The Indoor Climate of a Naturally Ventilated Church

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SUMMARY
The indoor air climate of a church, with a total building volume of 9500 m^3, was investigated from January to October, 2008. During this time, infiltration and ventilation measurements were performed at four periods ranging from 17 to 45 days. The local mean age of air was determined in several locations at different heights using passive samplers and homogeneous emission of PFTs. In addition, the temperature and relative humidity was measured at selected locations. The total infiltration of fresh air into the church was found to be mainly driven by the difference between indoor and outdoor temperature. The rate of infiltration ranges from 780 m^3/h (Δt=14.8 °C) in January to 240 m^3/h (Δt=3.5 °C) in August. The local mean age of air in the upper and lower air volumes were found to be roughly equal, both during the heating season and in the summer. This indicates that the air volume in the church is well-mixed throughout the year. Transient measurements to assess the effects of doors opening in the summer were also performed using pumped sampling.

KEYWORDS
Air infiltration rate, Natural ventilation, PFT, Homogeneous emission technique, Relative humidity

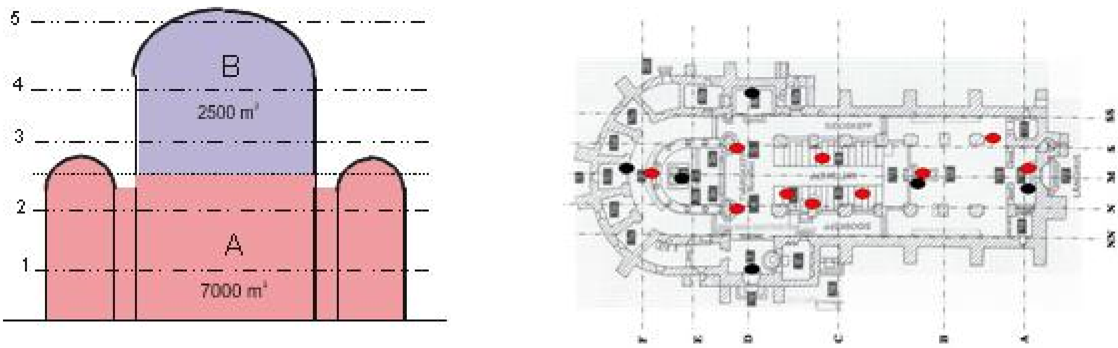
INTRODUCTION
Varnhem Monastery Church in Skara Pastorate erected around 1150 AD is a popular tourist attraction with many visitors during the summer period. The church is naturally ventilated which means that the rate of infiltrated ventilation air is determined by leakage in the building envelope, the difference between indoor and outdoor temperature, and the wind load onto the church. During the heating season the temperature is kept at approximately 13 °C, but thermal comfort requires the temperature to be raised above 18 °C in periods of frequent use. However, raising the temperature will cause a lowering of the relative humidity (RH) which may harm wooden artefacts in the church. In addition, heating may introduce rapid variations of the RH over time that also is detrimental to artefacts. This is in contrast to the medieval situation where the indoor climate was stable with slow variations of the temperature and RH and where the artefacts suffered less. To obtain suitable preservation conditions, an indoor RH range during the heating season between 45…60% and daily amplitude of RH below 10% is recommended in churches (Schellen, 2002). It is a delicate task to devise a cost effective solution that satisfies both the ideal preservation conditions and the need for thermal comfort.

Another problem of excess moisture arises due to the large thermal mass and low thermal resistance of the building envelope. Since the interior surfaces reflect the average temperature, they are usually cooler than the infiltrated air during the warmer daytime and thus may cause condensation onto these surfaces. Excess moisture and a high local RH may promote growth of fungi, algae, and molds.

The objective of this study is to map the indoor climate of the church over a large part of the yearly cycle. The results will be part of the knowledgebase in the process of planning new installations to improve the indoor climate.

METHODS

Measurements have been performed in four time periods each ranging from 15 to 47 days. (Period 1: January 10-24, 2: February 18 – March 13, 3: June 17 – July 29, and 4: August 21 – September 16.) The infiltrated ventilation air was measured using the homogeneous emission tracer gas technique described in NORDTEST Standard VVS 118 (1997) and ISO 16000-8. Perfluorocarbon tracer gases (PFTs) was used and tracer gas sources were spread evenly in the church room to obtain a homogeneous rate of emission. Passive collection onto 15 to 20 SKC charcoal tubes were used for long term averages (Stymne and Boman, 1994). To determine whether any convection cell developed in the roof region, different tracer gases were employed in the zone A or B in figure 1. The natural variable measured is the local mean age of air τ [h]. In steady state conditions, the local air change rate ACH [h^{-1}] is obtained as the inverse of τ and the corresponding total air flow rate [$m^3 \cdot h^{-1}$] as the total room volume divided by τ (Etheridge and Sandberg, 1996). Temperature and RH were measured in 5 to 10 positions with a frequency of one value (averaged from eight measurements) per hour. Outdoor temperatures, RH, as well as wind direction and speed were obtained as three hour averages from the nearby (44km) SMHI weather station at Hällum. At June 17, the transient effects of opening doors were investigated using simultaneous pumped sampling for 10 minutes onto charcoal tubes with calibrated and programmable SKC sampling pumps. For this study, the porch (anteroom) was included in the homogeneous emission zone and the temperature and RH was measured every 2 minutes in a great number of positions.



a) **b)**

Figure 1. Layout of the church. a) Vertical cross section showing the location of levels 1 to 5. The height is 13.5 m and the width is 17 m. The volume estimates (for the large church room) are 7000 m^3 and 2500 m^3 for the lower zone A and the upper zone B, respectively. b) Horizontal cross section. In this example showing the locations of the passive collectors (red) and temperature and RH loggers (black) on level 1. The distance from the west entrance to the large church room to the eastern chancel is 57 m.

RESULTS AND DISCUSSION

Infiltration of ventilation air and air mixing

The local mean age of air in the two zone measurement described in Figure 1a) is shown in Figure 2. Using two different tracer gases effectively labels the time each air volume element spends in each of the two regions. The ratio between the times spent in region B and A is approximately 0.29 and is virtually the same in all measuring positions. This indicates that the mixing of the air volume in the church is good and there are no stagnation points. Theoretically, the ratio in a fully mixed system should be the same as the ration between the volumes 2500/7000=0.36, but the volume estimates are quite rough. The fact that the temperature at the roof level never is 0.5 to 1 °C warmer than the floor level also indicates a well mixed air volume.

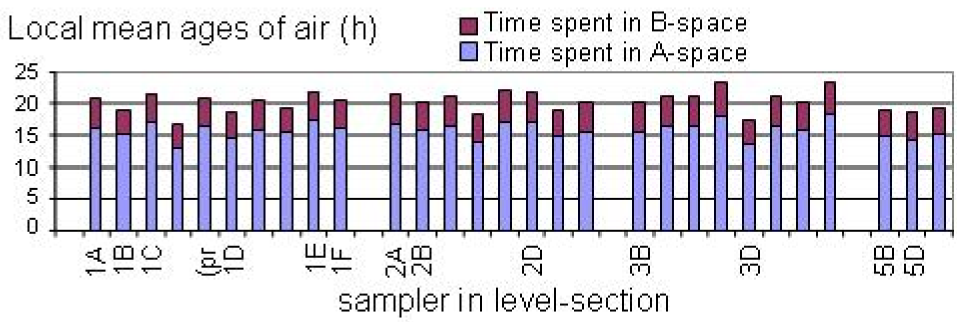


Figure 2. Local mean ages of air at different positions in the church. The upper and lower parts of the bars indicate the time air has spent in the upper and lower part of the church respectively.

The average total air flow rate of infiltrated ventilation air and temperatures for each measurement period is presented in figure 3. The close correlation between flow rate and the difference between the outdoor and the indoor temperatures indicates that the temperature difference is the main driving force for the rate of infiltrated air. The corresponding mean ages of air for the measurement periods are 12.7, 20.7, 34.4 and 39.5 h, respectively. These can also be interpreted as the response time until a new steady state is established in the ventilation system.

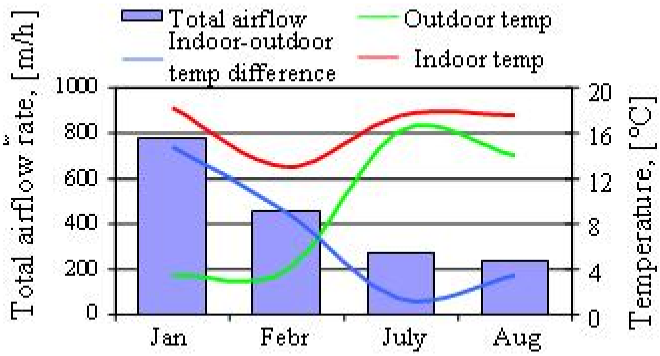


Figure 3. The total infiltration rate of ventilation air (bars) and temperatures (lines: outdoor green, indoor red, and outdoor-indoor blue) in each of the measurement periods.

Temperature and relative humidity

The average inside and outside temperatures and RHs are presented in Figure 4. RH is too low in January and too high in June-September for the recommended preservation conditions. In August-September RH exceeds 70 % that may promote microbial growth. These high levels of RH in June-Sept correspond well with the previous measurements of Kalamees and Sasi (2008) in a similar medieval church.

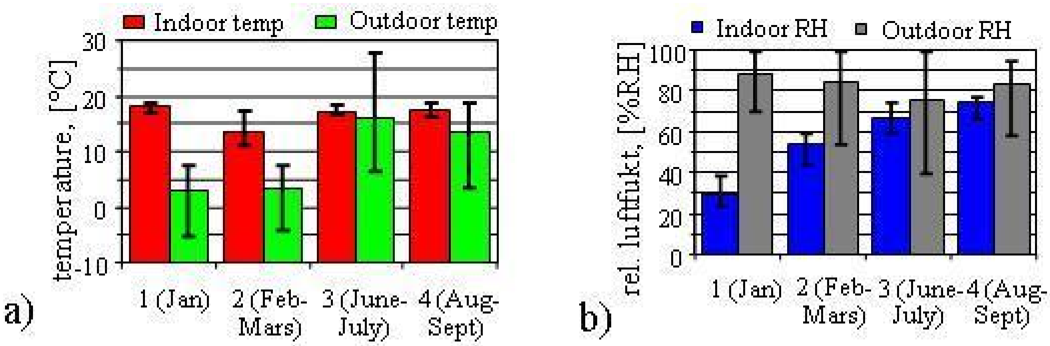


Figure 4. a) Average temperatures inside (red) and outside (green) b) Average relative humidity inside (blue) and outside (grey). Error bars indicate max-min values in each measurement period.

Simulation of door openings

When the entrance doors are held open, the outside air enters the church room along the floor in a quite narrow plume whose effect is lost approximately 10-15 m into the church room. In the upper part of the inner entrance doorway old air flows out from the church. The stagnation point is located approximately at 2/3 of the doorway height. A smoke probe indicates that the wind speed is 0.5 and 0.2 m/s in the lower and upper levels of the doorway. When the door is open, there is a net flow of air into the church through the doorway. A corresponding amount of air the presumably leaves the church via leaks in the building envelope. When the doors are closed the effect quickly disappears. The estimated flow through the door is only 6 % of the total infiltration of air through leaks and is therefore of minor importance.

CONCLUSIONS

We have shown that the air volume in the church is well mixed throughout the year. All calculations for installations must therefore consider the total air volume of the church. The RH becomes too low for preservation of artefacts when the temperature is raised during the heating season. On the other hand RH becomes too high during summer and fall. Modifying the RH will be an important issue during the planning process of a new installation. The infiltration rate of ventilation air through leaks in the building envelope greatly exceeds the air flow rate through an open entrance door.

ACKNOWLEDGEMENT

Skara Pastorate is gratefully acknowledged for assistance and for financing the investigation.

REFERENCES

Etheridge, D ; Sandberg, M. 1996. ”Building Ventilation Theory and Measurement”. John Wiley

Kalamees, T., Sasi, L. 2008. Indoor Air 2008, 17-22 August 2008, Copenhagen, Denmark - Paper ID: 816

NORDTEST (1997). “Ventilation: Local mean age of air – homogeneous emission technique”. Nordtest Method: NT VVS 118, Nordtest Finland.

Schellen, H.L. 2002. Heating Monumental Churches. Indoor Climate and Preservation of Cultural Heritage. Technische Universiteit Eindhoven, 228 pp.

Stymne H, Boman CA, 1994. "Measurement of ventilation and air distribution using the homogeneous emission technique - a validation". Healthy Buildings '94, Proc. of the 3rd International Conference, **vol. 2**, pp 539-544, Budapest, Hungary 1994.