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INDOOR ENVIRONMENT IN SWEDISH PASSIVE HOUSES

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SUMMARY

The purpose of this study was to evaluate the indoor air quality (IAQ) in newly built low energy houses. Measurements were performed in 22 passive houses and 21 conventional buildings during 2012-2013 and 2013-2014 heating seasons. The measured parameters were temperature, relative humidity, concentration of CO_2, NO_2, formaldehyde, volatile organic compounds, and live microbiological flora. Air exchange rates (AER) were determined from the concentration-time profiles of CO_2. The median AER was slightly higher in the passive houses than in conventional buildings (0.66 h^{-1} vs. 0.60 h^{-1}). The median concentrations in passive houses and conventional buildings were 9.7 and 11 $\mu g/m^3$, respectively, for NO_2, 12 and 16 $\mu g/m^3$ for formaldehyde, and 230 and 145 $\mu g/m^3$ for TVOC. The indoor microbiological flora did not differ, with a few exceptions, from outdoors. The IAQ in the passive buildings was judged to be relatively good with regard to the parameters measured in this study.

INTRODUCTION

The building sector uses about 40% of energy in Sweden. The demands to save energy have recently led to the concepts of low-energy buildings and passive-house buildings. Directive 2010/31/EU of the European parliament and Council (European Union, 2010) states that from the 1st of January 2021, all new buildings in the European Union should incorporate energy saving techniques and be "near zero energy buildings" (nZEB). Passive buildings are a type of low-energy buildings exploiting e.g. efficient insulation and heat exchange techniques to reduce energy consumption for space heating. Air exchange is achieved by mechanical ventilation, providing good control of the air exchange rate (AER).

An economic analysis of energy savings in passive and low-energy houses compared to conventional houses showed clear economic advantages of passive houses, even when the higher investment and construction costs were accounted for (Audenaert et al., 2008). Long-term monitoring of a passive-house school buildings and day-care centers in Germany showed excellent energy saving potential combined with a comfortable indoor climate (temperature, relative humidity) and good indoor air quality with respect to concentration of CO_2 (Peper et al., 2008). However, measures to save energy in buildings (e.g. tightening of building

envelopes, decreased ventilation rates) may lead to deteriorated indoor air quality often associated with sick building syndrome symptoms (Fisk et al., 2009).

Low-energy and passive houses are becoming more and more common during the past couple of years. There is little knowledge about indoor environment and indoor air quality in such buildings. Concentrations of air pollutants in passive houses have received limited attention. The objective of this work was to investigate the indoor air quality in Swedish passive houses and to make comparisons with newly built conventional buildings.

METHODOLOGIES

The 22 passive and 21 new conventional buildings were selected in collaboration with the construction industry and property owners and managers participating in the project. The buildings were mostly located in city suburbs or residential areas of the Swedish cities Gothenburg, Kungsbacka, Malmö, Stockholm and Kalmar. They were both single-family houses and apartments in multi-family houses. The measurements were performed during the heating seasons 2012/2013 and 2013/2014. All houses were built between the years 2010 and 2013.

Passive samplers for nitrogen dioxide (NO_2), formaldehyde and volatile organic compounds (VOC) were placed centrally in the dwellings. The formaldehyde samplers were DSD-DNPH Aldehyde Diffusive sampling Device (Supelco, Bellefonte, PA), for VOC, Tenax adsorbent tubes (Perkin-Elmer) were used and the IVL passive samplers were used for NO_2 (Ferm and Rodhe, 1997). The samplers were exposed for 7-10 days at each occasion and they were analyzed for the target compounds after returning to the laboratory. Temperature and relative humidity were monitored by HOBO U12-012 data loggers (Onset Computer Corp., USA). CARBOCAP®CO_2 monitors (GMW22, Vaisala, Finland) were used to measure the CO_2 concentration and the data were logged using the HOBO logger. The measuring interval was 5 minutes. The sensors were placed in the main bedroom of each dwelling and the occupants were instructed to refrain from opening their windows during the sampling period. The CO_2 concentration-time profiles were used for calculating the air exchange rates by fitting the logarithmic function to concentration decay.

NO_2 was analyzed by wet chemical technique. Formaldehyde was analyzed, after eluting from the sampler, by liquid chromatography/UV detection. VOCs were thermally desorbed from the solid adsorbent and analyzed by gas chromatography/mass spectrometry and quantified as Total Volatile Organic Compounds (TVOC) in toluene equivalents.

Live mycoflora was characterized as an indication of potential moisture damage. Cultures of airborne fungal particles were collected essentially according to ISO/CD 16000–19 (2012) on Rose Bengal agar media (agar strip HS; Biotest-Serum Institute GmbH, Frankfurt/Main, Germany) using a Reuter Centrifugal Sampler (RCS, Folex-Biotest-Schleussner Inc., Farfield, NJ, USA) during a 4-min sampling period (40 liters/min). Samples were collected inside (in the living room) and outside (on the balcony or terrace) of each home at exactly the same location. After return to the laboratory, the strips were incubated at 25 C° for 7-10 days before microscopic examination. The numbers of cultivable airborne fungal particles were determined as colony forming units (CFU) per cubic meter of sampled air. The microflora was identified according to Samson et al. (2010).

RESULTS AND DISCUSSION

The summary of results from the study is presented in Table 1. The numbers are median values calculated separately for the passive houses and conventional houses.

Table 1. Median values of the indoor climate parameters and concentrations of air pollutant.

Parameter	Unit	Passive houses	Conventional houses
Temperature	^{o}C	22.0	22.0
Relative humidity	%	29	38
Air exchange rate	h^{-1}	0.66	0.60
Nitrogen dioxide	$\mu g/m^3$	9.7	11
Formaldehyde	$\mu g/m^3$	12	16
TVOC	$\mu g/m^3$	230	145

Results from the present study are compared to those representative of the Swedish housing stock, which were recently published by Langer and Bekö (2013). The authors used data from a Swedish survey on energy performance, technical status and indoor environment of 157 single family houses and 148 apartments in multi-family houses. Data were collected during the 2007-2008 heating season in dwellings constructed before 2005.
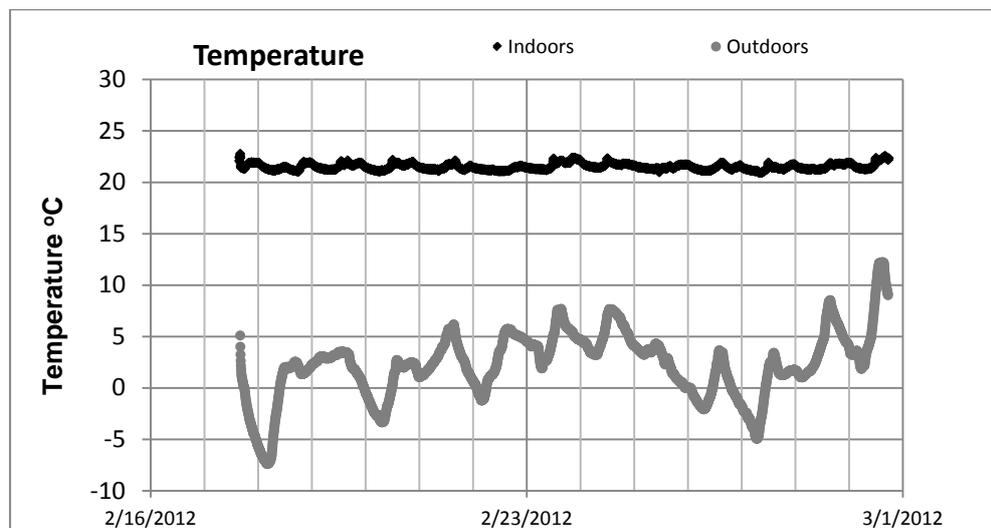

Figure 1. Example of the indoor and outdoor temperatures in one of the passive houses. The mean (SD) indoor and outdoor temperature was 21.5 (0.3) °C and 2.3 (3.3) °C, respectively.

The mean indoor temperature was the same both in the passive houses (22.0 ± 1.4) oC and the conventional buildings (22.0 ± 1.1) oC. The mean indoor temperature in all homes from the survey on the Swedish housing stock was (21.9 ± 1.5) oC, nearly identical with the mean temperatures from this study. The mean relative humidity was lower in the passive houses (29 ± 7) % than in the conventional buildings (37 ± 9) % and it was similar to the mean relative humidity in the Swedish housing stock (33 ± 6) %. It should be mentioned that the indoor

temperature within the same dwelling was remarkably stable despite the variations of the outdoor temperature. Relative humidity indoors followed the trend of the outdoor variations. Figures 1 and 2 are examples of temperature and relative humidity in one of the passive houses measured in February 2012.
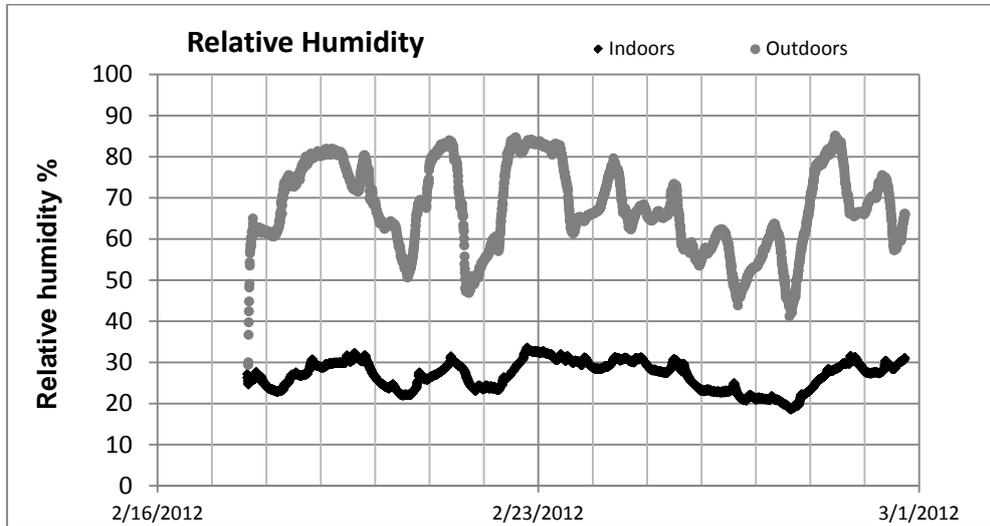

Figure 2. Example of the indoor and outdoor relative humidity in one of the passive houses. The mean (SD) indoor and outdoor RH was 27 (3) % and 68 (11) %, respectively.

The median air exchange rates of 0.66 h^{-1} and 0.60 h^{-1} in in the passive houses and the conventional buildings, respectively, are above the value of 0.5 h^{-1} required by the Swedish building code (Boverket, 2009). It may reflect the fact that both types of buildings are equipped with mechanical ventilation system, most often exhaust-supply ventilation with heat recovery (ESHR-system). The air exchange rates in the passive and new conventional buildings may also suggest that the property managers of these buildings are especially careful with good function and maintenance of the ventilation systems. The median air exchange rate in the Swedish housing stock was 0.38 h^{-1} and 80% of all the dwellings had an air exchange rate below 0.5 h^{-1}. Only about 15% of the dwelling from the survey had the ESHR-type of mechanical ventilation system (Langer and Bekö, 2013). Low ventilation rates were also reported in an earlier study from Sweden where around 80% of the single-family houses and 60% of the multifamily houses did not fulfil the minimum requirement for air exchange rate (Bornehag et al., 2005).

The statistical distribution of the concentrations of NO_2, formaldehyde and TVOC are shown in Figures 3, 4 and 5. The bottom and the top of the boxes represent 25th and 75th percentiles and the band near the middle of the box is the median. The ends of the whiskers indicate 10th and 90th percentiles. The circles show the values below the 10th and above the 90th percentiles. The horizontal dashed lines represent the recommended guideline values for indoor air.

The median concentrations of NO_2 in the passive and conventional houses of 9.7 µg/m³ and 11 µg/m³, respectively, were somewhat higher than the value of 8.0 µg/m³ for the Swedish housing stock. The values relatively well reflect the ambient concentrations. Outdoor air is the major source of indoor NO_2. The indoor/outdoor ratio is normally ~1.0 in the absence of indoor combustion sources. That was the case in this study, although the I/O ratios were slightly higher than one (1.42 for passive houses and 1.27 for conventional houses). The

World Health Organization (WHO, 2010) suggests a guideline value of 40 µg/m^3 for the annual average indoor NO_2 concentration. No values in the present study exceeded this value.

The median concentrations in passive houses and conventional houses were 12 and 16 µg/m^3, respectively, for formaldehyde, and 230 and 145 µg/m^3 for TVOC. The corresponding values for the Swedish housing stock were 17 µg/m^3 (formaldehyde) and 180 µg/m^3 (TVOC). The formaldehyde concentrations were all well below the 30-minute average exposure limit of 100 µg/m^3 (WHO, 2010). The median concentrations of TVOC were lower than 300µg/m^3, which has been recognized as a guideline value by the German Federal Environment Agency (UBA). However, the TVOC concentrations exceeded this guideline value in about 40% of the passive houses, but only in 10% of the newly built conventional dwellings.
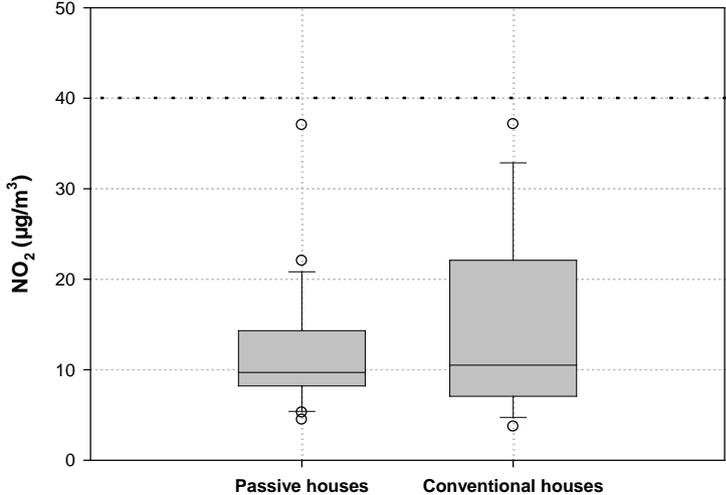

Figure 3. Boxplot of the concentrations of NO_2 in the passive houses and conventional houses.
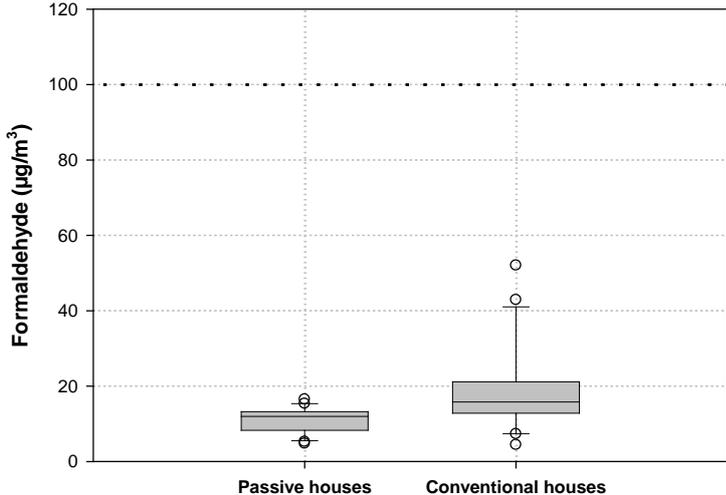

Figure 4. Boxplot of the concentrations of formaldehyde in the passive houses and conventional houses.
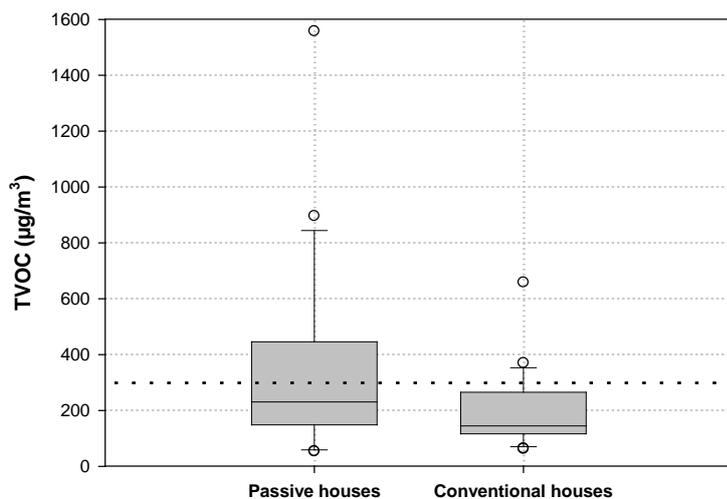
Figure 5. Boxplot of the concentrations of TVOC in the passive houses and conventional houses.

The number of cultivable airborne fungal particles inside and outside the passive houses ranged between 6 - 455 and 12 - 1800 CFU/m^3 air, respectively. No water-indicating microorganisms were found in any of the samples (STM 2003, US EPA). Considering the numbers of CFUs and the mycoflora found there are no indications from this study that mould growth constitutes any problem in these buildings.

The number of cultivable airborne fungal particles inside and outside the newly-built conventional houses ranged between 13 - 490 and 69 - 690 CFU/m^3 air, respectively. In six of the 21 houses the counts were greater inside than outside. In three of these houses the mycoflora inside was different from that of outside with the presence of water-indicating organisms (e.g. *Ulocladium* sp., *Phoma* sp., *Phialophora* sp.). In two homes water-indicating mould species were found, however without elevated amounts of live mould particles indoors. Thus, in total, 5 homes displayed a deviant mycoflora (not normal constitution of mould families in the indoor air) which may indicate the presence of mould growth and moisture damage in these buildings (Samson et al 2010, STM 2003).

CONCLUSIONS

The results of the study suggest that the indoor air quality in the newly built passive and conventional houses generally is good taking into account the parameters measured in this study. The air exchange rates were higher in these buildings compared to the Swedish housing stock due to carefully controlled mechanical ventilation. The temperature lied within the comfort zone and the relative humidity was rather low, especially in the passive houses. The concentrations of NO_2, formaldehyde and TVOC were similar to those observed in the Swedish housing stock and lower than the respective limit values, except for TVOC concentrations in about 40% of passive houses and 10% of conventional buildings. The mycoflora in the indoor air of the studied passive houses corresponded nicely to the composition of species present in the outdoor air. Fewer live mould particles were also found inside these houses compared to the outside air. In conventional newly-built houses, however, 30% displayed elevated amounts of live mould particles indoors and in 25% of the houses mould species associated with water-damage were found.

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