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THE INFLUENCE OF AIR EXCHANGE ON THE STABILITY OF THE INDOOR CLIMATE IN SKOKLOSTER CASTLE

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Abstract

Skokloster Castle is a historic masonry building without any active climate control and hosting an important and heterogeneous collection of artefacts. Despite being cited as a good passive preservation environment, conservators are observing decay in the collections related to the indoor climate that may call for a re-evaluation of the climate control strategy.

Air exchange is generally considered one of the driving forces influencing the indoor climate in unheated historic buildings. This study was developed to better understand and evaluate its influence on the indoor climate stability of the castle. The present study has outlined an experimental procedure for the assessment of the influence of air exchange that can be used in historic buildings in general.

Air exchange rate was measured in seven rooms using tracer gas passive sampling. The results were related to an analysis of the variability of indoor temperature (T), relative humidity (RH) and mixing ratio (MR). A connection with short-term RH fluctuations, considered the most dangerous for hygroscopic materials, was identified. Problems connected with mould growth and high RH levels were also considered and discussed.

1   Introduction

Skokloster castle, located north of Stockholm, is a heavy stone and brick building, completed in 1676 hosting an important and heterogeneous collection of artworks and objects (Fig. 1). The building envelope is characterized by masonry walls and lead glass windows with limited air tightness. An inner corridor, which is in direct connection with outdoor air through the staircases, connects the rooms. The building is open to visitors from May to September. There is no active climate control system, with the exception of a few rooms on the bottom floor used for offices. The factors influencing the indoor climate of the castle are the heat and moisture transfer through the envelope, the hygrothermal inertia of the structure and of the interiors and solar radiation and wind.

Despite being cited as a good passive preservation environment, conservators are now observing decay to the collections related to the indoor climate that may call for a re-evaluation of the climate control strategy. The main problem is related to reoccurring mould growth in some rooms. A recent condition survey of easel paintings has also showed considerable mechanical damage that has been associated with levels and variations of RH. Gotland University has been monitoring the indoor climate of the castle since 2009 in order to get a better understanding of the present indoor climate and what needs to be done about it.

A general survey of the indoor environmental conditions of the castle was made by Broström and Leijonhufvud.[1] The results showed that the yearly T range in the rooms was between -7.4 °C and 29 °C inside, between -15 °C

Figure 1: View of the castle.

and 35 °C outside. Annual RH average of all rooms was 70%, 9% lower than outside. RH variations detected inside the castle were reduced when compared to the outdoor climate. For all rooms, the average seasonal variation inside was 48% as compared to 85% outside; the minimum values of RH detected in the rooms were in the range of 33 to 56%, while the maximum values were in the range of 87 to 97% (Figs. 2 and 3). There were considerable differences among the rooms in terms of short term variations affecting hygroscopic materials. Air exchange was identified as one of the main factors determining this situation. A reduction of the air exchange rate was suggested as a strategy to limit RH fluctuations. On the other hand, one of the main problems affecting the collections was related to high indoor RH levels, leading to mould growth in some rooms, as described by Bjurman and Leijonhufvud.[2]

The present paper will therefore analyse the general effect of air exchange on the hygrothermal parameters inside the building focusing on its influence on the stability of the indoor climate and trying to understand whether an improvement of the air tightness of the building envelope could be beneficial without increasing the mould risk.
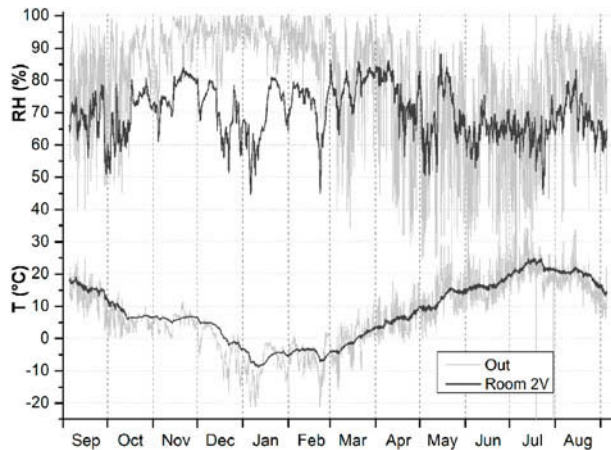

Figure 2: Yearly trends of RH (%) and T(°C) in Room 2V (dark grey) compared to outdoors (light grey).
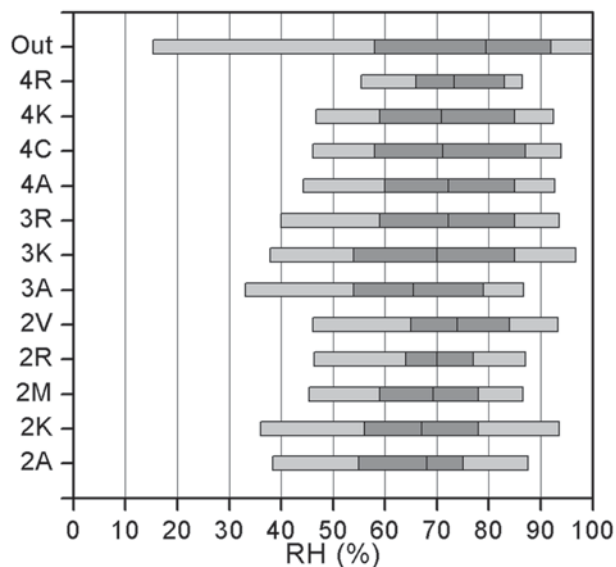

Figure 3: RH in twelve selected rooms: seasonal range (light grey), range of a 30-day moving average (dark grey). The line in the middle of each bar is the seasonal average.

2 Materials and methods

2.1 Indoor climate measurements

The study is based on data collected in Skokloster Castle by previous research projects and analyses performed by Gotland University.[1] The monitoring campaign was carried out from the 15th of June 2008 to the 9th of September 2010 in 25 different rooms outspread on different floors and in different directions. 45 data loggers of the type TinyTag plus2 were used during the campaign. Temperature (T) and relative humidity (RH) data for the whole year were obtained by the monitoring campaign. The corresponding mixing ratio (MR) was then calculated.

2.2 Measurement of the air exchange rate

The air exchange rate was expressed as Air Changes per Hour (ACH). Measurements were made following the Nordtest Method standard NT VVS 188:1997:[3] homogeneous emission of tracer gas was used to measure the local mean age of air, utilising passive tracer gas sources and diffusive samplers. The measurement is based on the fact that the local steady concentration of a contaminant distributed with equal source strength in all parts of the space will attain a value which is proportional both to the local mean age of the air and the contaminant source strength per volume. The inverse of the local mean age of the air in a zone is defined as the 'room-specific ventilation flow rate' or 'local air change rate'. In naturally ventilated environments, this parameter, expressed as ACH, can be considered the equivalent of the specific ventilation flow rate, usually used for the ventilated system as a whole to express the flow rate of outside air entering into a ventilated room, divided by the volume of the ventilated room.

Measurements were made according to the following schedule:
Autumn: from 2009-10-10 to 2009-11-23 – 44 days.
Winter: from 2010-01-21 to 2010-03-04 – 42 days.
Spring: from 2010-04-21 to 2010-05-27 – 36 days.
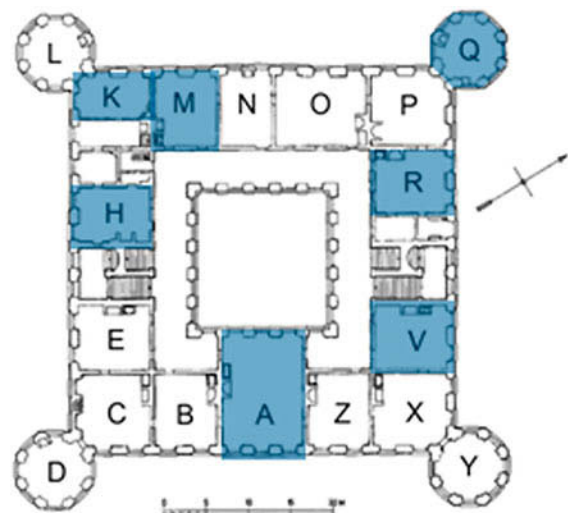Summer: from 2010-07-14 to 2010-08-23 – 40 days.

Figure 4: Plan of the first floor of Skokloster Castle. The analysed rooms are highlighted.

On the basis of the results obtained, seven rooms on the second level (first floor) of the castle were selected and investigated during this study (Fig. 4).

2.3   Procedure to evaluate the influence of air exchange on fluctuations

In order to evaluate the effect of the air exchange rate, expressed as the average ACH in the surveyed periods, it was necessary to find a comparable indicator for temperature, relative humidity and the mixing ratio in the same seasonal periods. The standard deviation (σ), was chosen as a proper indicator of the general variability of the parameters in a given period of time. In the seven selected rooms, standard deviation of T, RH and MR was thus calculated for the same period for which the corresponding average ACH was determined.

Graphs comparing ACH and σ of T, RH and MR in the same seasonal periods were plotted to see if it was possible to find a correlation between those values, according to the following hypothesis:

$\sigma_n(T) = f_T(ACH_n)$
$\sigma_n(RH,) = f_{RH}(ACH_n)$
$\sigma_n(MR) = f_{MR}(ACH_n)$

where **n** is the number of days on which both σ and average **ACH** are calculated. The first results have suggested to focus this type of analysis on mixing ratio, since it is not dependent on temperature and, compared to temperature and relative humidity, it is the parameter less influenced by solar radiation, heat gains or thermal properties of the walls. It is thus considered a good indicator to detect air movements in indoor environments.[4]

The next step was to focus the analysis on relative humidity, given its importance for the conservation of hygroscopic materials. In this case we have to find a valid method to distinguish seasonal variations from short-term fluctuations, which were supposed to be more related to air exchange and, at the same time, potentially risky for hygroscopic materials. The EN 15757:2010 standard[5] suggests a procedure to identify RH short-term variations by the calculation of the difference between the current value and a central 30-day moving average value, considering the values surveyed in the fifteen days before and in the fifteen days

after (Fig. 5). A RH fluctuation from the seasonal average is considered outside the safe range when its magnitude is more than 1.5 the standard deviation calculated over 13 months.

In this study the method was adapted to analyze the influence of air exchange on indoor climate fluctuations. The difference between each surveyed value and the corresponding 30-day moving average value was calculated, while standard deviation of the differences was calculated on the same period of days on which air exchange measurements were performed.

In order to show to what extent outdoor fluctuations were transmitted to and/or buffered in the indoor environment a specific parameter was created, the Climate Fluctuations Transmittance (CFT). It expresses the ratio between the standard deviation of the indoor fluctuations and the standard deviation of the outdoor fluctuations:

$$CFT_{n1} = \sigma_{n1}(X_{in} - MA_{n2} \cdot X_{in}) / \sigma_{n1}(X_{out} - MA_{n2} \cdot X_{out})$$

where σ is the standard deviation, **MA** is the moving average, X_{in} are the indoor values (T or RH or MR), X_{out} are the outdoor values (T or RH or MR), **n1** is the number of days for which σ is calculated (36-44 days in ACH measurements) and **n2** is the number of days for which **MA** is calculated (30 days following the EN15757 standard).

As in the procedure to evaluate the general influence of air exchange rate on hygrothermal parameters, CFT was plotted with ACH in order to find a correlation:

$CFT_n(T) = f_T(ACH_n)$
$CFT_n(RH) = f_{RH}(ACH_n)$
$CFT_n(MR) = f_{MR}(ACH_n)$

where **n** is the number of days on which both average **ACH** and σ in the **CFT** are calculated. Given the importance of RH fluctuations for the conservation of hygroscopic materials, results regarding CFT will be presented for relative humidity only, but the method (as well as the EN15757 procedure) can also be applied to the other parameters, i.e. temperature and mixing ratio.

Linear regression was carried out and the Pearson's correlation coefficient (r) was calculated: the closer the value is to 1, the stronger the correlation.

3   Results and discussion

3.1   General influence of air exchange on hygrothermal parameters

The air exchange in the analyzed rooms generally ranges from 0.2 to 0.9 ACH, depending on the location of the room and the time of the year (Fig. 6). Higher values were detected in the corridor (1-2 ACH) and sometimes in the towers and corner rooms that are more exposed to outdoors.

Nevertheless it must be underlined that values detected do not represent exclusively air infiltration from outdoors but also air movements between the rooms. This bias is introduced by the method chosen for the tracer gas tests: with the single-gas sampling technique, not only the air exchange between outdoor cli-
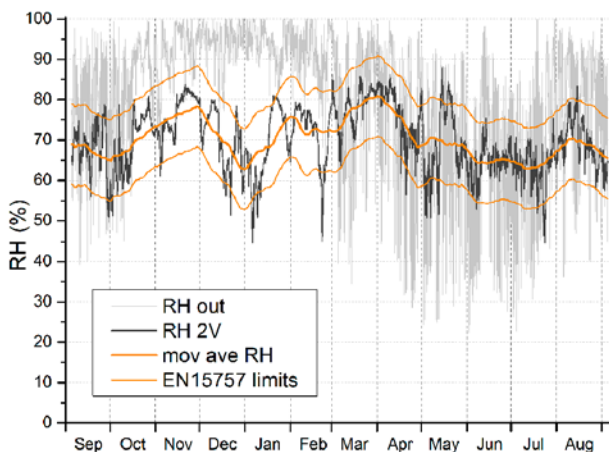

Figure 5: Yearly graph of RH in room 2V (dark grey). The RH monthly moving average (thick orange line) and the safe RH range according to the EN15757 standard are also included.
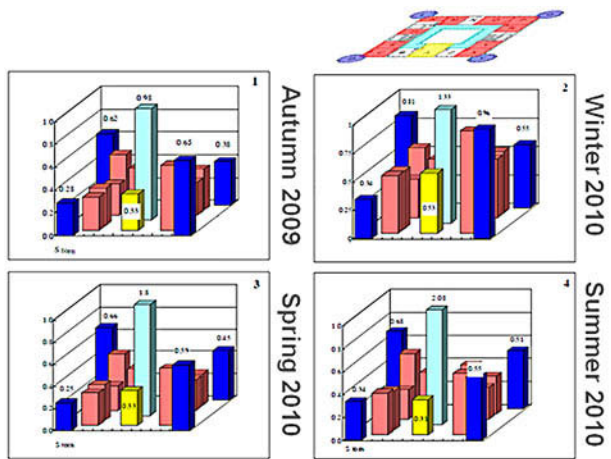
Figure 6: Air exchange measurements expressed as ACH in first floor rooms in different seasons. The towers (blue) and the corridor (cyan) have the highest values.
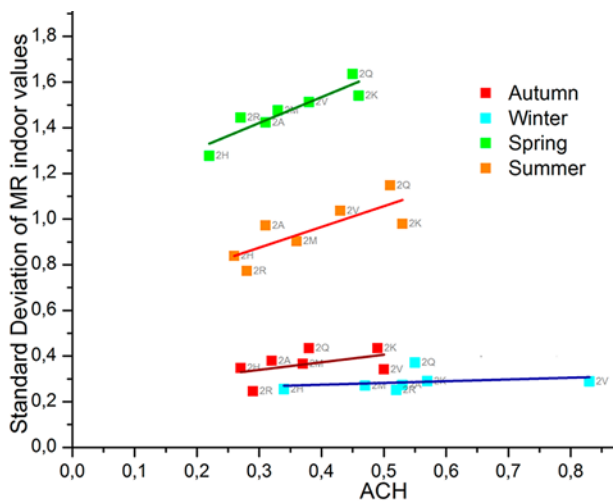

Figure 7: Standard deviation of indoor MR as a function of ACH in different seasons. Different seasonal patterns are highlighted. Air exchange seems to have an higher influence on MR variations in spring and summer (r = 0.91 and 0.79, respectively) than in autumn or winter (r = 0.47 and 0.28, respectively).
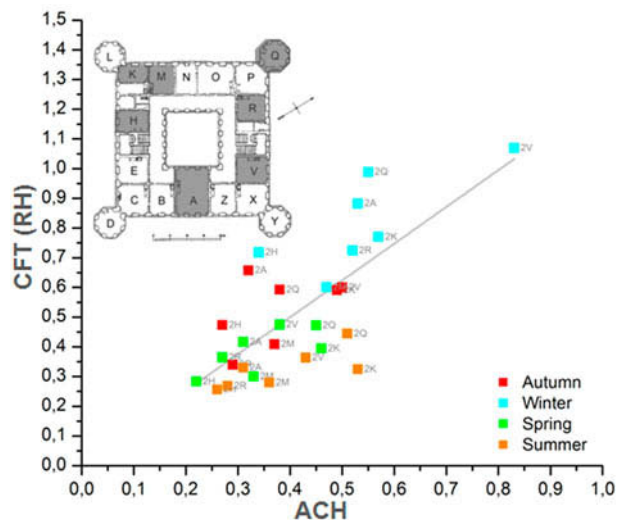

Figure 8: CFT of RH as a function of ACH. Different seasons are highlighted. Linear regression is used to show the correlation coefficient considering all the values for the whole year (r = 0.73).
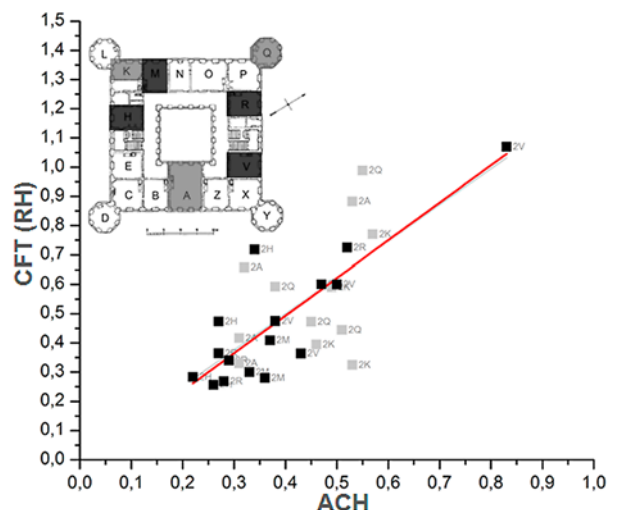

Figure 9: CFT of RH as a function of ACH. Linear regression is used to show the correlation coefficient considering the values of the four most similar rooms for the whole year (r = 0.86).
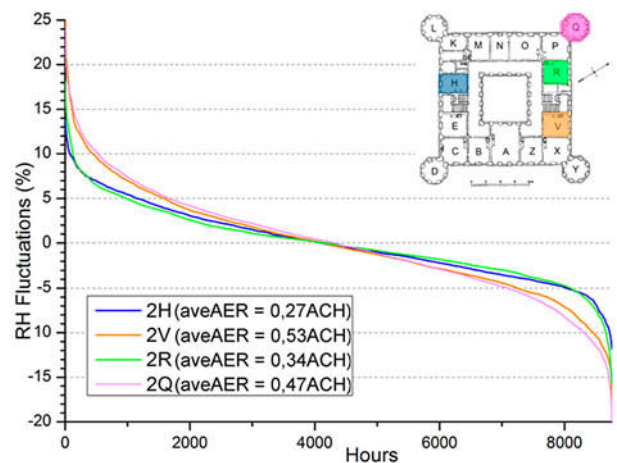
Figure 10: The duration graph is a cumulative presentation of RH levels in rooms 2H, 2Q, 2R and 2V. A flatter curve indicates a more stable climate.

mate and indoor climate is measured, but also the air exchange between the various rooms of the buildings (e.g. the round corridor). A double-sampling technique could be helpful in solving this problem by distinguishing the indoor air circulation from air leakage or infiltration through the envelope.

The graph comparing ACH values with MR variations, expressed as standard deviation, highlights different seasonal patterns (Fig. 7). Autumn and winter values have flatter trends while similar ACH values correspond to larger variations in spring and summer. The strongest correlation was found in spring (r = 0.91). In summer we have a good correlation as well (0.79) while it seems poorer in autumn and winter (r = 0.47 and 0.28, respectively). On the one hand this should be due to seasonal differences in the magnitude of MR. On the other hand the results could also be influenced by the fact that in spring and summer the castle is open to visitors and windows are more likely to be opened. As a consequence, the amount of outdoor air on the total exchanged air should be higher and this could result in a stronger influence of air exchange on MR variations in summer and spring, although the

amount of air changes per hours is generally similar to the autumn and winter one.

3.2 Influence of air exchange on RH fluctuations

In Fig. 8 the climate fluctuations transmittance of RH was plotted as a function of ACH. In this case seasonal patterns are not so evident and a strong correlation (r > 0.7) can be found between the CFT of RH and the air exchange. This indicates that in Skokloster Castle, regardless of seasonal trends and the position and orientation of the rooms, RH short-term fluctuations are directly connected to air exchange. A higher air exchange rate is therefore expected to cause a higher level of fluctuations and, as a consequence, a potential higher risk for the hygroscopic materials in the collections. If we consider only the rooms with similar characteristics, such as shape, dimensions, ratio between volume and surface exposed outdoors (Fig. 9) there is an even stronger correlation. For all the seven analysed rooms during the four seasons, the Pearson correlation coefficient was 0.73. The same coefficient calculated on four more similar rooms was 0.86. This would suggest that, despite other factors have an influence on RH fluctuations (e.g. temperature variations or moisture transfers), the Climate Fluctuations Transmittance can give good results if used as an indicator in order to evaluate the influence of air exchange on RH fluctuations in different indoor environments.

The results obtained are confirmed by duration curves, as shown in Fig. 10. Yearly indoor values of RH fluctuations in four rooms with different ACH, different shape and different orientation, were plotted in a cumulative graph. The two rooms with a lower air exchange rate (i.e. 2H and 2R) show flatter curves and lower peaks if compared with the two rooms with higher air exchange rate (i.e. 2V and 2Q), indicating a higher stability of RH levels.

With regard to the observed influence of strong wind in RH drops or peaks, wind speed was measured and its variations were compared with RH indoor trends in some rooms in order to find some connections, but results are still not significant and a deeper analysis is probably needed to obtain a better comprehension of this issue.

3.3 Expected influence of a reduction of air exchange on mould growth and on RH high levels

It is common to associate low air exchange rates with moisture problems. However, it is not necessarily so. In environments like the analysed rooms of Skokloster castle, where there are no internal moisture sources, the difference between indoor and outdoor MR is generally small throughout the year. Thus mould risk would depend on differences in T and RH over the short term. A previous study showed that a key factor for mould risk seems to be the temperature levels in the rooms.[2] As a consequence, north-facing rooms (2R, 2V) with less solar gain, have lower T and higher RH. This results in a higher mould growth risk and there have been mould problems indeed in both the
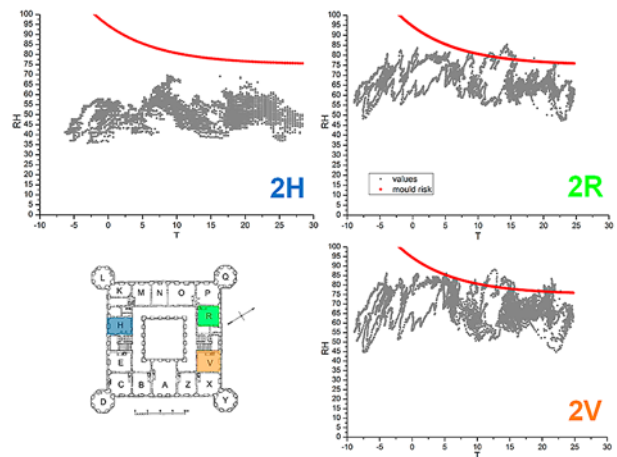

Figure 11: Mould growth risk evaluation in rooms 2H, 2R, 2V. Values above the red line may result in mould growth.
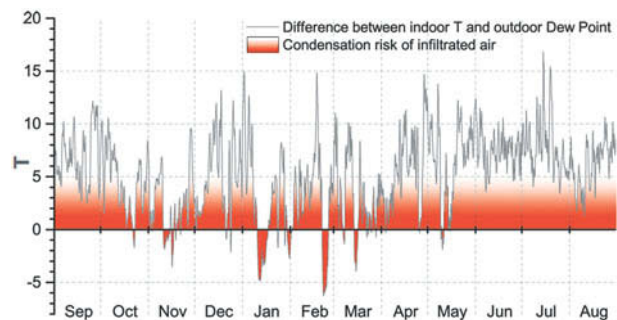

Figure 12: Difference between outdoor dew point and indoor temperature in room 2V. Values close to or below 0 °C have to be considered risky if outdoor air infiltrates into the room.

rooms, regardless of the different RH stability and ACH shown in Fig.10.

Sedlbauer isopleths[6] were used to describe the mould risk in the rooms (Fig. 11). Values above the red line can result in mould growth if given time long enough. Room 2H has the lowest air exchange rate and has no mould growth risk, while room 2V has the highest air exchange rate and a significant mould growth risk. Room 2R has a low air exchange rate and at the same time quite a high risk. A correlation between air exchange and mould growth risk is thus not implied but it can be claimed that in analysed rooms a lower air exchange rate does not necessarily result in a higher mould growth risk.

With high humidity levels outdoors and low temperatures indoors, the outdoor dew point can fall below the indoor temperature, which would mean a potential risk of condensation of outdoor air entering the rooms (since the rooms are unheated surface temperatures are generally in equilibrium with air temperatures). In such a situation, a lower air exchange rate could reduce the risk. Fig. 12 shows the difference between the indoor T in room 2V and the outdoor dew point.

Anyway, the current strategy of passive climate control is not sufficient to keep RH below dangerous levels in rooms in the north part of the building and an active intervention is probably required. A comparative experimentation of different climate control strategies (dehumidification, conservation heating or adaptive ventilation) is currently going on in some rooms to

establish the more effective and energy-efficient method to reduce the mould growth risk.

4   Conclusions

The study has assessed the effect of air exchange on the hygrothermal parameters inside the building focusing on its influence on the stability of the indoor climate and trying to understand whether an improvement of the air tightness of the building envelope could be beneficial without increasing the mould risk. A specific method was developed and a new parameter, called Climate Fluctuations Transmittance, was proposed.

Based on measurements from Skokloster castle, the present investigation has shown that a reduction of the air exchange rate can provide a more stable indoor climate. A correlation between air exchange and RH short-term fluctuations was found, indicating that a reduction of the air exchange rate could be an effective strategy to lower the risk for mechanical damage on hygroscopic materials.

It is generally thought that an improvement of air tightness can cause a higher mould growth risk. However, this study shows that in a building like Skokloster Castle, with no internal moisture sources, this is not necessarily true. Nevertheless, passive control is probably not enough to lower dangerous RH levels in rooms in the north part of the building and active control is probably necessary.

The Climate Fluctuations Transmittance has proved to be effective for the purposes of this study. Results could be improved by a deliberately selected dataset, based on the most suitable rooms and on the most significant periods to be analysed. Having the same 30-day period of ACH measurements for each season would make the data more coherent and fully corresponding with the calculated moving average

In conclusion, the method proposed in this study through the use of the Climate Fluctuations Transmittance parameter can be used as a general procedure to assess the influence of air exchange in unheated historic buildings. Nevertheless further applications to other case studies are needed to validate the method.

5   Acknowledgements

6   References

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