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A 3-year follow-up of indoor air quality and comfort in two energy-efficient houses

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ABSTRACT

In order to improve the knowledge of the indoor environment quality of energy-efficient buildings, a 3-year follow-up study was carried out in two wooden-framed low-energy single-family houses in France. Several indoor air indicators and indoor environmental parameters were measured during seven weeks in total from the pre-occupancy stage up to three years of occupancy. Questionnaires were used for each investigation to record the family activities and perceived comfort of occupants. The ventilation systems presented some shortcomings, including the failure to reach the designed exhaust air flow rate and induced occupant dissatisfaction. Regarding the measured pollutants, both houses didn't present any specific indoor air pollution. The variability of indoor air quality over time was explained by the high emissions from the new building materials, products, and paints during the first months after completion and then more episodically by human activities during occupancy. Regarding the thermal comfort and even if occupants were globally satisfied, overheating and under-heating were observed. According to our results and in order to guarantee the health and the well-being of occupants in these buildings, it would be useful to integrate the solar shadings at the very first stage of the building design, to design more quiet, user-friendly and robust ventilation systems and to implement mandatory inspection as well as frequent maintenance by professionals and finally to promote the labelling of low-emitting construction and decoration products, furniture and consumer products.

1. Introduction

The impact of global warming due to anthropogenic greenhouse gas emissions has promoted energy efficiency and support for renewable products around the world. In France, the government has pledged to cut its greenhouse gas emissions by four-fold from the 1990 baseline by 2050. For the existing buildings, the government has committed an extensive program to reducing their energy consumption by 38% between 2009 and 2020 [1]. For the new buildings (built after January 1st, 2013), the enforcement of the 2012 Thermal Regulation (RT 2012) aims to generalize energy-efficient buildings with a reinforced airtight envelope [2]. Following the reinforcement of the Thermal Regulation, especially between 2000 and 2012, the required primary conventional energy consumption of the new buildings was divided by about four: from 190 kWh/m^2 per year to less than 50 kWh/m^2 per year. Over the same period, the required air leakage rate of the envelope was divided by two: from about 4 Air change per hour (ACH) at 50 Pa to less than 2 ACH at 50 Pa for single-family houses. Buildings are now built with much higher airtightness requirements in order to prevent uncontrolled ventilation heat losses. In order to satisfy energy performance and ventilation requirements, the mechanical ventilation systems are increasingly used. Moving from buildings with infiltration rate by air leakage to airtight buildings mainly mechanically ventilated is a large step change in terms of culture. There are increasing concerns regarding the impact of the airtight construction on health and well-being of the occupants such as the possible degradation of the indoor environment quality (IEQ), the effectiveness of the mechanical ventilation system in maintaining healthy indoor environment, the potential impact of occupants behaviour on the operation of the equipment (ventilation, heating, cooling, etc). To date few data on indoor air quality (IAQ) in energy-

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efficient buildings is available. A first review on IAQ in energy-efficient buildings concluded that further researches are needed [3]. More recently, a review of the background information regarding low-carbon housing in the United Kingdom [4] cited just one study conducted in four energy-efficient houses [5]. Some authors [6] reported in a review of case studies published between 2008 and 2013 in ASHRAE's “High Performing Buildings” magazine that most of these studies mentioned IAQ design construction but generally did not provide measured IAQ data. In the same year, research priorities focusing on IAQ in highly energy-efficient buildings were proposed to fill the gap of knowledge and take into account the health and comfort of the occupants of these future buildings [7]. In conclusion, data relative to IAQ and more generally to IEQ in energy-efficient buildings are urgently needed to have an overview of any possible problems in such buildings to rapidly adjust the building practices and/or occupants' habits.

In this context, the French Indoor Air Quality Observatory (OQAI) has launched a specific research program dedicated to IAQ and comfort in energy-efficient buildings. A first study was carried out in seven energy-efficient newly built houses (house “A” to house G”) before and during the houses' first year of occupancy [8]. It provided the indoor concentrations of some pollutants such as volatile organic compounds, aldehydes and particles and made possible to find some hypotheses concerning the pollutants sources. Although the ventilation systems allowed an air exchange rate of 0.5 h^{-1} and higher, some shortcomings were reported and occupants complained about noise annoyances and complexity of use. No conclusions were drawn on the potential changes of the IEQ over time because the measurements and observations were carried out in a relatively short period of time and were not repeated. The monitoring was extended by two supplementary years in two of these houses (house “B” and house “E”) to study the potential changes over time of ventilation conditions and IEQ parameters and to consolidate the first results.

This three-year follow-up study aims specifically to:

- follow the operation of the ventilation system over time and to collect regularly the feedbacks of occupants relating to the acoustic comfort, the use and the maintenance of this system,
- describe the time trends in indoor concentrations over a long period,
- describe the thermal comfort during repeated seasons in these buildings in which heating and cooling energy use are reduced.

In addition this three-year follow-up study completes, with additional parameters and over a longer period, the results provided by the rare previous longitudinal studies of IAQ in energy-efficient houses [5,9–12].

2. Materials and methods

2.1. Description of the measurement sites

Two single-family detached houses (house “B” and house “E”) located in the western area of France (Pays-de-la-Loire) were investigated in this study (Table 1). They were built in 2009 within the requirements of the former French 2005 Thermal Regulation (RT 2005) but can be considered as highly energy-efficient homes as defined by the RT 2012, in particular because of their high airtightness levels and their low theoretical energy consumption. These houses were part of the earliest energy-efficient houses built in France. Their inhabitants (architects of the building) were aware of IAQ and have chosen low-emission building products to avoid indoor air pollution.

2.2. Measurement protocol

The IAQ parameters was monitored immediately after the completion of the houses, from June/July 2009 to January 2012 (Table 2). Seven weeks of measurements were performed for each house: one week in the pre-occupancy stage and six weeks over 3 years in the occupancy stage during summer (2009, 2010, and 2011) and in winter (2009–2010, 2010–2011, and 2011–2012). The thermal comfort parameters were measured in the occupancy stage during each weekly investigation and, in addition, the temperature was measured continuously until December 2012. The exhaust air flow rate was measured in the pre-occupancy stage and twice in the occupancy stage (winter 2010–2011 and winter 2011–2012). The sound pressure level generated by the balanced mechanical ventilation with heat recovery (MVHR) was measured one time during the occupancy stage (winter 2011–2012).

The measurement protocols for assessing IAQ and thermal comfort have been previously presented in detail [8,13]. Briefly, the IAQ parameters were measured weekly on-line as follows: 1) the total volatile organic compounds (TVOC in μg/m^3 toluene equivalent; uncertainty of ±38 μg/m^3) were measured every 10 min with a photoionisation detector (PGM 7240 – RAE Systems); 2) the carbon dioxide (CO_2 in ppm; uncertainty of ±3% of reading +50 ppm) was measured every 10 min by a non-dispersive infrared probe (TSI Q-Trak 8552); 3) the number of particles/cm^3 (diameter: 0.3–20 μm) was measured every 10 min by an optical portable aerosol spectrometer (dust monitor 1.108 – Grimm); and 4) the carbon monoxide (CO in ppm; uncertainty of ±3 ppm) was measured every 5 min with an electrochemical sensor (gas monitor Draeger Pac III). The target volatile organic compounds (VOCs) and aldehydes were sampled by diffusive samplers over 7 days (Radiello®) and were analysed and quantified in μg/m^3 by gas chromatography, mass spectrometry and flame ionisation, and high-performance liquid chromatography with detection by UV absorption respectively. The analytical uncertainties were estimated to be 15% for the VOCs and 10% for the aldehydes. These compounds were measured following the same protocols as those implemented in the national survey on IAQ in French dwellings conducted by OQAI [14]. All the analytical methods and the detection limits for each compound have been previously detailed [15]. All other organic compounds whose concentrations exceeded 1 μg/m^3 were identified and quantified as μg/m^3 toluene equivalent. For the statistical calculation, each concentration of these organic compounds below the limit of quantification (LOQ) was replaced by LOQ/2, and each value below the limit of detection (LOD) was replaced by zero. The mass concentrations of $PM_{2.5}$ (μg/m^3) were sampled with a sampling system (Chempass, Model. 3400, Thermo Fisher Scientific) coupled to an air sampler (Microvol 1100, Ecotech) on Teflon filters at 1.8 l/min from 5 pm to 8 am on weekdays and for 24 h per day on weekends and then weighed in the laboratory (uncertainty of ±13 μg/m^3). The outdoor mass concentrations of $PM_{2.5}$ were collected from the continuous measurements made by the air quality monitoring network of the Pays-de-la-Loire region (Air Pays-de-la-Loire). The indoor temperature (T in °C) and relative humidity (RH in %) were measured during occupancy during each week of investigation with Hydrolog sensors (Rotronic, uncertainty of ±0.3 °C and ±1.5% RH at 23 °C). Outdoor and indoor temperatures were continuously measured from January 2010 to December 2012 with wireless temperature sensors. Because MVHR systems are not often checked during/after the completion of the building, we decided to measure the exhaust air flow rate in order to compare it with the designed exhaust air flow rate and to determine the noise level generated by the ventilation systems. The exhaust air flow rate (l/s) and the sound pressure level (LAeq in dB(A)) were occasionally measured for each fan speed of the MVHR system, respectively, by an array of