RELATIONSHIP BETWEEN VENTILATION, AIR QUALITY AND ACOUSTICS IN ‘GREEN’ AND ‘BROWN’ BUILDINGS

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ABSTRACT
This paper discusses a pilot project involving direct monitoring of ventilation, indoor-air quality and acoustical conditions in ‘green’ and ‘brown’ buildings on the UBC campus. The objective was to determine the relationships between various building concepts and environmental factors, and the implications of the results for the ventilation-system concept/design, especially in ‘green’ buildings. Measurements were made in four categories of rooms in buildings with natural, displacement and forced-air ventilation systems, without and with acoustical treatment. Measurements were made of ventilation rates (air changes per hour), indoor air-quality (fibre concentrations, VOC concentrations, ultrafine-particulate concentrations), and the acoustical conditions (noise levels, reverberation times). Environmental results were correlated with the type of ventilation system and with one another. The buildings studied, the measurements performed and the main results are described. The lessons learned about building ventilation-system design are discussed.

INTRODUCTION
One primary purpose, and a design goal, of a building is to provide a comfortable, healthy and productive environment for the occupants – especially in ‘green’ (sustainable) buildings. There are four key elements of a building that interact to create the indoor environment. These are:

- the structure (including the windows in the envelope)
- the HVAC concept/system
- the outdoor environment
- the occupants’ activities.

In the end, the aspects of the built environment that directly influence the occupants of a building are ventilation, indoor air quality (IAQ), acoustics and lighting. Certainly, acceptable quality of each of these factors is a prerequisite for occupant satisfaction and productivity, and they must be considered carefully in the design of a building. Lighting was not part of the study reported here.

There is a close relationship between the three factors, ventilation (in general, the HVAC concept/system), IAQ and acoustics, and the design of each influences the performance of the others significantly. The application of various standards, methods and criteria in building design results in different conditions and qualities of the resulting ventilation, air quality and acoustical environment in different buildings. This provides an opportunity for investigation and evaluation of the impacts of various design concepts on the internal environmental conditions of buildings.

The present study investigated the relationship between the building design concept and resulting environmental factors, and the relationship between these, in ‘green’ and conventional, non-‘green’ (‘brown’) buildings. Previous unpublished UBC studies in ‘brown’ buildings with forced-air HVAC systems found that the resulting ventilation quality and noise levels are inversely related; rooms that have adequate ventilation are often noisy, and quiet rooms often had inadequate ventilation. Furthermore, the introduction of noise-control measures may adversely affect both the ventilation quality and IAQ.
The reduction of energy consumption, using natural ventilation (if applicable) and by the design of the concept of ‘green’ buildings is considered very seriously in building design nowadays. Of course, introducing a new type of HVAC system influences the ventilation, indoor-air and acoustical qualities directly. In order to evaluate the environmental factors comprehensively, spaces in both ‘green’ and ‘brown’ buildings were chosen such that different types of ventilation concepts/systems – forced-air, displacement and natural – were involved. This paper presents observations about the results and the relationships between them.

**METHODOLOGY**

As mentioned, the factors investigated in this study were acoustics, ventilation and indoor-air quality. Following are details of the environmental factors measured:

- **Acoustics:**
  - background-noise levels (unweighted and A-weighted octave-band and total, NC, RC II)
  - mid-frequency reverberation times ($RT_{mid}$)
  - noise isolation (octave-band, NIC);

- **Ventilation:**
  - air-exchange rate (ACH = air changes per hour);

Ventilation rate was quantified by measuring the air flow entering the spaces, and using the SF$_6$ tracer-decay method.

- **Indoor-air quality:**
  - (glass)fibre dust (fibre concentration)
  - ultrafine particulates (ratio of indoor-to-outdoor PC, inside PC – 20% of outdoor PC; $PC = $ particulate concentration, $UPC = $ ultra-fine particulate concentration)
  - Volatile Organic Compounds (VOC concentration);

$CO_2$ was not considered as an indicator of air quality in this survey. Clearly, $CO_2$ concentration depends on the number of sources (occupants). At the time of monitoring, the number of occupants was not at its usual value in most of the study spaces. To eliminate the influence of unstable environmental elements on the results as far as possible, $CO_2$ level was not considered as one of the environmental components. Nevertheless, based on the measured ACH, $CO_2$ levels can be easily calculated for each space.

In order to investigate the above components more comprehensively, spaces were chosen which were easy to access, and which included a broad range of HVAC systems, furnishings and acoustical treatments. Hence, three buildings on the UBC campus, with rooms which contained the types of spaces required for this study, and which were adjacent (and, thus has similar outdoor environmental conditions), were selected for monitoring. These three buildings were: 1) Bldg_K, a ‘green’ building with LEED Silver ranking, 2) BLDG_C (‘brown’) and 3) Bldg_M (‘brown’). The buildings were located next to campus roads, but were generally in quiet external environments.

Selected spaces on the first and second floors of Bldg_K have natural and displacement ventilation and are conditioned by thermal slabs embedded in the ceiling. On the third floor, forced-air ventilation is used for both ventilation and air-conditioning purposes. All of the spaces in BLDG_C and Bldg_M have forced-air ventilation, some with acoustical treatment involving glass-fibre sound absorption.

In view of the fact that the acoustical conditions in any space are a function of its geometry, furnishings and furniture density, the rooms investigated were divided into four main groups:

- **Office spaces** – these were generally small rooms with a maximum of two occupants. The spaces had natural or forced-air ventilation, with carpets and acoustic tiles, and generally high or low furnishing density.

- **Small classrooms** – these spaces were generally larger than the spaces in the first group; they had forced-air or natural ventilation systems, and the major distinction that they possessed acoustic ceilings.
• Large spaces with substantial acoustic treatment – this category included large-volume spaces ventilated with displacement and natural ventilation systems; they had acoustic tiles and were carpeted, and contained a high furniture density.

• Large spaces with some acoustical treatment – these spaces covered a wide range of common, large educational spaces with different types of acoustical treatment and furnishings.

This pilot study involved a total of only 13 rooms; because of the statistical limitations associated with such a small sample size, the results are more indicative than definitive.

OBSERVATIONS
Following is a summary of the main preliminary observations made from analysis of the results:

Ventilation
Obviously, whatever type of ventilation system is involved, the ventilation quality depends on the correct design and selection of the equipment. As expected, the ventilation rate and quality were different from space to space. In spaces with forced-air systems, as was the case for the delivered airflow, the ventilation rate covered a broad range of values from completely inadequate to completely satisfactory.

In naturally-ventilated spaces, the main factor influencing the ventilation rate was the status of the windows (open or closed). In all of those spaces, the ventilation rate was very low; with windows closed, the rate dropped to approximately zero. The two other factors affecting the ventilation in these spaces were the outdoor temperature and the existence of ventilators (ventilation ducts, channels or openings) for airflow between the spaces and the adjacent environments (controlled-pressure spaces). The outdoor temperature, as well as affecting the window status in different seasons, may also lead to different qualities of air circulation in spaces.

Acoustics
In naturally-ventilated spaces, the acoustical conditions depended completely on the window status. Background-noise level (BNL) was low when the windows were closed, but opening the windows to increase the ventilation rate led to higher mid- and high-frequency noise.

In spaces with forced-air systems, the velocity of the air at the duct outlet had a significant effect on BNL. In such spaces, it was observed that, in spite of high ventilation rates in some of the rooms BNL, especially at low and mid frequencies, was lower than in similar spaces with less airflow. This shows that the correct duct design and air velocity have more impact on BNL than simply the rate of air delivered to the space. Furthermore, in rooms with heat pumps or displacement systems with nearby exhaust fans, the acoustical conditions were unsatisfactory, especially at low and mid frequencies. This was observed even when the fans and associated ducts were all acoustically treated.

The other influence of the HVAC system is on the noise isolation between one room and its adjacent spaces (corridors, for instance). The measurement results demonstrated that the noise isolation in spaces with return-air ducts was lower than that in spaces using doors grills. Moreover, Z-ducts in naturally-ventilated spaces significantly reduced the noise isolation, even when they were lined with sound-absorbing materials.

Besides having different HVAC systems, the other attributes of the spaces were the type and density of their acoustical treatment and furniture. RT\textsubscript{mid} decreased with the amount of absorbing material (i.e. acoustic ceiling, carpet, wall absorption and furniture) in the space.

Indoor Air Quality
In non-industrial buildings such as those studied here, Indoor-air-quality problems arise when there is an inadequate amount of ventilation air being provided, given the amount of contaminants present in the space. Following are the main observations for the various IAQ factors:
(Glass)fibre dust
The main source of fibres in the spaces investigated was acoustics tiles and duct liners. According to the air-sampling results, whatever is the ventilation concept, the highest fibre concentration was observed in spaces with greater amounts of furnishings;

The lowest fibre concentration was measured in spaces with low furnishing densities. In addition, the fibre concentration was higher in spaces with acoustic ceiling tiles, compared with other spaces. The influence of a carpet on the amount of released fibre was lower than that of acoustic tiles; however, the correlation between carpets and fibres was still positive.

In addition to the above, the ventilation rate also impacts the fibre concentration in rooms. Comparing spaces with similar furnishings (e.g. with no carpet or with ceiling tiles), it was observed that the fibre concentration in naturally-ventilated spaces was higher than in mechanically-ventilated rooms. Clearly, this was due to lower ventilation rates in the former spaces.

Ultra-fine particulates
The main source of ultra-fine particulates in the spaces surveyed was pollutants (combustion products, etc.) in the outdoor air. Obviously, the best way to decrease UPC in such spaces is to provide clean, filtered air. The results from the spaces studied confirmed this in that in rooms with mechanical-ventilation systems the particulate concentration was lower than in spaces with natural systems, with windows open or closed (see Figure 1).

In spaces with higher ventilation rates, the ratio of indoor-to-outdoor PC was lower, while in rooms with lower ventilation rates, due to the lack of adequate filtered air, the value of PC – 20% outdoor PC was higher. Furthermore, one of the important points observed was the beneficial influence of ventilators in naturally-ventilated spaces in reducing UPC. In spaces with a natural system without a ventilator to the ambient environment (a controlled-pressure space – i.e. a corridor or atrium) more time was required for the reduction of the particle concentration.

VOC
As with fibre dust, a close relationship was observed between the VOC concentration and the amount of acoustical treatment and furnishings. VOC concentration was higher in spaces with acoustic tiles and/or carpets. In spaces with natural-ventilation systems, in spite of lower ventilation rates, because of furnishings and the application of inadequate acoustical treatments, VOC concentrations were lower than in rooms with mechanical ventilation.

RESULTS
After considering the environmental factors independently, the relationships between these elements and the concepts involved in the building design were investigated. The two main building concepts investigated were construction style (i.e. ‘brown’, hybrid or ‘green’) and ventilation system (i.e. natural, displacement or forced-air). Figure 2 presents the results with the highest correlation coefficients between the ventilation-system concept and environmental factors. The results can be summarized as follows:
In spaces with natural-ventilation systems:
- the levels of unweighted low-frequency and total noise were lower
- the number of air changes per hour was lower
- the fibre concentration was lower (due to the type of furnishings in the spaces surveyed)
- the ratio of indoor-to-outdoor UPC was high (due to no filtration and inadequate control of outdoor air)
- the indoor temperature was lower at the time of monitoring (i.e. winter).

In spaces with displacement ventilation systems:
- the unweighted and A-weighted mid-frequency noise levels were high
- total A-weighted sound-pressure level were higher
- the NC level of the noise was higher (because of nearby exhaust fans).

In spaces with forced-air ventilation systems:
- the unweighted low-frequency and total sound-pressure levels were high
- the number of ACH was higher
- the fiber concentration was higher (due to the type of furnishings)
- the ratio of indoor-to-outdoor PC was significantly lower
- the indoor temperature was higher at the time of monitoring (i.e. winter).

Figure 3 shows the results with the highest correlations between the different construction styles. These results can be summarized as follows:

In ‘brown’ buildings:
- the NC level was lower than in hybrid and ‘green’ buildings; this was mainly due to the presence of spaces with displacement ventilation and of naturally-ventilated spaces with open windows in other groups
- the VOC concentration in rooms was lower
- the ratio of indoor-to-outdoor PC was lower.

In hybrid buildings:
- unweighted and A-weighted low, mid and total sound-pressure levels were higher
- rooms had greater NC levels
- ventilation rates (ACH) were higher.

‘green’ buildings had:
- lower unweighted low-frequency noise levels
- lower total, unweighted sound-pressure levels
- lower ventilation rates
- lower fibre concentrations in the spaces (due to the absence of acoustic tile and carpets, and the low furniture density)
- higher ratios of indoor-to-outdoor PC
- lower indoor temperatures (in winter).

As another part of the investigation, the impact of window status in naturally-ventilated rooms on the environmental conditions inside the spaces was investigated. Figure 4 shows the most sig-
significant correlations when the windows were open. In general:
- the unweighted and A-weighted levels of noise in all frequency bands and, therefore, total sound-pressure levels were noticeably increased
- the magnitude of the indoor – 20% outdoor PC was greatly increased; this was due to the introduction of high volumes of unfiltered air into the spaces by opening the windows.

Moreover, it was observed that ventilation rate had a significant negative correlation with PC. In addition, as previously mentioned, VOC concentration was lower in spaces with lower ventilation rates (i.e. naturally-ventilated spaces, in general); this was further confirmed by a high positive correlation between ventilation rate and VOC concentration.

CONCLUSION
The main conclusions of this pilot study are as follows:
- forced-air ventilation gives better IAQ, but higher HVAC noise levels; IAQ and noise level are directly related
- in naturally-ventilated spaces with radiant ceiling slabs, lack of acoustic treatment gives lower fibre concentrations, but worse acoustical conditions
- naturally-ventilated spaces have unsatisfactory ventilation quality but acceptable noise levels with the windows closed, and satisfactory ventilation quality but excessive noise levels with the windows open, even without significant external noise sources
- naturally-ventilated spaces with few furnishings or sound-absorbing materials have higher IAQ
- acoustical treatment can enhance acoustic quality, but worsens IAQ.

The results suggest that the optimum building design would use a mechanical-ventilation system designed according to current standards, with a ventilation rate conforming to current standards (to dilute contaminants), and with a carefully selected amount, type and location of acoustical treatment (use materials which generate less contaminants such as fibres, VOCs, etc.; use wall absorption in combination with radiant ceiling slabs).