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Sanitary aspects of domestic ventilation systems: an *in situ* study

Joris Van Herreweghe*, Samuel Caillou, Marilyn Roger and Karla Dinne

Belgian Building Research Institute (BBRI),
Avenue Pierre Holoffe 21, 1342 Limelette, Belgium
*Corresponding author: joris.van.herreweghe@bbri.be

ABSTRACT

With the continuous improvement of the energy performance of buildings, ventilation plays a crucial role in the control of pollutants from indoor sources and related comfort and health effects. However, the ventilation system itself could possibly also be a source of indoor air pollutants such as microbial contaminants. Profound scientific and technical knowledge on the impact of the design, installation and maintenance on the real performances of ventilation systems is currently lacking. Therefore within a collaborative research project at the Belgian Building Research Institute (BBRI) the acoustic performance, energy consumption, air quality and ease of maintenance of five exhaust ventilation systems and twenty-eight balanced ventilation systems were evaluated *in situ*. Within this paper the results of the microbial analysis of the air quality part are presented. Different air sampling techniques were used to evaluate the supply and the indoor air in relation to the outdoor air. The impact of the accumulation and development of micro-organisms within the ventilation systems, especially in the ducts, the filters and if present on controllable supply grids, was also evaluated. The results indicate that the outdoor air quality has a major influence on the quality of the supplied and indoor air, especially for the mould load. However, human activity and the indoor environment tend to have a high impact on the indoor bacterial load. Exhaust ventilation systems were found to hardly alter the quality of the supplied air, leaving the indoor air microbial quality largely dependent on the outdoor air quality. In contrast balanced ventilation systems are capable of reducing the mould load, and to a lesser extend the bacterial load, of the supplied air. Filtration of the supplied air in the first place serves to protect the ventilation system from becoming dirtied. Nevertheless, the observed reduction in mould load of the supplied air within balanced ventilation systems can be regarded as an asset. However, the effectiveness of this filtration/protection was found to be largely dependent on the quality of the filters, filter housing (by-pass leakiness) and their state. These findings underscore the importance of a rational design, a proper installation and the importance of good maintenance.

KEYWORDS: Mechanical ventilation, air quality, moulds, bacteria

ABBREVIATIONS: EvS: Exhaust ventilation System, BvS: Balanced ventilations System, CFU: colony forming units;

1 INTRODUCTION

People spend on average more than 90% of their time indoors. In general, indoor air is more polluted than outdoor air (Tilborghs *et al.* 2009). Moreover, some indoor air pollutants, from chemical, biochemical as well as microbial origin, are recognized as important risk factors for our health. This especially holds true for the so called YEPI's (young, elderly, pregnant and immunodeficient), which in addition spend even more time indoors. Therefore, the absolute importance of indoor air quality is widely recognized by local (Tilborghs *et al.* 2009), European (European Commission 2003) as well as international organizations (World Health Organization 2009).

Ventilation is of utmost importance and even becoming more important for several reasons. First and foremost for the supply of fresh air and oxygen and the removal of humidity, since the latter might in turn cause mould and off odour issues. Further, ventilation also prevents the accumulation of harmful substances emitted by materials, although priority should be given to the use of low emitting materials. Last but not least, the continuously improving energy efficiency of buildings and its related increased air tightness resulted in an enhanced dependency on mechanical ventilation systems.

Basically two main mechanical ventilation systems can be distinguished. An exhaust ventilation system (further abbreviated as: EvS) comprises a natural supply through adjustable supply grids in windows or walls, an air flow through the house and mechanical extraction in the humid places of the house. A balanced ventilation system (BvS) consists of a mechanical supply and extraction with heath recycling and air filtration. In a variant of this system the supply air is sucked in through a traditional Canadian well (= earth heat exchanger). Alternatively, the supplied air might also be cooled or heated (depending on the season) by a glycol driven earth heat exchanger (hydraulic Canadian well).

Obviously these systems themselves might also have an influence on the sanitary aspects of the supplied and indoor air. Therefore the aim of this research project was to investigate this influence through system- and air sampling in 33 residential buildings equipped with a mechanical ventilation system (5X EvS and 28X BvS), but without visible dampness/moisture or mould problems.

2 MATERIALS AND METHODS

Different air sampling techniques were used to evaluate the supply and the indoor air in relation to the outdoor air. All samples were collected at the maximal ventilation capacity of the system. The supply air was sampled at the tip of supply duct in the living room, after removal of the supply valve. Indoor air was sampled in the living room on the coffee table. For viable fungal and bacterial air contaminants, an Air Sampler (RCS Plus, Biotest Hycon®) equipped with Hycon® agar Strips (Total count (TC) and Yeast and Mould (YM)) was used. A sticky surface sampler, Air-O-Cell®, was used to determine the total fungal particulate load of the air samples. The impact of the accumulation and development of micro-organisms within the ventilation systems, especially in the ducts, the filters and if present on controllable supply grids, was evaluated by ATP-tests, surface sampling as Swab and Rodac, in addition to culturing methods. Moulds were identified based on microscopic examination of tape samples taken directly from the surface or culture plates/agar strips. Concerning the statistical analysis, outliers were defined as values < Q1 (quartile) - 1.5xIQR (Inter Quartile Range) or > Q3 + 1,5xIQR. Mould removal efficiency was calculated as follows: $= \left(1 - \frac{\text{Supply}}{\text{outdoor}}\right) \text{x}100$

3 RESULTS AND DISCUSSION

The interpretation of microbial air sample data is far from standardized and a frame of reference is still lacking. Instead a number of arbitrary numeric standards for “acceptable” levels of indoor micro-organisms have been proposed, but none of them is currently generally accepted. Current interpretation is based on the comparison of the types and levels of micro-organisms detected indoors versus those in matched outdoor samples. Ideally, there should be no difference in the types observed indoors and outdoors, and additionally the indoor levels should be lower (Codina *et al.* 2008). This forms the general rule of thumb that was used to interpret the obtained measurements in this study.

3.1 Seasonal influences

Although the outdoor environment is regarded as a good source of clean and fresh air, the outdoor air is already loaded with biological (moulds, bacteria, pollen,…) and chemical contaminants. This however doesn’t pose direct problems for healthy people, but means that when outdoor air is used by a ventilation system, it always forms a potential source of eventual problems. The amount of micro-organisms in the outdoor air does not remain constant, but is influenced by the geographical location, climate and meteorological conditions (Codina *et al.* 2008). Since our collections were spread throughout the year, they should anyhow reflect the seasonal influences.

As expected the fungal load in the viable air samples was clearly influenced by the seasons (data not shown). Based on the comparison of the median of the seasonal subpopulations, higher outdoor levels were observed in autumn and the highest levels in summer. Winter accounted for the lowest levels. Independent on the system type (EvS or BvS), the indoor fungal levels were observed to be linked to the outdoor levels, although the supply and indoor air were generally less loaded than the outdoor air. This observation is less clear for winter time, which might be due to the overall lower microbial load of the outdoor air in this season.
In contrast, no clear seasonal influence could be observed for the bacterial load of the collected viable air samples. Furthermore, the indoor air was always observed to be more loaded than the supply and outdoor air. These results suggest that the indoor environment (dust, human activity,…) itself might largely contribute to the bacterial load of the indoor air. This assumption is supported by other studies and our own findings (see 3.3.1).

For both system types, 57% of all samples were collected during autumn and summer. For EvS 43% was additionally collected in spring, while for BvS 22% of all samples were collected in winter and 21% in spring. In spite of this dissimilarity, no significant differences were observed for the outdoor fungal levels between the datasets for both systems. This means that both datasets can be compared, although keeping the difference in sample size in mind.

3.2 Exhaust ventilation systems

3.2.1 Viable bacteria

As can be seen in Figure 1 below, the bacterial load in the indoor air (288;366 CFU/m³: Median (M); Average (Av)) is slightly higher than the load in the supply air (263;245) and both are more charged than the outdoor air (100;170). However, these differences are not significant based on a one way ANOVA statistical analysis ($\alpha = 0.05$). Little bacteria were found on the adjustable supply grids (Swab analysis, data not shown). This means that the higher bacterial load in the supply air in comparison to the outdoor air cannot be attributed to accumulation of bacteria on the supply grids. However, when sampling supply air at an adjustable supply grid, there is always a risk to aspirate indoor air due to the limited dimensions and accessibility of these grids. This might be a possible reason for the higher bacterial load in the supply samples in comparison to the outdoor samples.

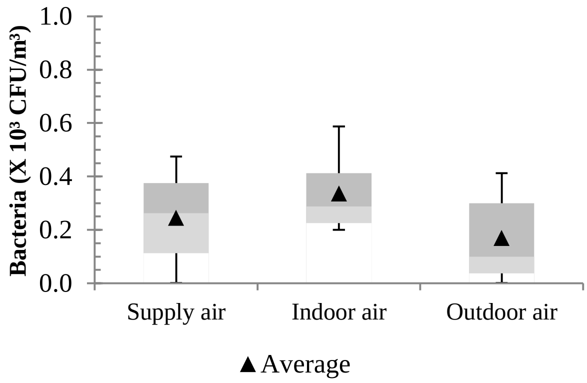

Figure 1: Box-whisker plot of the viable bacterial load expressed in CFU/m³ determined by RCS air sampling for EvS.

3.2.2 Viable moulds

Unlike our observations for the bacterial load, the indoor air is the least charged with mould particles (306;329), followed by the supply air (513;548) and the outdoor air (819;848) (see Figure 2: A). As can be seen from Figure 2B a direct relationship between the supply- and outdoor air was observed for the EvS. This actually forms a logical finding, since in Ev systems the outdoor air is just passed through an adjustable supply grid, which theoretically doesn't alter the microbial composition of the outdoor air. It also means that the sanitary performance of an Ev system is more seasonal dependent. This was clearly illustrated in our dataset by three different measurements for the same Ev system in three different seasons. While the measurements for spring and autumn are quite normal, the measurements for the summer time form an outlier in this dataset for all three collected air samples (Supply, Indoor and Outdoor) (No.1 2nd (summer) in Figure 2A). Furthermore, the value for the ATP-measurement on the outside of the adjustable supply grid exceeded the overall observed values. Finally, Air-O-Cell analysis confirmed the massive presence of *Cladosporium* spp. spores in all three samples.

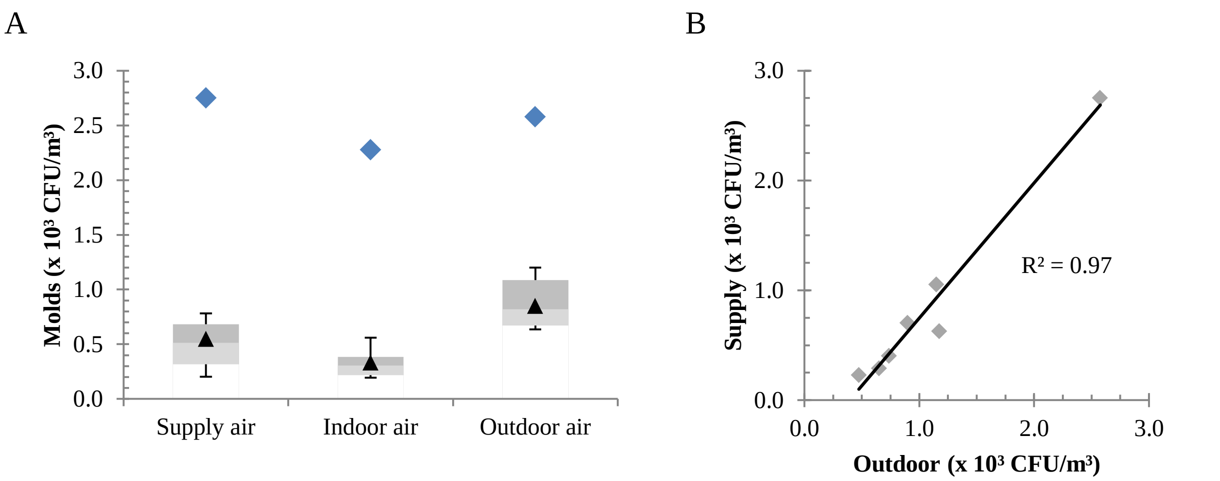

Figure 2: A) Box-whisker plot of the viable mould load expressed in CFU/m³ determined by RCS air sampling for EvS. Legend: ▲ average ◆ outlier No.1 2nd (summer). The outlier was excluded from the dataset for the descriptive statistical analysis. B) Viable mould load in the supply air in function of the outdoor air, both expressed in CFU/m³.

3.3 Balanced ventilation systems

3.3.1 Viable bacteria

For balanced ventilation systems the indoor air was found to contain more bacteria (325;467) than, in descending order, the outdoor (125;205) and the supply air (25;63) (see Figure 3A). The bacterial load in the supply air was observed to be significantly reduced (one way ANOVA, Tukey Post-hoc test, $\alpha = 0.05$) in comparison to the outdoor air. This reduction is most likely due to the presence of the air filters in the ventilation systems. These filters are coarse- or fine dust filters, which in the first place serve to protect the interior of the ventilation system, but additionally can be used to alter the microbial composition of the supplied air. The diameter of bacteria ranges from 0,5 µm to 2 µm. Technically spoken this means that the typical filter types present in Bv. systems (see Table 1 in appendix) do not restrain bacteria on a large scale, based on impact retention. However, the bulk effect of a dusty filter or electrostic interaction between the filter and the bacterium can result in bacterial removal. One outlier in our dataset (No.20) is directly in line with this hypothesis due to the fact that the filters were changed not long ago before the measurements (no bulk effect) in combination with a high outdoor bacterial load. Another outlier (No.16) comprises the measurement on a system equipped with very old (> 2.5 years) G3 sock filters, which is a filter type vulnerable to leakiness. Furthermore, a study of Möritz *et al.* (2001) demonstrated that F7 type air filters were able to retain airborne bacteria and moulds with an efficiency of 70-80% when the outdoor air was relatively dry (<80% RH) and warm (>12°C).

On the other hand, although the supplied air is reduced in its bacterial load, the indoor air contains a significantly (P-value < 0.0001) higher amount of bacteria in comparison to the supply (see Figure 3B) and the outdoor air. This actually means that the relatively clean supply air gets again loaded with bacteria coming from the indoor environment (indoor dust,…) and human activity. Two studies (Hospodsky *et al.* 2012, Qian *et al.* 2012) have already shown that direct human shedding (skin, hair and nostrils) and resuspended floor dust are the most important sources of indoor bacteria whenever a room is occupied. Since the major source of bacteria can be found indoors, there is no direct need for filter types with higher bacterial retention efficiency.

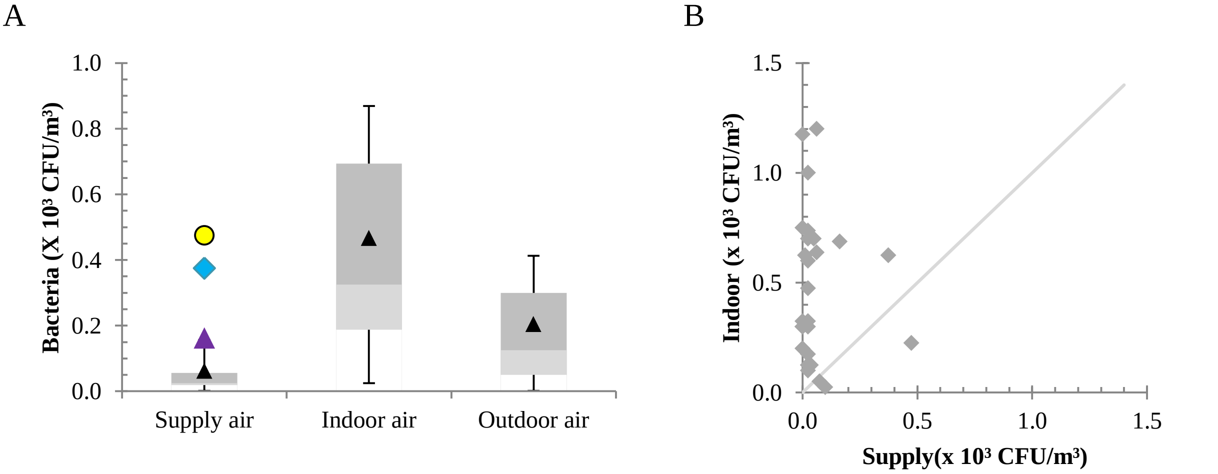

Figure 3: A) Box-whisker plot of the viable bacterial load determined by RCS air sampling for BvS. Legend: ▲ average, Outliers are shown as a separate data point: ◆ No.16 (autumn), ○ No.20 (autumn), ▲ No.35 (winter) B) Viable bacterial load in the supply air in function of the outdoor air

3.3.2 Viable moulds

As indicated in Figure 4A the supply air (163;365) in balanced ventilation systems is less loaded with mould particles than the indoor air (250;505) and the outdoor air (663;1016) respectively. The fact that the supplied air contains fewer moulds than the outdoor air is the result of the filters present in the system (see Figure 4B). These are, depending on their type, theoretically capable of retaining mould spores (2-10µm (Baily 2005)) based on impact retention. Apparently the relative clean supply air gets again slightly loaded with moulds. The potential sources for this phenomenon are materials present indoors like plants, kitchen waste, dust as well as an additional air change rate independent of the ventilation system (open doors and windows, air leakages in the building envelope,…). All exceptional values (outliers Figure 4A) can be attributed to samples collected in autumn and summer, the two seasons with the highest outdoor mould levels (see 3.1). For No.2 an exceptional high mould load was observed in the outdoor air sample, which was collected in summer time. Although the filters present in the system (G4 type) reduced the outdoor mould load with nearly 70%, still high mould levels were found in the supply and indoor air samples. On the other hand for exception No.19, which is also characterised by a high mould load in the outdoor air, the filters (G4) still remove the vast majority of the mould load (96.7%) resulting in no exceptional values for supply and indoor samples (See section 3.3.3 for a description of the other exceptions). Figure 4 B represents the number of moulds (x 10^3 CFU/m³) in the indoor air in function of the number in the outdoor air. The vast majority of the samples can be found beneath the grey line (indicating an indoor/outdoor value of 1), meaning that the indoor air contains fewer moulds than the related outdoor sample (see section 3.3.3. for a description of the exceptions).

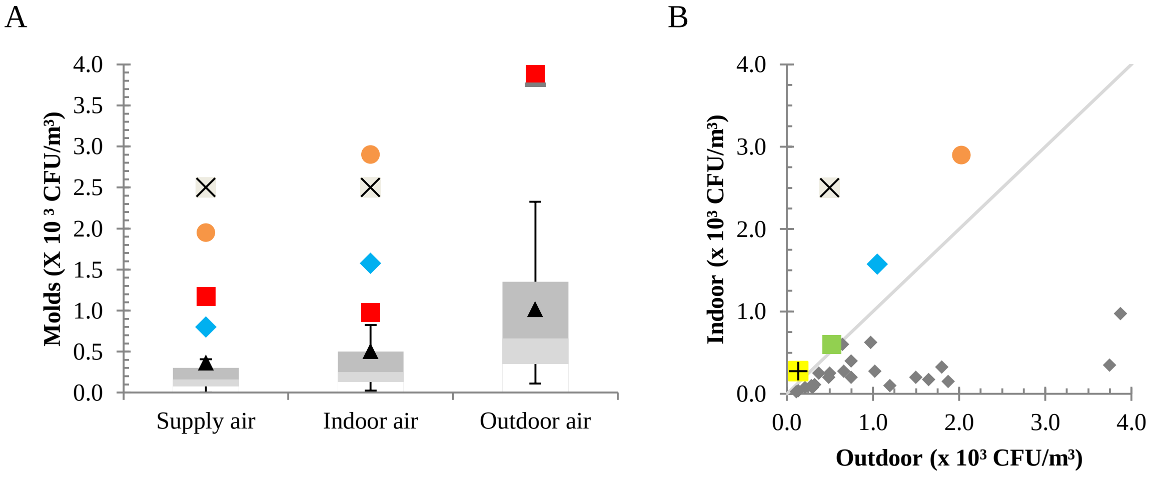

Figure 4: A) Box-whisker plot of the viable mould load expressed in CFU/m³ determined by RCS air sampling. Outliers are shown as a separate data point: ▲ average, ■ No.2 2nd (summer), ● No.15 (summer), ◆ No.16 (autumn), ▬ No.19 (autumn), ✕ No.37 (under construction) B) Viable bacterial load in the supply air in function of the outdoor air. Legend: ● No.15, ◆ No.16, ■ No.21, ✚ No.34 and ✕ No.37

3.3.3 Filter analysis and performance

Filters present in ventilation systems in the first place serve to protect the interior of the ventilation system, but additionally can be used to improve the quality of the supplied air. Within this project no direct performance measurements were conducted on the filters. However, comparison of the supplied air in relation to the outdoor air gives an impression of the filter performance, although any influence of the duct system is also included (see Figure 5 A). As can be seen from Figure 5A, the mould load of the supplied air is generally reduced in comparison to the outdoor air. Only two out of 28 samples have a supply/outdoor value >1 (No.34: house with serious construction errors, No.37 house under construction) and one has a S/O value ≈1 which could be due to leaking filters (by-pass leakage). The mould removal efficiency increases with a decreasing mesh size, although the differences between the finest filters (or combination of a coarse and fine dust filter) is rather small (see Figure 5 B). As can be seen from Figure 5 C, the mould removal efficiency of the filters tends to decrease in function of their age. In any case, old filters form a potential contamination risk (see No.16 in Figure 5 C), but also new filters may not function properly. For example point No.15 in Figure 5 C represents a filter of 52 days old with a mould removal efficiency of 3.7% which is most likely related to the fact that it is a sock filter, which is a filter type vulnerable to leakiness. Further point No.21 in Figure 5 C, represents a system with wrongly installed filters and a vertical supply air intake, resulting in clear visual pollution of the system. Finally point No.34 represents a house with serious constructions errors and a potential mould source in the ventilation ducts.

For balanced ventilation systems equipped with a Canadian well, large amounts of bacteria were observed on the pulsion filters (4 out of 6 cases; Rodac and Swap analysis; data not shown). So far, no clear influence on the bacterial load of the supply air was observed, however all samples for these systems were collected in winter time. The appearance of condensation in the Canadian well in summertime might form a potential risk for high levels of bacteria in the supply air of these types of systems, but this remains to be investigated.

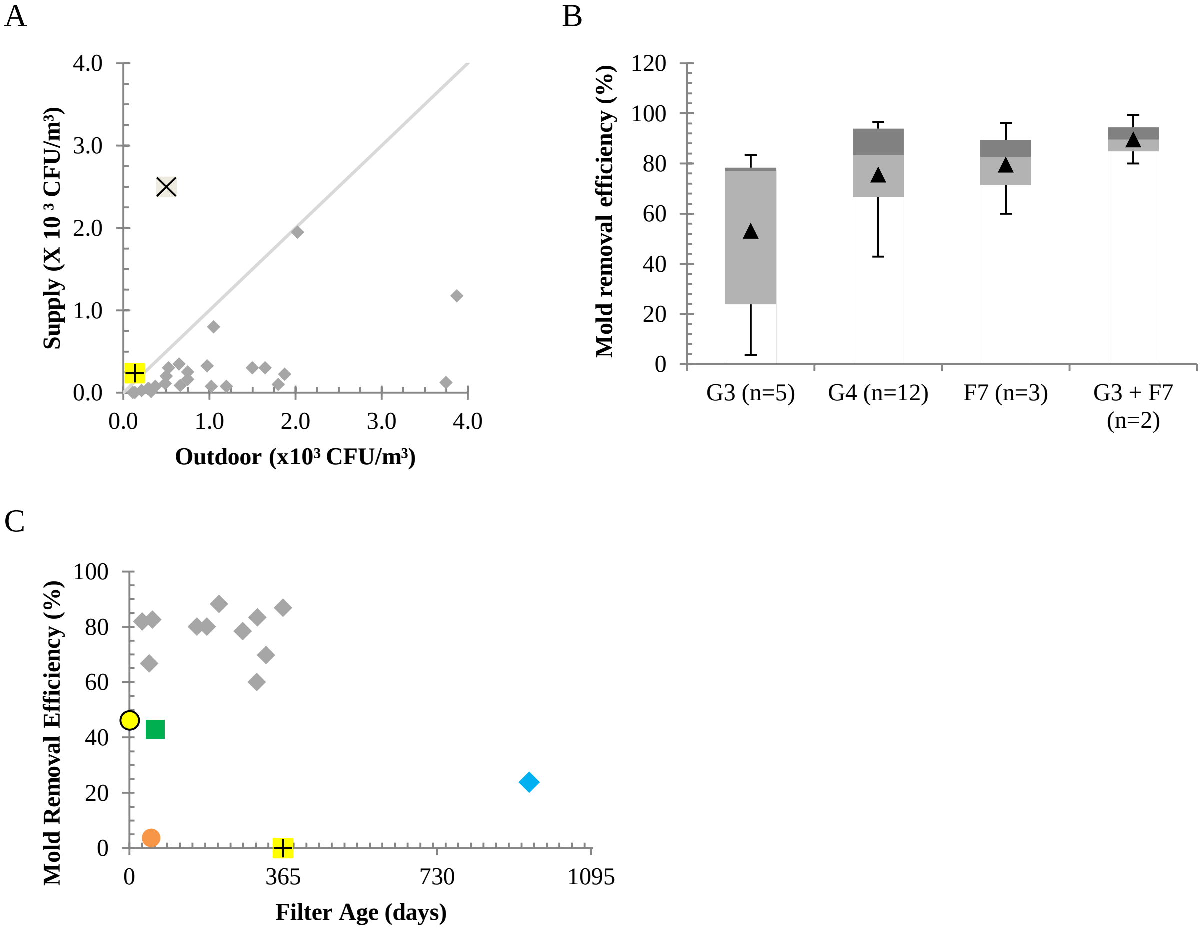

Figure 5 A) Viable mould load in the supply air in function of the outdoor air. Legend: + No.34 and × No.37 B) Mould removal efficiency (%) versus filter type present in the system (exceptions No34, 37 and 15 were excluded from the graph), ▲ average. C) Mould removal efficiency in function of the filter age. Legend: ● No.15; ◆ No.16; ○ No. 20; ■ No. 21; + No.34.

3.4 Most commonly identified mould genera

As mentioned earlier, the interpretation of the microbial viable air sample data was based on the assumption that the indoor microbial levels should be lower than the outdoor levels and there should ideally be no difference in the mould types present in both samples. In the majority of the samples no distinct differences were observed in the identified mould genera. *Aspergillus* (Supply: 33%, Indoor: 31% and Outdoor: 34%), *Cladosporium* (65%,72%,89%) and *Penicillium* (70%,86%, 69%) were the most abundantly identified mould genera. The frequency of occurrence in the different samples is shown between brackets. The fact that these genera were the most abundant is however not surprising, since the spores of these moulds are relatively small and easily airborne. As a result these spores are also easily collected by air sampling. Moreover, samples were collected in houses without visible mould and dampness problems, rendering the chance of collecting the spores of associated mould genera, which are usually larger and less airborne, less likely.

4 CONCLUSIONS AND RECOMMENDATIONS

For both systems the bacterial load in the indoor air samples was higher than in the outdoor and supply samples. These results suggest that human activity has a higher impact on the indoor bacterial load than the supply from outdoors through the ventilation system. For both systems the mould load in the outdoor air was higher than the load in the indoor and supply air. However, for the exhaust systems the supply air is more loaded than the indoor air and the mould content of the supply- and indoor air was found to be directly related to that of the outdoor air. No direct relation between the number of bacteria and moulds present on the adjustable supply grids and extraction ducts and the microbial load of the supplied and indoor air was observed for EvS. This however does not exclude the necessity of maintenance. In contrast, for the balanced systems the indoor air contained a slightly higher mould load in comparison to the supply air. The supply air was drastically reduced in mould load in comparison to the outdoor air, which is due to the supply filter present in balanced ventilation systems. Furthermore, seasonal variations have an influence on the hygienic quality of the supplied air by the ventilation system. This influence is clearer in exhaust systems in comparison to balanced systems. Although the effect of the outdoor air on the quality of the supplied air for balanced systems largely depends on quality of filters and their airtightness.

Based on the results of our *in situ* measurements as well as on on-site observations the following recommendations can be formulated to prevent ventilation systems from becoming microbially contaminated and finally in the worst case a potential indoor microbial source. These recommendations are categorized in three subgroups related to: the design, installation and maintenance of the system.

Design:

As concluded earlier (see point 3.3.1), the major source of bacteria can be found indoors. Therefore, there is no direct need for filter types with higher bacterial removal efficiency. Further a coarse dust filter (type G4) has already a satisfying mould removal efficiency and is sufficient to protect the system (see Table 1 and Figure 5 C). On the other hand, leaking filters have a baleful influence on the microbial quality of the supply air. Therefore priority should be given to the airtightness of the filters and the combination of the filter and its housing in the system, rather than the improvement of their efficiency. This includes: avoiding the use of sock filter types which are vulnerable to leakiness, preventing the possibility of incorrect installation, prevention of air passing around the filters (by-pass), provide a good accessibility to the filters in order to facilitate maintenance. Whenever more efficient filters are desired, an F7 fine dust filter can be combined with an inline coarse dust filter (G3 or G4) in front of the exchange unit

Installation:

A vertical supply air intake should be avoided in order to prevent the accumulation of dirt on the pulsion site of the system (ducts, heat exchanger and filter). Also the filters are at risk to become wet, which might result in microbial growth. Further, a certain distance between the fresh air intake and the exhaust of the consumed air and other exhausts (chimney, aeration of wastewater,…) should be respected. It is absolutely not recommended to launch the system in a building under construction (see outlier No.37 in Figures 4 and 5). Finally, the ducts should be protected against possible contamination shortly after production and remain covered during storage, transport, installation and until occupation of the house.

Maintenance:

For a balanced ventilation system, the state of the filters has a direct impact on the microbial quality of the supply air. Therefore it is recommended to clean the filters every 2 to 3 months using a vacuum cleaner, ideally equipped with a HEPA14 filter. Once a year, the filter pair should be replaced, preferably before winter time. Additionally the grill of the supply air intake and the supply and extraction mouths should be cleaned. For the ducts, a regular inspection and/or cleaning (rigid ducts) or replacement (flexible ducts) is recommended.

Exhaust ventilation systems require less maintenance, but a 3 monthly based inspection and yearly cleaning of the controllable supply grids and extraction ducts is recommend.

5 APPENDIX

Table 1: Air filters typically used in balanced ventilation systems and their characteristics according to Filtration Engineering Ltd (Cheshire, UK) using test standard BS EN 779

Intended removal	Filter class	Nearly 100% retention for particles	Average performance according to EN779
Coarse dust	G3	>5µm	80-90% Arrestance
	G4	>5 µm	≥ 90% Arrestance
Fine dust	F7	>2 µm	80-90% Efficiency

6 ACKNOWLEDGEMENTS

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