Climate control in Danish churches

Poul Klenz Larsen

Abstract

The climate control in Danish churches is a compromise between the demand for human comfort and the need for preservation. Most medieval churches are heated in winter and left unheated in summer. The consequence of this heating practice is large variations in the relative humidity. To control the relative humidity within reasonable limits, the churches should be heated all year, and the temperature should be adjusted to an annual cycle. A moderate relative humidity can also be achieved by mechanical dehumidification, but the effect will sometimes be spoiled by evaporation of water vapour from an internal source. Some churches have the ability to humidify the indoor climate by capillary migration of moisture through the structure. Such processes must be accounted for when devising the heating strategy for a particular church. Further investigation is needed to locate the source of the passive humidification. The conflicting interests of congregation and conservation can sometimes be solved with transparent walls or glass doors to define specific climate zones with independent climate control.

Figure 1. Climate control in Danish churches is a compromise between conflicting interests and sometimes calls for unconventional solutions.

Introduction

Danish medieval churches contain a variety of polychrome wooden sculpture and wall paintings. Many items have survived centuries of neglect due to natural disasters, epidemic diseases or religious changes, so it seems to be a fairly safe place for valuable pieces of religious art. In our days, the main worry is not warfare or the plague. A risk assessment analysis would identify the indoor climate as the main threat to the preservation of these objects. Conventional museum and archive set points for temperature and relative humidity are not much help when specifying the appropriate climate for Danish churches. The history and the condition of the objects must be taken into consideration when proposing a climate strategy for each individual church. The problems arise from the fundamental fact that the priest is sensitive to temperature, whereas the altarpiece responds mainly to the relative humidity. Wall paintings are susceptible to damage by precipitation of salts, which depends on variations in both temperature and relative humidity. The organs go out of tune and the organist catches a cold if the temperature is not constant. Heating has a major influence on the relative humidity, so the demand for thermal comfort does not provide healthy conditions for preservation. It is a delicate job to devise heating strategies that will satisfy both conservation and congregation. This paper presents a summary of the considerations reported by other authors followed by a few case studies where unconventional solutions are tested, as a compromise between the conflicting interests.

Background

The first permanent heating installations in Danish churches were stoves of cast iron. We don't have any climate records from those days, but the soot was a problem for the conservation of wall paintings. Central heating systems were introduced from the beginning of the 20th century, providing a much cleaner and drier indoor environment. Warm air systems were preferred for village churches heated intermittently. The advantage was a fast rise of temperature, but they were less suited for tall rooms.

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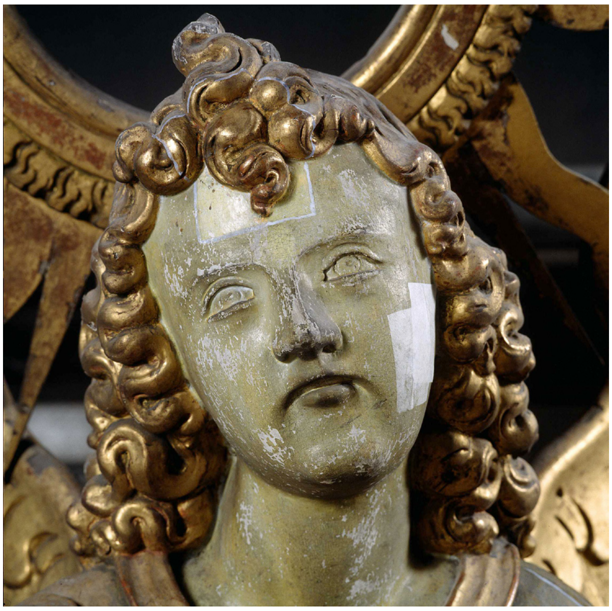

Figure 2. Detail of the altarpiece in Sct. Olai Church in Helsingør. The paint has cracked and partly delaminated due to variations in relative humidity caused by constant heating. Photo by Roberto Fortuna, the National Museum of Denmark.

Most of the heat concentrated below the ceiling, where only the angels would benefit, and left the humans cold at floor level. Lund Madsen [1] used a thermal mannequin to measure the influence of different heating systems on the thermal experience. Electric radiant heating panels mounted under the bench seats provided the best thermal comfort at a moderate air temperature. This work led to the design of a pew with integrated heating foils at the back and under the seat.

Camuffo [2] introduced the Friendly Heating concept, which involved a novel pew design with radiant heating elements mounted under the seat, at the back and below the kneeling rail. A detailed study was conducted by Limpens-Neilen [3] with focus on the convective air movements in the pew and the consequence for thermal comfort. It is possible to heat the person without heating the building, but there is a limit to how much radiant heat a person can endure in a cold building and still be comfortable. The main drawback for all kinds of pew heating is that it only heats up the congregation. The chancel and other adjacent spaces must be heated by conventional heating systems.

Korsgaard [4] established the heating regulation for Danish churches and defined two climatic categories for churches: the permanently heated and the intermittently heated. The larger urban churches with frequent services belong to the first category, for which the basic temperature should be no more than 15°C in winter. The small village churches with only a Sunday service make up the second category, where 8°C is the set point for the basic temperature. The threshold values are chosen as a compromise between the need to save energy and the need for human comfort. In both categories the maximum temperature for services is 18°C, which should be reached within 6 hours starting from the basic temperature. The demand for rapid heating was a precaution suggested by Künzel and Holz [5] to protect wooden objects. If the rise and fall in temperature were fast, the objects would not feel the change in RH before it was over. Several later authors have disproved this assumption. For both climate categories, the regulation states that the relative humidity should be between 50% and 80% all year round. These rather broad limits are a compromise to reduce biological activity and to prevent mechanical damage caused by drying shrinkage.

Mecklenburg et al. [6] proposed the interval 40% - 70% RH to be safe for most wood species, glues, paints and grounds, but the interval was much reduced if the object had equilibrated to a higher RH. Their investigations did not give any information regarding the influence of time on the stress induced by changes in the RH. Bratasz & Koslowski [7] reported a rapid response to changing RH of the shrinkage of wooden objects. According to their measurements on polychrome wooden sculpture in situ in Eglise Rocco del Pietro, even diurnal variations affect the surface layers and lead to cracking. Their work was only concerned with the mechanical damage to the wood itself, but the

Figure 3. Detail of the wall paintings in Rorby church near Kalundborg. The paintings deteriorated by the precipitation of salts due to diurnal fluctuations in the relative humidity caused by intermittent heating. Photo by Roberto Fortuna, the National Museum of Denmark.

paint layers on the surface are the more vulnerable. Olstad, Haugen and Nilsen [8] investigated the effect of climate variations on test specimens of polychrome wood in a micro scale. They found that small and rapid changes in both RH and temperature caused damage and proposed a maximum change of 10% RH to be safe. The influence of short heating events required by the Danish heating regulations remains a subject for further investigations.

Wall painting is an integrated part of the building and will therefore experience a different climate than the objects within the church, because of the temperature gradient between the wall surface and the room. A study by Padfield et. al. [9] in Gundsømagle Church showed that the influence of intermittent heating was reduced significantly because of the thermal inertia of the limestone walls, so the RH at the surface remained almost constant. But the falling RH in the church caused evaporation of water vapour from the surface. Investigations in Tirsted Church by Klenz Larsen [10] indicated that a perpetual moisture migration towards the inside surface is a hazard to wall paintings, because salts accumulate at the surface. The paintings in the chancel suffered severe salt damage because of permanent low RH in the winter, caused by the heating. A further complication was the composition of the salt contamination in the plaster. Salt would precipitate from solution at any RH in the range 30% to 70 %, which coincided with the natural climatic variation in the church. Recent work by Sawdy & Heritage [11] concludes that salt mixtures are more sensitive to fast and large variations in RH than to slow and small variations. This result is supported by a study by Klenz Larsen [12] of wall paintings located in the vaults in Fanefjord church. The drop in RH caused by diurnal heating episodes led to the precipitation of salt at the surface and the deterioration of the paintings. A similar situation was studied in Rørby church [13], where a climate chamber was built to protect the vault against climate variations; it prevented salt deterioration. The safe RH-range for salt contaminated wall paintings depends on the salt species and should be defined in each individual case.

The geometry of the interior, the structure and materials of the building should be taken into consideration. Unlike most modern buildings, the churches have great thermal inertia, which will level out diurnal variations in temperature. The few and small windows allow little solar heating in summer but also reduce heat loss in winter. The natural stability of the relative humidity depends on the ventilation rate and may be overruled by too much infiltration of outside air. Brostrøm [14] developed a mathematical model for the hygrothermal behaviour of a stone church. The model would enable calculation of the heating power and the heating time required, when designing a new heating installation. Brostrøm also suggested various models for calculating the influence on the indoor RH from water vapour evaporating from the walls. Studies by Schellen [15] have demonstrated good agreement between computer simulations and measurements in Dutch churches. The question is, can computer programs designed for modelling indoor climate in modern buildings be relied upon to predict the consequence of preventive interventions in medieval churches.

Case studies

The Gothic cathedral of Sct. Olai in Helsingør is a large brick masonry structure with a magnificent baroque altarpiece. The last restoration was undertaken in 1967, but 30 year later the gilding and paint was cracking and peeling. It was essential to improve the climatic conditions in the church, which was at that time permanently heated by a central heating system with large cast iron radiators. The temperature was around 20°C all year round, and the RH drifted from 80% in summer to 20% in winter. This variation is a natural consequence of the annual fluctuation in the water vapour content of the outside air. If the ventilation rate is large, and the internal moisture supply is small, the indoor water vapour concentration (the absolute humidity) will be the same as outside. To reduce the drying in winter, the average temperature should not be more than 15°C. But this was not acceptable, partly because of cold draughts below the large windows and in the central nave. Floor heating was established to maintain thermal comfort at a reduced temperature. The large windows had double glazing installed to prevent convective air movements and to reduce the natural ventilation. This intervention

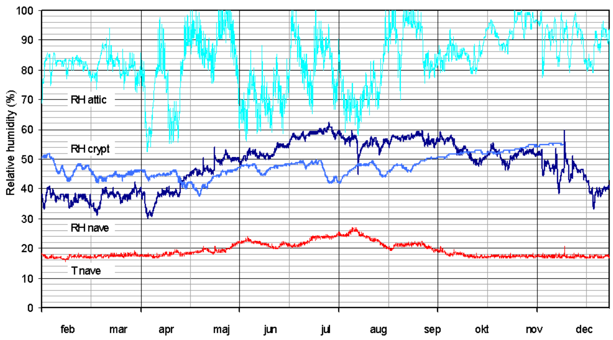

Figure 4. Climate records from Sct. Olai Church in Helsingør in 2003. The climate was measured in the nave, the crypt and the attic. The temperature in the attic and in the crypt is not displayed.

Figure 5. Detail of the windows in Sct. Olai church. The framing for the double glazing was custom designed to fit the original leaded windows. Photo by Poul Klenz Larsen

is usually not allowed for architectural reason, so a custom designed frame was fitted inside the original windows. These changes have improved the climate in the church, so the annual average variation in RH is limited to 30%-60% with little diurnal fluctuation. An unexpected complication occurred during construction work, when numerous crypts with wooden coffins were found below the old floor. The mummified bodies wearing fine clothes were in quite good condition, so their microclimate had been congenial for centuries. We were worried about how the new floor heating would influence

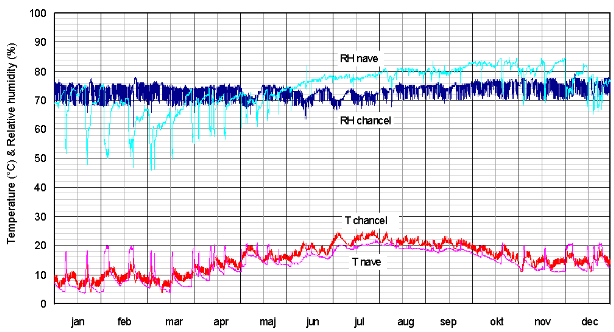

Figure 6. Climate records from the nave and the chancel in Dybe Church on the west coast of Jutland. The RH in the nave is regulated by hygrostat controlled heating.

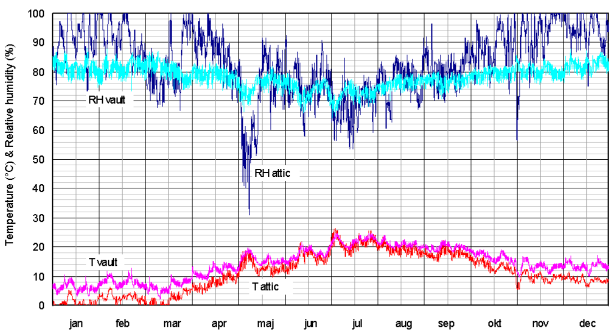

Figure 7. Climate records from the attic and the vault surface in Dybe Church. The RH at the surface of the chancel vault is not as constant as in the chancel itself, because the surface temperature is influenced by the temperature variations in the attic.

their preservation, and arranged a series of vertical pipes installed in the concrete slab. The pipes would allow monitoring and eventually ventilation if necessary. However, it was reassuring to learn that the climate below the floor was much more stable than above, with an annual drift in RH from 40% to 55 %. No doubt the golden altarpiece would have been better preserved in an underground dungeon. The attic, on the other hand, would be a bad place to store wooden objects, because the RH is too high and too unstable.

Dybe church is located at the west coast of Jutland, close to the North Sea, where the natural airborne deposition of sea salt is large. The decoration of the chancel vault suffered severe damage due to sodium chloride, which may have been brought in as aerosol from the nearby sea during the church's 800 year lifetime. For centuries the salt had remained in solution due to a permanent high relative humidity in the unheated building. But when a new electric heating system was installed, the deterioration of the wall paintings progressed rapidly. The heating caused the RH to drop below 75% in the winter, so the salt would precipitate and disrupt the paintings in the vault. The salt contamination of the individual bricks was too severe to be treated from the surface.

Figure 8. View through the glass door in the chancel arch at Dybe church. The lime painting in the vault is visible in the chancel. The heating elements on the wall below the vault are controlled by a hygrostat to keep the RH at 70-80% all year. Photo by Roberto Fortuna, the National Museum of Denmark.

Figure 9. View through the transparent wall into the chapel in Ølsemagle church. Fragments of the wall paintings are visible on the wall and in the vault. The chancel is unheated, so a cool and humid climate is maintained all year, except for special occasions when the glass door is opened. Photo by Roberto Fortuna, the National Museum of Denmark.

It was decided to restore the paintings and prevent further decay by climate control. A glass door was installed to separate the chancel from the nave. The door would remain closed at all times, except for the services, when it was opened for one hour. The climate in the chancel was regulated with the help of a hygrostat, turning on a little heat to keep the RH in the range 70% - 80%. One should be aware that the RH measured inside the chancel is not the same as the climate at the surface of the vault. In winter the RH is higher at the surface because the temperature is slightly lower, but in summer the RH is a little lower because the attic is heated by sun radiation. But the RH is still much more stable than in the nave, which is heated at irregular intervals over the winter. This simple installation has now worked for 3 years and no damage has been observed.

A similar solution was adapted for Ølsemagle church in Zealand. The congregation wanted to use a former chapel on the north side of the nave for extra seats on special occasions. The extension had been used as a tool shed for many years, unheated, with a stable but humid indoor climate all year. The walls and the vault had well preserved fragments of wall paintings, which would possibly deteriorate in a warmer and dryer indoor environment. There are many reports about lime paintings suddenly flaking due to a change in the heating practice. In some cases the installation of new heating systems has even led to the rediscovery of wall paintings which had been covered for centuries by thick layers of lime wash. The paintings were revealed because the lime wash lost adhesion when the structure dried out due to the improvement in heating capacity. The conservator demanded as little change in the climate as possible, so a transparent glass wall was installed in the arch, with a door to open for the Christmas ceremony. On ordinary days the chapel is not accessible. No heating was installed, but the heat transmission from the nave keeps a slightly higher temperature than before, with an average RH at 80%.

The small village church in Karlslunde south of Copenhagen has a Romanesque nave and apse made of a soft limestone. The main attraction is a baroque altarpiece, which had suffered severe damage due to drying shrinkage. After conservation, the congregation had a dehumidifier permanently installed to keep a constant indoor RH all year round. The altarpiece itself had been equilibrated to 50% RH during a prolonged visit to the conservation workshop. The climate records showed that the RH in the church was around 50% all year. In summer the indoor air was drier than the outside air, due to the influence of the dehumidifier. But in winter, the inside air was more humid than outside, even though the dehumidifier was still running. A permanent surplus of water vapour in the air can only be maintained by a powerful water source, which was most likely to be the outer walls. The local porous limestone is well known for the ability to absorb rain and dew on the outside and conduct the liquid moisture through the structure. The moisture is released to the inside by evaporation at a constant

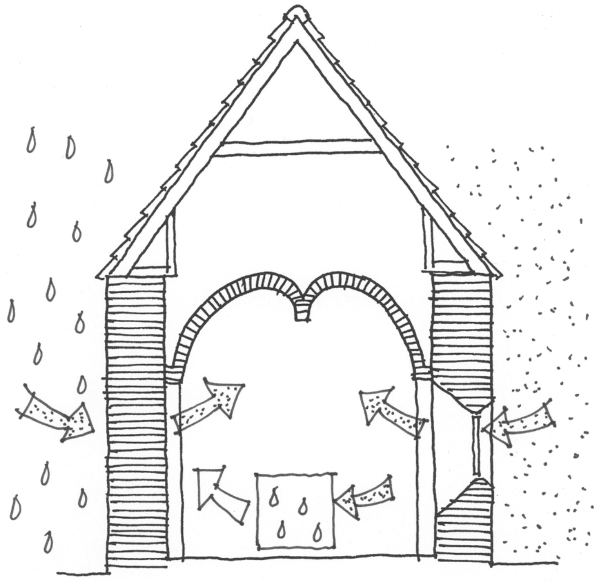

Figure 10. Diagram illustrating the climate control in Karlslunde church. In summer, water vapour is supplied from the outside air through natural ventilation. In winter, water vapour is probably released from the building structure by evaporation. The dehumidifier removes moisture from the interior all year and maintains a constant RH independently of temperature.

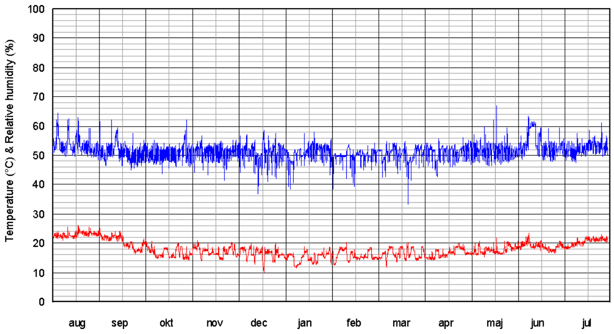

Figure 11. Climate records from Karlslunde church south of Copenhagen. The RH is controlled to 45-55% all year by a mechanical dehumidifier, except for a few episodes, when the RH suddenly jumped to 60% due to a malfunction.

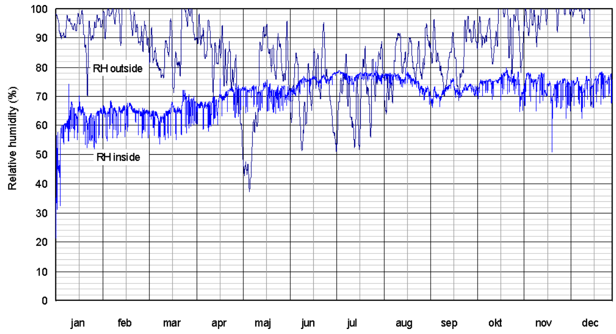

Figure 14. Climate records from Ollerup church. The relative humidity is within the range 60-80%RH, except for the brief episodes of heating for Sunday services, where the RH drops below 60%.

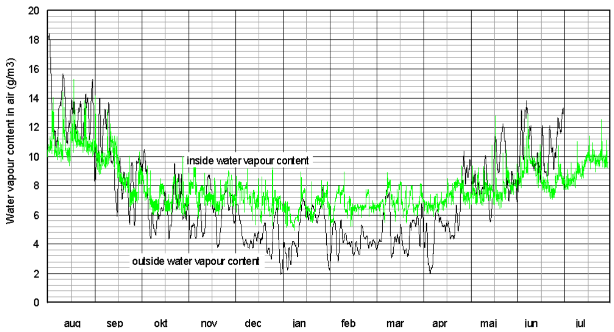

Figure 12. The content of water vapour in the air inside and outside calculated from the climate records in Karlslunde church. In summer the air is drier inside than outside due to the dehumidifier, but in winter the inside air is more humid than outside, in spite of the dehumidification. There is an internal source of moisture, possibly the limestone walls acting as passive humidifiers.

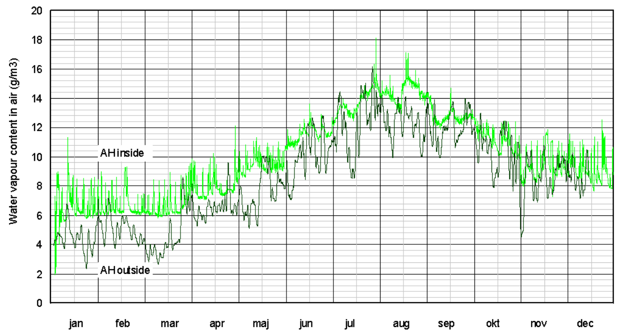

Figure 15. The content of water vapour in the air inside and outside, calculated from the climate records in Ollerup church. Most of the year the inside air is more humid than the outside air. This seems to be a consequence of the permanent heating. There is an internal source of moisture, possibly the brick masonry walls acting as passive humidifiers.

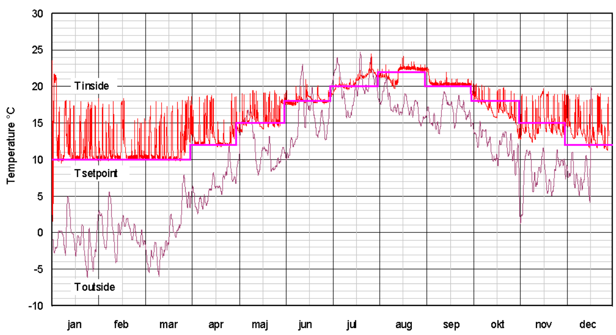

Figure 13. Climate records from Ollerup church, located on Fyn. The temperature is adjusted stepwise to a new set point for each month. The church is heated to 18°C for services.

rate, due to the permanent gradient in RH. Thus the indoor climate in Karlslunde is a state of equilibrium between the constant injection of humidity from the walls and the removal of water by the machinery. It is a benefit for the preservation of the altarpiece, but it may be a damaging preventive measure in the long run, if salts accumulate at the interior surface of the wall.

Ollerup Church is a brick masonry structure located in a village on Fyn. The congregation was worried about the condition of the organ, which played out of tune because of climate variations. The church was intermittently heated in winter by electric panels mounted below the bench seats. The heat was turned off over the summer, and the heating by solar radiation was small, so the temperature would never exceed 18°C. This is a general problem for many village churches with narrow windows and a ventilated attic. A new heating strategy was proposed for the church to be heated all year to a variable set point ranging from 10°C in winter to 22°C in summer. The set point was adjusted stepwise to a fixed temperature every month. At first the congregation was reluctant to allow heating in summer, because this was not required for human comfort. But the summer heating keeps the RH below 80% even on the most humid days, so the variations in RH are within 60-80% all year. There are some occasions during the winter when additional heating to 18°C for services brings the RH further down, but not as much as expected. Every heating event shows a simultaneous rise in absolute humidity of approximately 2 g/m^3. The absolute humidity quickly falls back to the natural level, which is also more humid than outside for most of the year. In February, the surplus of water vapour is largest, but even in summer there are episodes with considerable moisture surplus. There seems to be a constant moisture migration to the inside, driven by the heating. The concept of controlling RH by adjusting the temperature should be used with care, because it may result in considerable moisture migration.

Conclusions

The main challenge for climate control in Danish churches is not to design advanced heating systems but to devise the appropriate heating practice. Too much heating in the winter or too little heating in the summer causes the trouble. Most medieval churches have small windows and thick massive walls, which allows little solar heating of the interior. The summer indoor climate is therefore chilly and humid, with RH above 80% for several months. The damp environment facilitates mould growth, and pests are encouraged to breed and feed on any organic substance. The polychrome wooden objects suffer damage from drying shrinkage during the winter, when the RH is reduced due to the heating. Wall paintings are susceptible to salt decay, because the most common salts will dissolve and precipitate as the RH varies in the range 30-80 %. Recent investigations suggest the annual and diurnal change in RH should be less than 10%RH to protect the paint on wooden artwork and wall paintings.

There are two ways of moderating the RH in Danish churches. One way is to control the water vapour content in the air and another way is to adjust the air temperature to an annual cycle. The first principle involves the use of a mechanical dehumidifier. This apparatus will be able to control the RH within a reasonable interval over the year. Most churches will only need dehumidification a few months over the summer to prevent the RH from getting too high. Even so, many architects and conservators have an intuitive aversion to dehumidifiers. There is a fear of drying damage due to malfunction, and uncertainty about the long term effect of lowering the RH. As shown in the Karlslunde case, there is certainly a risk of accelerating salt migration because of the perpetual passive humidification by the building structure.

The RH can be controlled by temperature regulation, either by a hygrostat or by adjusting the temperature set point according to the average outdoor temperature. The hygrostat gives a fairly constant RH, because there is a fast response to sudden changes in the outdoor climate. Fixed temperature set points cannot give better control than 10% RH over the day, which may be harmful to sensitive objects or salt contaminated wall paintings. In some churches the moisture content of the inside air will be higher than outside because the building structure releases moisture. If the windows remain single glazed, which is the case in most churches, there will be long lasting episodes of condensation in the winter. The dew may lead to corrosion of the metal window frame. The condensation is best avoided by double glazing, which is usually not allowed for aesthetic reasons.

In some churches the climate records indicate a higher water vapour content inside than outside. The high humidity level is not a consequence of conventional humidity buffer effects, because this always requires episodes of moisture deficit to be levelled out by episodes of moisture surplus. A permanent water vapour surplus can only be maintained by a constant source of moisture. It appears to be the masonry walls, acting as passive humidifiers and influencing the indoor climate by a constant evaporation. Such constant flow of moisture can eventually lead to salt accumulation on the inside of the walls or vault. Further investigation is needed to locate the source of the passive humidification.

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