{2.5} levels via an increased infiltration level and with indoor human activities in winter. The air temperature and relative humidity were higher in summer than in winter (between 20 and 26 °C in summer, versus between 20 and 22 °C in winter between 45 and 58% RH versus 29 and 34% RH, respectively).

Compared to the IAQ of standard French houses, the median concentrations of PM_{2.5}, radon, benzene and toluene were lower in the houses studied. The air temperature and the formaldehyde concentrations were similar to those found in typical French houses, whereas the concentrations of ethylbenzene, m- and p-xylene, 1,2,4-trimethylbenzene and acrolein were slightly higher (less than 1.5-fold). In contrast, concentrations of hexaldehyde, acetaldehyde, styrene, o-xylene, n-decane and n-undecane exceeded the levels in typical French dwellings by more than 50%. The concentrations of these compounds seem to be related to new construction. The relative humidity of the study houses was lower than in French dwellings, possibly due to the constant and permanent ventilation occurred by the MVHR systems and due to limited water production linked to the under-occupancy of the study houses. The levels of indoor pollutants in the study houses were within the guideline values for indoor air quality used in France, but the PM_{2.5} level exceeded the levels set by WHO recommendations. The MVHR systems exhibited commonly reported shortcomings but provided sufficient ACH (≥ 0.5 h⁻¹). In summer, the inhabitants improved the houses' ventilation by opening windows, as in conventional dwellings. MVHR systems

seem to be difficult to use, and high noise levels can be produced at the highest fan speed. Finally, in airtight buildings, the mechanical ventilation systems must work constantly; if they shut down, without ventilation through open windows, indoor air quality can become poor and present a risk to human health.

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Table 1 - Main characteristics of the seven new single-family detached houses investigated in this study in terms of construction, equipment and occupancy

	House code						
	A	B	C	D	E	F	G
Region	Centre	Pays-de-Loire	Ile-de-France	Ile-de-France	Pays-de-Loire	Rhône-Alpes	Rhône-Alpes
Building type	one storey single detached house with attached garage	two storey single detached house	two storey single detached house	two storey single detached house	one storey single detached house	two storey single detached house	two storey single detached house
Completion date	March 2008	June 2009	June 2009	December 2009	June 2009	July 2009	November 2009
Energy-Efficient building certification	BBC-Effinergie (obtained)	BBC-Effinergie (on going)	Passivhaus (obtained)	Passivhaus (obtained)	in accordance with Passivhaus	in accordance with Passivhaus and with the 14 targets defined by HQE Programme	in accordance with Passivhaus and with the 14 targets defined by HQE Programme
Building airtightness (vol/hour at 50 pascals pressure) [m ³ /h.m ² at 4 pascals pressure]	3.33 [0.41]	0.89 [0.19]	0.48 [0.12]	0.29 [0.06]	0.62 [0.11]	0.49 ^a [0.15 ^a]	0.49 ^a [0.15 ^a]
Annual consumption of conventional primary energy ^b (kWh/m ² /year)	63	46	missing data	missing data	79	missing data	missing data
Construction type	masonry	timber	timber	timber	timber	timber	timber
Insulation material	Fiberglass wool	cellulose / wood fiber / wool wood	cellulose / wood fiber	cellulose / wood fiber	cellulose / wood fiber / wool wood	Fiberglass wool	Fiberglass wool
Ventilation system (number of normal fan speeds / one boost setting)	MVHR ^c (2/1)	MVHR ^c (3/none)	MVHR ^c (4/none)	MVHR ^c (4/none)	MVHR ^c (3/none)	MVHR ^c (1/1)	MVHR ^c (1/1)
Main heating system	Heat pump	Wood stove	Heat pump	Heat pump (leisure wood stove)	Wood stove	Heat pump	Heat pump
Hot water production	Thermodynamic hot water	Solar hot water with electric booster	Solar hot water with electric booster	Solar hot water with electric booster	Electric hot water tank	Solar hot water with electric booster	Solar hot water with electric booster
Cooking fuel	electricity	electricity	electricity	electricity	electricity	electricity	electricity
Choice of low-emissions building products and materials	no	yes	yes	yes	yes	yes	yes

Household composition	2 adults / 1 children	2 adults / 2 childrens	2 adults / 2 childrens	2 adults / 2 childrens	2 adults	2 adults / 2 childrens	-
Occupation rate ^d	0.75	0.67	0.67	0.67	0.40	0.80	-
Smoking status	No smoker	No smoker	No smoker	No smoker	No smoker	No smoker	-

^a building air-tightness measured in a test house in the same housing scheme that buildings F and G and taken by default because of their similar construction method

^b annual consumption of conventional primary energy for heating, cooling, ventilation, auxiliaries, production of domestic hot water and lighting facilities according to the French thermal regulation RT 2005 (kWh/m²/year)

^c mechanical ventilation with heat recovery

^d occupation rate = number of inhabitant / number of main rooms

Table 2 - Strategy of sampling/measurement and accuracy/uncertainty of indoor air quality parameters

Parameter	Sampling /Measurement methods	Accuracy/ uncertainty	Sampling /Measurement locations	Sampling /Measurement durations
TVOC	photoionisation detector	$\pm 38 \mu\text{g}/\text{m}^3$ in.toluene eq.	living room	Every 10 minutes during each week of investigation
CO ₂	non-dispersive infra-red probe	± 50 ppm	main bedroom	Every 10 minutes during each week of investigation after the inhabitants moved in
VOC	Sampling by passive sampler with Carbograph 4 adsorbents / Analysis by , gas chromatography, mass spectrometry and flame ionization	± 15 %	main bedroom	During each week of investigation
aldehydes	Sampling by passive sampler with 2,4- dinitrophenylhydrazine (2,4-DNPH)-coated Florisil / Analysis by high-performance liquid chromatography and detection by UV absorption	± 10 %	main bedroom	During each week of investigation
CO	electrochemical sensor	± 3 ppm	Each room that contained combustion equipment	Every 5 minutes during the winter week of investigation
PM _{2.5}	sampling system coupled to an air sampler	$\pm 13 \mu\text{g}/\text{m}^3$	living room	from 5 pm to 8 am on weekdays and for 24 hours a day on weekends during each week of investigation
Radon	Passive radon dosimeter	± 8 to 11 Bq/m ³	Living room Main bedroom	During more than two months after the inhabitants moved in

Table 3 - Measured ACH per room and estimation of average ACH (h^{-1}) by house depending on the fan speed of the MVHR system in six houses (confidence interval). n.m.: not measured; n.e.: not estimated

House code	Fan speed of MVHR system	Measured ACH of the living room (h^{-1})	Measured ACH of the main bedroom (h^{-1})	Estimated average ACH house (h^{-1})
A	switched off	n.m	n.m	n.e
	low	0,4 (0,3-0,6)	0,5 (0,3-0,6)	0,6 (0,4-0,7)
	medium	0,8 (0,6-0,9)	0,7 (0,6-0,8)	0,9 (0,8-1,1)
	boost	n.m	n.m	n.e
B	switched off	0,05 (0,04-0,06)	0,04 (0,03-0,05)	0,04 (0,03-0,05)
	low	0,2 (0,1-0,3)	0,6 (0,5-0,7)	0,3 (0,2-0,4)
	medium	0,3 (0,2-0,4)	1,2 (1,1-1,4)	0,5 (0,4-0,6)
	high	0,6 ^b	1,2 ^b	n.e
C	switched off	<< 0,01 ^c	<< 0,01 ^c	<< 0,01
	low	0,3 (0,2-0,4)	0,1 (0,03-0,2)	0,3 (0,1-0,4)
	medium	0,7 (0,6-0,7)	0,5 (0,4-0,5)	0,5 (0,4-0,6)
	high	0,6 (0,5-0,7)	0,5 (0,4-0,6)	0,5 (0,4-0,6)
	very high	1,3 (1,2-1,4)	0,8 (0,7-0,9)	1 (0,8-1,1)
D	switched off	0,1 ^b	<< 0,01 ^c	<< 0,01
	low	0,2 (0,1-0,3)	0,3 (0,3-0,4)	0,2 (0,1-0,2)
	medium	0,3 (0,2-0,4)	0,4 (0,3-0,5)	0,3 (0,2-0,3)
	high	0,4 ^b	0,7 (0,6-0,8)	0,4
	very high	n.m	n.m	n.e
E	switched off	0,02 ^b	0,1 ^b	0,02
	low	0,2 ^b	0,2 ^b	0,1
	medium	0,6 (0,5-0,7)	0,4 (0,2-0,5)	0,4 (0,3-0,4)
	high	0,3 ^b	0,3 ^b	0,24
F	switched off	0,2 ^b	0,1 ^b	0,1
	normal	0,6 (0,5-0,6)	0,5 (0,5-0,6)	0,5 (0,4-0,5)
	boost	n.m	n.m	n.e

^b graphically estimated ACH value from the decay curves of the tracer gas concentration because of the loss of data / confidence interval not calculated

^c: ACH value near zero but not quantifiable because of the lack of decrease of tracer gas concentration

Table 4 – Descriptive statistics of CO₂ level (ppm), T (°C) and RH (%) measured weekly in the main bedrooms of six occupied houses by season. (Sum: summer; Win: winter; P25: 25th percentile; P75: 75th percentile; n.a.: not available)

House code		CO ₂ (ppm)				T (°C)				RH (%)			
		Mean [min-max]	P25	Median	P75	Mean [min-max]	P25	Median	P75	Mean [min-max]	P25	Median	P75
A	Sum	695 [372-1840]	463	578	911	25.2 [23.2-27.1]	24.6	25.1	25.7	47.4 [39.2-57.9]	45.1	47.4	49.8
	Win	788 [378-1207]	684	811	883	20.5 [14.2-22.6]	20.0	20.5	21.0	30.8 [21.3-41.2]	28.4	30.0	33.0
B	Sum	381 [291-861]	314	351	413	24.2 [19.8-28.0]	23.1	24.2	25.4	46.3 [26.0-64.9]	42.7	46.2	51.4
	Win	722 [467-1257]	595	701	823	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
C	Sum	879 [366-1942]	501	656	1371	20.6 [19.3-25.0]	19.8	20.3	21.1	44.9 [33.2-53.4]	42.6	45.1	47.0
	Win	920 [415-1679]	586	778	1320	19.7 [16.8-26.7]	19.2	19.5	19.8	34.7 [24.1-41.2]	32.7	34.3	37.0
D	Sum	738 [331-1829]	367	449	1293	21.9 [18.7-25.1]	21.2	21.6	22.7	47.9 [38.2-59.4]	45.7	48.3	50.2
	Win	1013 [430-2030]	484	768	1654	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
E	Sum	451 [361-1229]	379	406	471	21.6 [17.9-23.2]	21.1	22.0	22.4	58.1 [34.4-75.9]	52.7	58.1	64.5
	Win	622 [360-1263]	475	573	701	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
F	Sum	504 [355-1032]	409	460	527	25.7 [24.6-27.2]	25.3	25.7	26.0	46.9 [36.6-62.1]	43.8	45.9	48.9
	Win	633 [415-1115]	521	642	705	21.8 [19.1-33.6]	21.1	21.6	22.2	30.5 [14.4-45.3]	27.9	29.3	33.2

Table 5 – Indoor TVOC, VOC and aldehyde levels ($\mu\text{g}/\text{m}^3$) measured weekly in seven new low-energy houses at the pre-occupancy stage (Pre) and during occupancy (Sum: summer; Win: winter). LI: Limit of identification ($<1 \mu\text{g}/\text{m}^3$); LD: limit of detection; LQ: limit of quantification; n.a.: not available; n.m.: not measured; Q.F.: quantification frequency

Chemical class and Compounds	Q.F. (%)	House A			House B			House C			House D			House E			House G			House F		
		Pre	Sum	Win	Pre	Sum	Win	Pre	Sum	Win	Pre	Sum	Win	Pre	Sum	Win	Pre	Sum	Win	Pre	Sum	Win
TVOC^a		130	169	< LD	15	6	128	1042	276	< LD	525	92	n.a	3087	17	569	n.m	12	96			
Aromatic hydrocarbons																						
alkylbenzenes ^b	72	<LI	<LI	25.1	19	<LI	9.8	25.9	14.7	29	5.8	30	26	92.1	<LI	28	<LI	<LI	20	33		
2-methyl-decahydronaphthalene ^b	6	<LI	<LI	<LI	<LI	<LI	<LI	4.6	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	
1,2,4-trimethylbenzene ^c	100	7.4	4.7	5.2	5.4	4.7	4.7	17.8	7.3	2.9	12	17	12	1.4	7.8	7.9	160	4.3	5.6			
benzene ^c	78	0.8	1.3	5	1	1.2	1.8	<LQ	1	1.7	1.9	<LD	1.2	1	<LQ	1.8	1.1	<LQ	5.8			
ethylbenzene ^c	94	<LQ	1.9	1.8	3.6	1.7	13.2	5.2	1.3	1.3	3.1	1.9	2.2	222.4	5.1	6.8	83.2	1.5	4.5			
styrene ^c	83	<LQ	<LD	1.9	5	1.8	4	<LD	1.3	1.2	1.4	1.8	1.6	7.2	0.2	0.8	4.4	1.8	5.4			
toluene ^c	94	2	15.6	20	11	5.4	6.2	19.6	5.1	4.2	5.6	<LQ	17	36.7	5.1	5.3	552	6.5	17			
m+p-xylene ^c	89	<LQ	5	5	10.7	3.7	38.4	15.3	2.9	2	11	4.7	6.2	569.3	<LQ	22	734	3	12			
o-xylene ^c	100	4.9	3.8	3.8	5.4	2	13.4	5.8	3.1	1.9	5.4	3.8	3.8	163.6	5.4	8.4	356	2.5	2.6			
Aliphatic hydrocarbons																						
pentane (sum of isomeres) ^b	56	<LI	<LI	13.8	5.6	<LI	<LI	<LI	15.4	5.4	7.8	10	5.5	<LI	<LI	3.7	<LI	<LI	3.3	93		
hexane ^b	11	<LI	3.7	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	2.4	<LI	<LI	<LI	<LI	<LI	<LI	<LI		
octane ^b	6	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	11.5	<LI	<LI	<LI	<LI	<LI	<LI		
nonane (sum of isomeres) ^b	17	<LI	6.9	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	12	49.2	<LI	<LI	<LI	<LI	<LI	<LI		
nonane ^b	22	<LI	2.2	<LI	<LI	<LI	<LI	30.1	<LI	<LI	12	<LI	<LI	16.7	<LI	<LI	<LI	<LI	<LI	<LI		
decane (sum of isomeres) ^b	28	<LI	18.7	<LI	<LI	<LI	<LI	61.2	<LI	<LI	45	<LI	43	52.9	<LI	<LI	<LI	<LI	<LI	<LI		
n-décane ^c	100	2.2	7.5	4.6	24.1	16	3.4	192.1	5.1	2.1	57	41	68	101.8	14	6.5	247	2	6.8			
undecane (sum of isomeres) ^b	28	<LI	9.4	<LI	<LI	<LI	<LI	88.6	<LI	<LI	23	<LI	39	46.2	<LI	<LI	<LI	<LI	<LI	<LI		
n-undécane ^c	100	7.2	8.4	16.5	37.9	24	3.4	127.7	12.6	2.7	27	28	39	93.4	26	5.7	313	3.1	22			
dodecane (sum of isomeres) ^b	6	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	15.6	<LI	<LI	<LI	<LI	<LI	<LI		
alkene ^b	11	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	16.2	<LI	<LI	<LI	<LI	<LI	3.4	<LI	
alkylcyclopentane ^b	6	<LI	<LI	<LI	<LI	<LI	<LI	9.7	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI		
alkylcyclohexanes ^b	22	<LI	5.7	<LI	<LI	<LI	<LI	196.1	<LI	<LI	<LI	<LI	16	107	<LI	<LI	<LI	<LI	<LI	<LI		
cyclohexane ^b	17	4.6	<LI	<LI	2.5	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	16.8	<LI	<LI	<LI	<LI	<LI	<LI		
methylcyclohexane ^b	6	<LI	<LI	<LI	5.6	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI		
Alcohol																						
phénol ^b	28	<LI	4.7	15.1	4.9	<LI	<LI	<LI	<LI	<LI	<LI	<LI	10	<LI	<LI	<LI	<LI	<LI	2.7	<LI		

Aldehydes																				
benzaldehyde ^b	39	<LI	7	<LI	3.6	<LI	5.4	<LI	<LI	<LI	<LI	<LI	<LI	23.6	<LI	2	24.9	3.7	<LI	
isovaleraldehyde ^b	67	5.7	3.2	<LI	6	<LI	<LI	4.4	7.5	4	<LI	8.7	4.5	13.1	7.3	5	<LI	3.9	<LI	
nonanal ^b	28	5.3	5.8	<LI	4	<LI	<LI	<LI	4.8	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	3.7	<LI	
acetaldehyde ^c	100	5	6.6	5.8	16.1	7.9	22.1	6.9	22.9	18.2	26	16	26	30.8	23	29	59.3	7.8	12	
formaldehyde ^c	100	12	28.5	12.3	48.3	20	31.1	61.3	41.4	39.7	6.1	13	12	21.7	17	20	31.6	21	19	
hexaldehyde ^c	100	83.7	44.9	14.6	112	29	36.1	170.1	105	48.8	70	78	93	684.9	96	88	856	58	43	
acrolein ^c	94	0.6	0.9	<LD	2.8	0.9	2.4	2.1	4.1	1.7	1.6	1.5	1.3	3.1	1.6	2.9	4.8	1	0.8	
Ketones																				
acetone ^b	17	4.7	3.5	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	6.5	<LI	<LI	<LI	<LI	<LI	
2-butanone ^b	6	5.1	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	
Esters																				
dibutyl decanedioate ^b	6	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	9.2	<LI
ethylacetate ^b	22	5.3	<LI	6.6	<LI	<LI	2.4	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	2	<LI
n-butylacetate ^b	22	<LI	<LI	<LI	6.5	<LI	548	<LI	<LI	<LI	<LI	<LI	<LI	108.2	<LI	2.5	<LI	<LI	<LI	
Glycol/glycoether																				
1,2-propanediol ^b	28	9.9	<LI	<LI	<LI	<LI	<LI	17.6	13.7	3.1	<LI	<LI	<LI	3.5	<LI	<LI	<LI	<LI	<LI	
2-butoxy ethanol /EGBE ^c	11	<LD	<LD	<LD	<LD	<LD	<LD	<LD	4.2	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	1.3	<LD
Terpenes																				
alpha-pinene ^b	100	19	16.4	13.7	43.2	13	9	56.4	25	13.6	10	6.4	6.6	294.4	18	6.8	47.4	5.8	13	
beta-pinene ^b	39	5	3.9	<LI	6.8	<LI	<LI	35.4	5.8	2.3	<LI	<LI	<LI	n.a	<LI	<LI	<LI	<LI	<LI	
camphene ^b	72	2.9	<LI	<LI	8.2	<LI	2.6	5.8	4.9	5.3	<LI	3.4	4.2	23.7	<LD	3.2	10.1	4.5	7.9	
eucalyptol ^b	6	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	2.6	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	
limonene ^b	89	5.5	6.3	9.2	18.3	6.6	4.7	24.5	13.5	9.4	9.2	<LI	7.1	92.3	11	9.2	<LI	2.9	11	
3-carene ^b	33	<LI	<LI	<LI	6.6	<LI	<LI	22.5	8.1	4.5	<LI	2.3	<LI	48.6	<LI	<LI	<LI	<LI	<LI	
4-carene ^b	6	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	6.5	<LI	<LI	<LI	<LI	<LI	
Chlorinated organic compounds																				
chloroalkane ^b	6	<LI	8.3	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	<LI	
tetrachloroethylene ^c	6	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	1.4	<LD
trichloroethylene ^c	17	<LD	<LD	<LD	<LD	2.1	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	3.4	5.7
1,4-dichlorobenzene ^c	6	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	5.8	<LD	<LD	<LD	<LD	<LD	<LD	<LD	
Acide																				
acetic acid ^b	39	<LI	<LI	<LI	<LI	<LI	3.2	<LI	13.5	15.4	<LI	n.a	<LI	<LI	<LI	5.4	<LI	n.a	<LI	

^a median concentration of TVOC measured by PID

^b calibrated as toluene equivalent

^c calibrated with a specific calibration

Table 6 – Comparison of the measured air exhaust rate (l/s) for four houses to the French regulations concerning residential-building ventilation [14].

House code	Rooms	Measured air exhaust rate (l/s) for high (boost for houses A and F) fan speed of MVHR system	Achievable air exhaust rate (l/s)	Measured air exhaust rate (l/s) in kitchen for low (normal for house F) fan speed of MVHR system	Minimum values of reduced air exhaust rate (l/s) in kitchen
A	WC1	4±3.6	8	-	-
	Bathroom 1	9±3.6	8	-	-
B	Bathroom 1	7±3.6	8	-	-
	Bathroom 2	13±3.6	8	-	-
C	WC1	10±3.6	8	-	-
	Bathroom 1	12±3.6	8	-	-
	Bathroom 2	11±3.6	8	-	-
	Living room combined with the kitchen	12±3.6	38	8±3.6	13
F	WC1	3±3.6	8	-	-
	Bathroom 1	7±3.6	8	-	-
	Bathroom 2	8±3.6	8	-	-
	Living room combined with the kitchen	32±3.6	38	26±3.6	13

Table 7 – Comparison of geometric concentrations of TVOC and of the most frequently quantified VOC and aldehydes in this study in three unoccupied houses (A, B and D) to the results of previous studies conducted in unoccupied and ventilated dwellings less than one year old. Some of these houses may have been energy-efficient and/or built with low-emitting material. n.m.: not measured

	Our study	[10]	[26]	[29]	[30]	[27]	[28]	[31]	[32]	[33]
Number and type of buildings	3 SDH ^a	2 APA ^b	4 SDH ^a	1 SDH ^a	12 APA ^b	1 SDH ^a	11 SDH ^a	14 APA ^b	228 APA ^b	1 APA ^b
Characteristic of buildings	EE ^c LE ^d for two	EE ^c and LE ^d	EE ^c	LE ^d	LE ^d	-	-	-	-	-
TVOC ^e	100,8 ^g	254 ^f -31 ^f	1429 ^h -1954 ^h	5000 ^f	250 ^{fi} -911 ^{fi}	n.m.	1520 ^{fg} -2720 ^{fg}	780 ^h	645 ^h -1606 ^h	517 ^f
hexaldehyde	86,7 ^g	0	n.m.	33	44 ⁱ -83 ⁱ	267	65,8 ^g -107,6 ^g	21 ^h	n.m.	n.m.
alpha-pinene	20,2 ^g	1	n.m.	50	46 ⁱ -89 ⁱ	232	90,7 ^g -156,3 ^g	61 ^h	1,0 ^h -7,1 ^h	n.m.
n-undecane	19,6 ^g	n.m.	57 ^h -75 ^h	13	50 ⁱ	n.m.	7 ^g -23 ^g	18 ^h	1,6 ^h -4,3 ^h	n.m.
ormaldehyde	15,2 ^g	16-21	41 ^h -59 ^h	120	8 ⁱ -10 ⁱ	94,9	41,7 ^g -44,2 ^g	19 ^h	40,1 ^h -65,9 ^h	457
n-decane	14,5 ^g	n.m.	n.m.	17	34 ⁱ	n.m.	12,2 ^g -31,9 ^g	32 ^h	3,3 ^h -5,2 ^h	n.m.
acetaldehyde	12,9 ^g	4-8	n.m.	n.m.	6 ⁱ -7 ⁱ	42,5	18 ^g -36 ^g	n.m.	7,2 ^h -12,2 ^h	n.m.
limonene	9,7 ^g	n.m.	n.m.	4,8	140 ⁱ	40,3	16,1 ^g -30 ^g	12 ^h	n.m.	n.m.
1,2,4-trimethylbenzene	7,8 ^g	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	1,9 ^h -2,8 ^h	n.m.
o-xylene	5,2 ^g	5-8	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.
toluene	5,0 ^g	25-58	10 ^h -19 ^h	84	19 ⁱ	n.m.	9 ^g -38,8 ^g	n.m.	131,8 ^h -305,5 ^h	182
m+p-xylene	4,5 ^g	n.m.	n.m.	<30	n.m.	n.m.	4,3 ^g -16,9 ^g	n.m.	n.m.	n.m.
ethylbenzene	1,8 ^g	n.m.	n.m.	12	n.m.	n.m.	n.m.	n.m.	8,4 ^h -46,1 ^h	26
acrolein	1,4 ^g	3	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.
styrene	1,1 ^g	n.m.	n.m.	n.m.	n.m.	n.m.	3,8 ^g -11,1 ^g	3 ^h	6,7 ^h -10,2 ^h	32
benzene	1,1 ^g	4	5 ^h -27 ^h	<35	n.m.	n.m.	n.m.	n.m.	0,3 ^h -2,5 ^h	13

^a SDH : single detached house

^b APA : apartment

^c EE: efficiency in energy

^d LE : built with low emitting material

^e TVOC measured by a photoionization Detector's

^f TVOC calculated from the total integrated signal between hexane and hexadecane

^g geometric mean concentration

^h mean concentration

ⁱ median concentration

Table 8 – Comparison of the mean concentration of TVOC and geometric mean concentrations of the most frequently VOC and aldehydes quantified in this study in six occupied houses (A, B, C, D, E and F) in summer and winter with the results of previous studies conducted in newly occupied and ventilated dwellings less than one year old. Some of these houses may have been energy-efficient and/or built with low-emissions material. n.m.: not measured

	Our study	[10]	[36]	[11]	[35]	[30]	[37]	
Number and type of buildings	6 SDH ^a	2 APA ^b	24 SDH ^a	1 SDH ^a	1 SDH ^a	219 SDH ^a 66 APA ^b 7 others	1 SDH ^a	1 APA ^b
Characteristic of buildings	EE ^c LE ^d for five	EE ^c and LE ^d	EE ^c	EE ^c	EE ^c	n.m.	n.m.	n.m.
TVOC	130 ^{eg}	[235 ^f -1011 ^f]	388	n.m.	n.m.	328 ^f	153 ^{fg}	n.m.
n-decane	14.7 ^h	n.m.	n.m.	[2.5-11.5]	[3.7-13.1]	35 ^g	n.m.	n.m.
n-undecane	16.0 ^h	n.m.	n.m.	[5.5-10.8]	[3.3-11.7]	n.m.	n.m.	409
benzene	1.9 ^h	[1-8]	n.m.	[0-27.1]	[1.8-25.4]	n.m.	n.m.	30
ethylbenzene	3.6 ^h	n.m.	n.m.	n.m.	n.m.	20 ^g	n.m.	11
styrene	2.0 ^h	n.m.	n.m.	n.m.	n.m.	64 ^g	n.m.	6
toluene	9.0 ^h	[19-88]	n.m.	[8.6-35.3]	[11-41.6]	27 ^g	12 ^g	464
m+p-xylene	8.8 ^h	n.m.	n.m.	[2.2-12.7]	[3.2-13.9]	n.m.	n.m.	13
o-xylene	4.5 ^h	[2-7]	n.m.	[2.4-5.4]	[1.5-6.3]	n.m.	n.m.	7
isovaleraldehyde	5.5 ^h	[0-7]	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.
acetaldehyde	16.5 ^h	[10-21]	n.m.	[40.6-68.6]	[18.3-55.8]	n.m.	12 ^g	n.m.
formaldehyde	22.8 ^h	[21-45]	33 ^g	[20.3-39.3]	[24.9-49.6]	134 ^g	13 ^g	n.m.
hexaldehyde	61.2 ^h	[0-19]	n.m.	[166-289]	[94.3-201]	5 ^g	n.m.	n.m.
alpha-pinene	12.2 ^h	[1-34]	n.m.	[52.4-100]	[17.8-48.6]	269 ^g	n.m.	475
limonene	8.3 ^h	n.m.	n.m.	[19.8-112]	[13.7-58.6]	35 ^g	23 ^g	127

^aSDH : single detached house

^bAPA : apartment

^cEE: efficiency in energy

^dLE : built with low emitting material

^eTVOC measured by a photoionization Detector's

^fTVOC calculated from the total integrated signal between hexane and hexadecane

^g mean concentration

^h geometric mean concentration

Figure

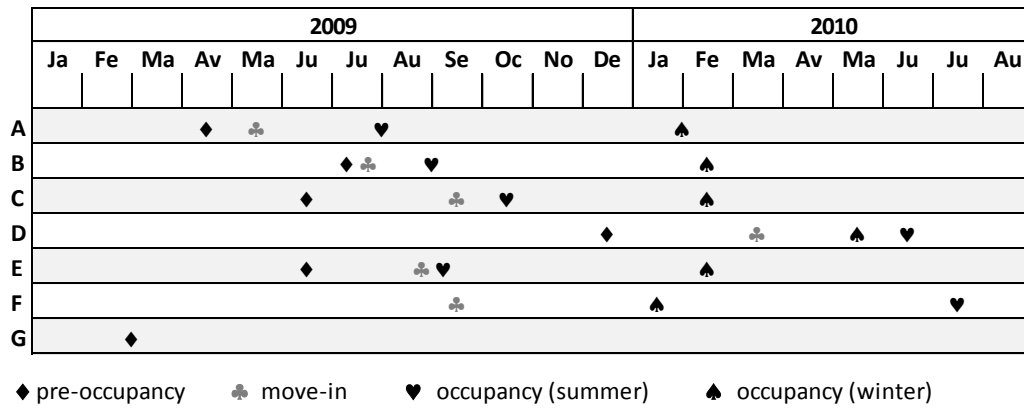


Figure 1 - Weekly investigation and moving dates of the seven new single-family detached houses between February 2009 and July 2010

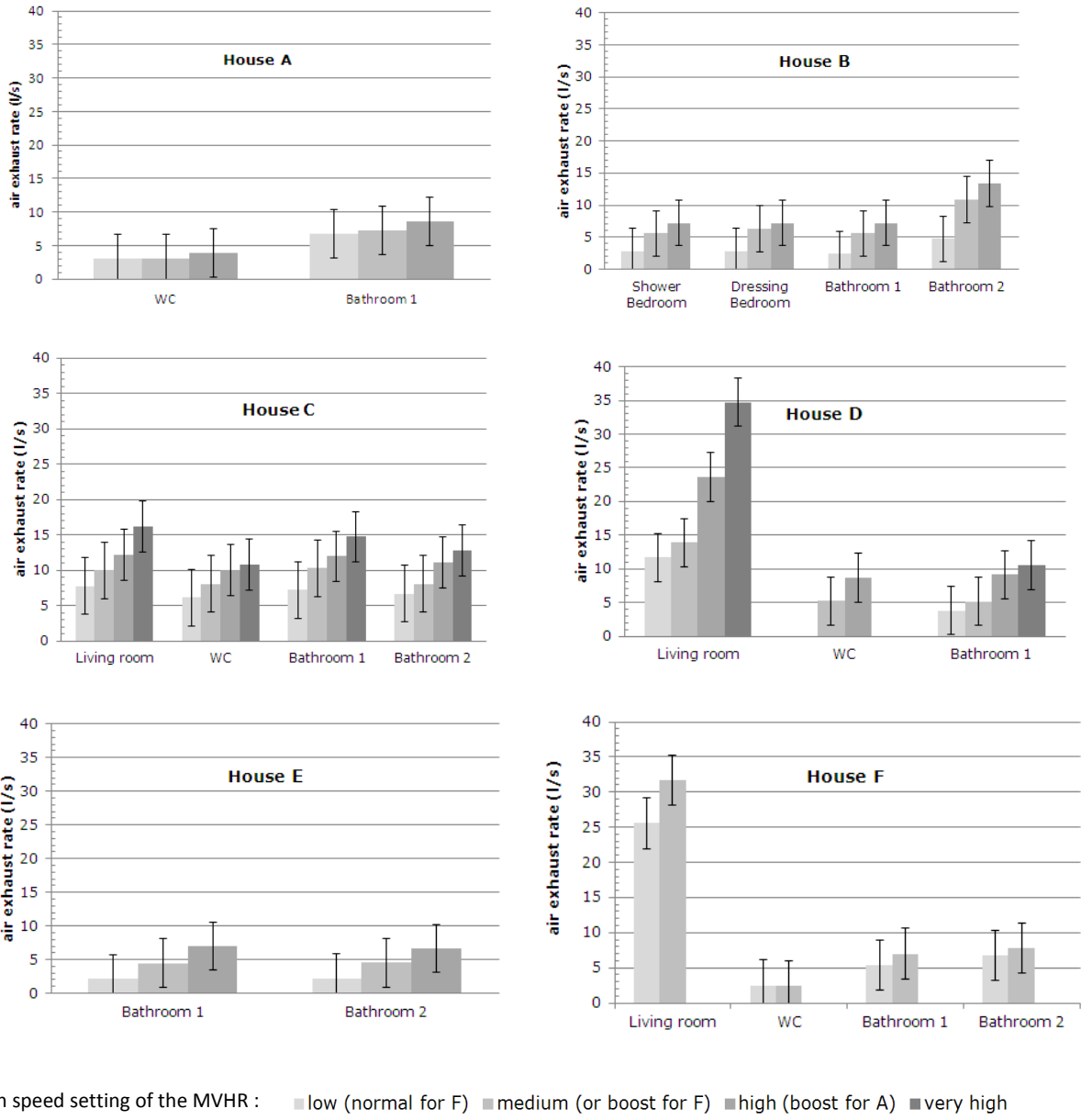


Figure 2 – Measured air exhaust rate (l/s) per room by the fan speed of the MVHR system in six houses

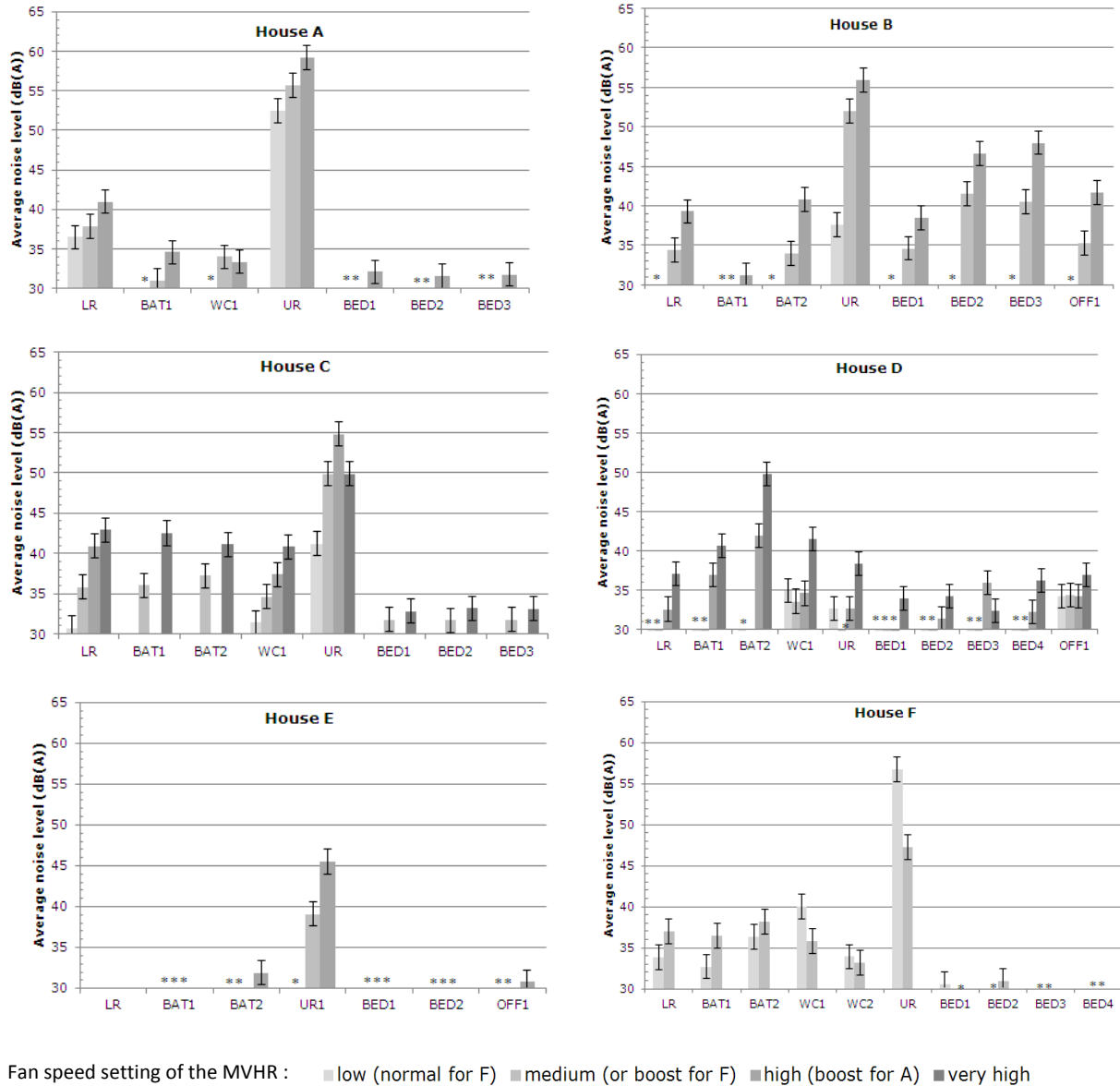


Figure 3 – Measured average noise level (dB(A)) per room depending on the MVHR fan speed in six houses (* average noise level value ≤ 30 dB(A)) (BAT: bathroom; BED: bedroom; LR: living room; OFF: office room; UR: Utility room)

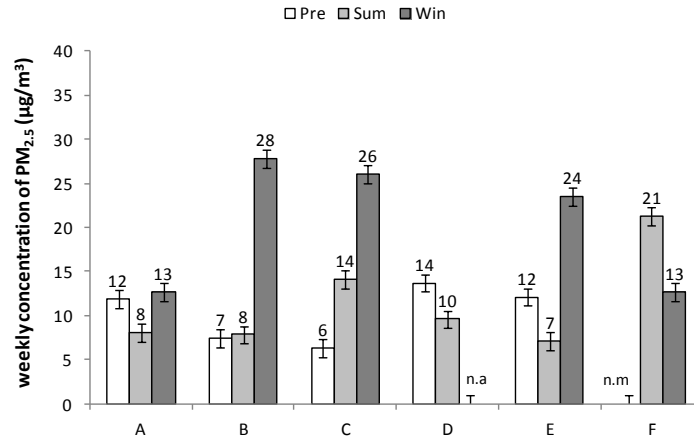


Figure 4 – Weekly mass concentrations of $PM_{2.5}$ ($\mu\text{g}/\text{m}^3$) measured in the living room for six houses during the pre-occupancy stage (Pre) and during occupancy (summer: Sum; winter: Win). n.a.: not available; n.m.: not measured

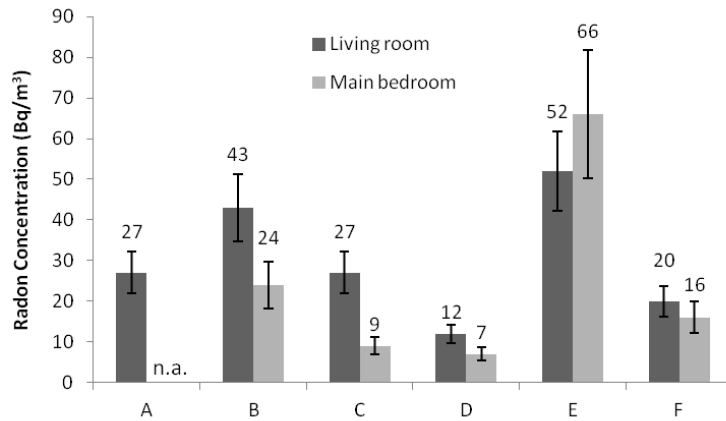


Figure 5 – Radon concentrations (Bq/m^3) measured in the living room and in the main bedroom for six occupied houses. n.a.: not available

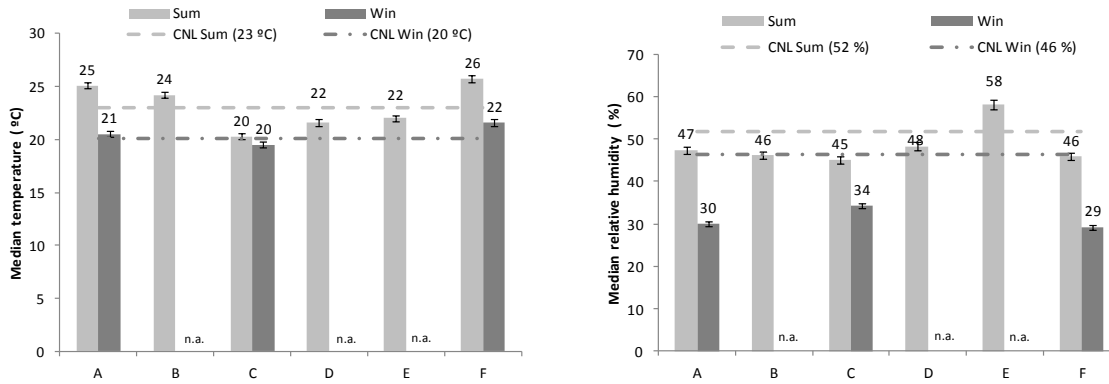


Figure 6 – Comparison of weekly median T (°C) and RH (%) measured in the bedroom for six occupied houses (Sum: summer; Win: winter) to the seasonal values measured in standard French dwellings (CNL). n.a.: not available

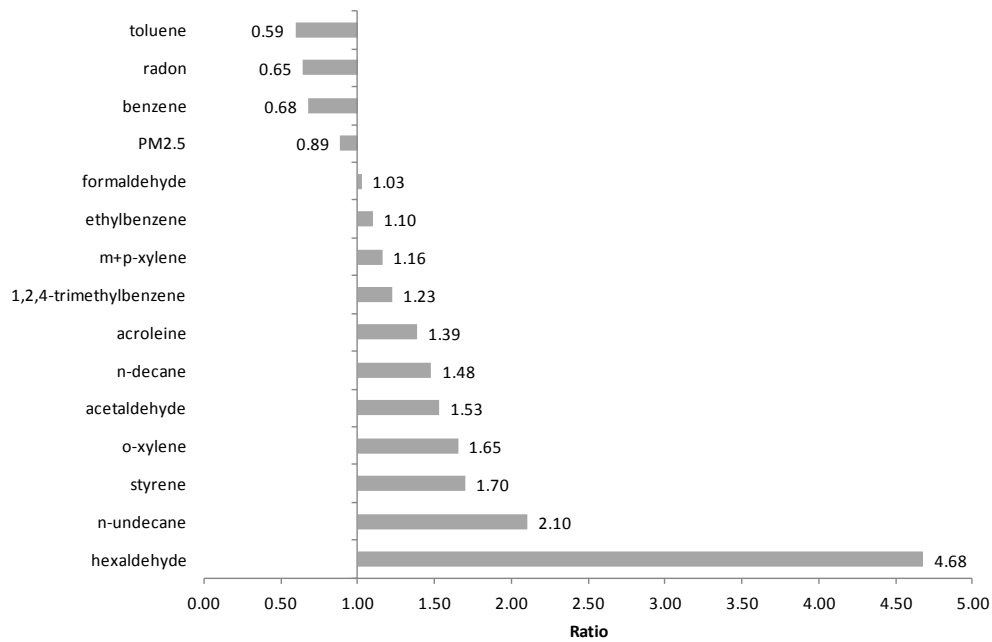


Figure 7 – Median ratio of the average concentrations of VOC, aldehydes, PM_{2.5} and radon measured in six occupied houses to the national median concentration in French dwellings

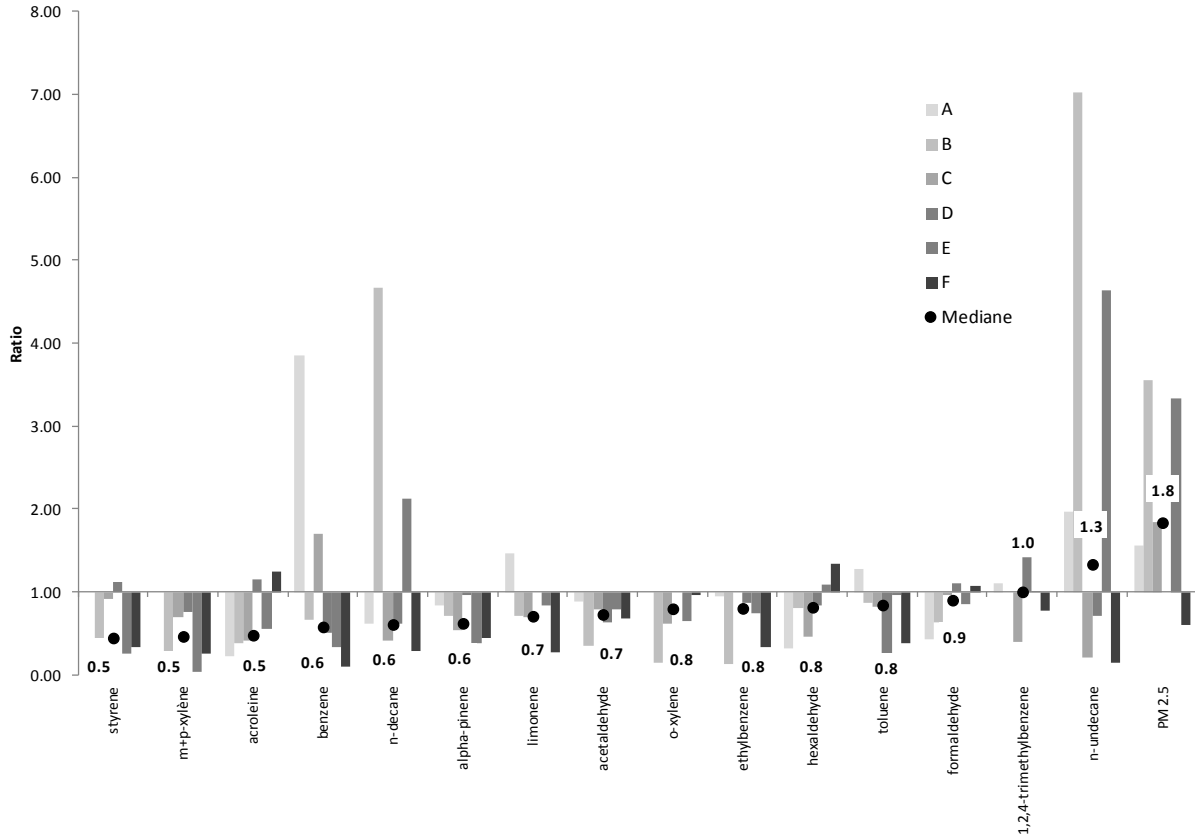


Figure 8 – Ratio of the concentrations of VOC, aldehydes and PM_{2.5} measured during the second survey to those measured during the first survey for each of six occupied houses and ratio of the median concentrations for all houses