SEVENTH FRAMEWORK PROGRAMME

Climate for Culture

Ralf Kilian, Tomáš Vyhlídal, Tor Broström (Ed.)

DEVELOPMENTS IN CLIMATE CONTROL OF HISTORIC BUILDINGS

Proceedings from the international conference "CLIMATIZATION OF HISTORIC BUILDINGS, STATE OF THE ART"

Linderhof Palace, December 2nd, 2010

Fraunhofer IRB Verlag

Ralf Kilian, Tomáš Vyhlídal, Tor Broström (Ed.)

DEVELOPMENTS IN CLIMATE CONTROL OF HISTORIC BUILDINGS

Proceedings from the international conference
"CLIMATIZATION OF HISTORIC BUILDINGS, STATE OF THE ART"

Linderhof Palace, December 2nd, 2010

FRAUNHOFER IRB VERLAG

Printing and Bindery:
Mediendienstleistungen des
Fraunhofer-Informationszentrum Raum und Bau IRB, Stuttgart

Printed on acid-free and chlorine-free bleached paper.

Fraunhofer Information-Centre for Regional Planning and Building Construction IRB
P.O. Box 80 04 69, D-70504 Stuttgart
Nobelstrasse 12, D-70569 Stuttgart
Phone +49 (0) 7 11/9 70-25 00
Fax +49 (0) 7 11/9 70-25 07
E-Mail irb@irb.fraunhofer.de
URL www.baufachinformation.de

CLIMATE CHANGE AND HISTORIC BUILDINGS – THE EU PROJECT »CLIMATE FOR CULTURE«

Cultural heritage will not be spared by climate change. The impending changes in climate and the need to change the way we use energy as well as the financial crisis and the increasing shortage of resources due to the expected population increase will create new challenges for the maintenance of museums and historic buildings.

In particular, rising energy costs caused by heating, air conditioning and lighting require the development of new concepts and solutions for the sustainable preservation of our cultural heritage. In times of economic recession and rising energy prices long lasting, durable measures for energy efficiency and cost reduction in building maintenance are becoming even more essential.

For conservation and restoration not only profound knowledge on the molecular level is needed, but also the development of new technologies and methods: improved acquisition of climate and microclimate parameters, improved simulation models for the prediction of indoor environments that take into account the influences of climate change, simulation software especially adapted for complex questions in historic buildings and the simulation of future damage prognoses for all the various materials that make up cultural heritage objects.

In the project »Climate for Culture«, funded by the EU from 2009 to 2014, researchers are investigating the impact of climate change on UNESCO World Heritage Sites. The project, coordinated by the Fraunhofer Institute for Building Physics (IBP), aims at assessing the risk of damage to historical sites and to the collections they contain, as well as developing strategies for long-term preservation and evaluating economic consequences. Although many historical monuments are exposed to hostile environments caused by the many visitors, there are other important factors contributing to the deterioration of World Heritage Sites, such as climate change, which is a long-term, substantial menace.

The multidisciplinary »Climate for Culture« project consists of 27 partners from all over Europe (+ Egypt). One of the main aims is to assess and evaluate indoor climate strategies for historic buildings and how to meet the energy efficiency aims of the European Union while contributing to a sustainable preservation of the buildings.

Prof. Dr.-Ing. Klaus Sedlbauer
Fraunhofer Institute for Building Physics

FOREWORD

The most part of the European cultural heritage is preserved not in special galleries and museums but in historical buildings. Most of the castles, churches, mansions, monasteries etc. serve, often very long, for safekeeping of collections of artistic or historic artefacts and for exhibiting them to the public. Unlike the modern buildings marked by a high level of insulation and indoor environment services it is a delicate task to provide a satisfactory indoor environment in historic buildings. Particularly it is due to the well-known conflict between the contradictory points of view – namely the contemporary standards of preventive conservation and, to some extent, the visitors' comfort. The research in this field has brought some unexpected conclusions particularly as the heating and air-conditioning technology is concerned. As regards the galleries and museums it becomes more and more evident that the currently used requirements for internal environment turned out to be excessively rigorous as to the recommended narrow limits of environmental parameters. Such requirements bring about an inadequate demand for technology with high power inputs and expensive operation costs in the buildings operated in this way. In essence the presented research results can be summarized to a simple conclusion – the less invasive the indoor environment control the better the chance to achieve a long-term favourable preservation for the building structures, artworks and historic exhibits. Just this conclusion may well characterize the main message of this book and we hope that it will find an interest and understanding among some of those concerned with the multidisciplinary problems arising from the preventive conservation in historical buildings.

Prof. Ing. Pavel Zítek, DrSc
Czech Technical University in Prague

NOTE FROM THE EDITORS

These proceedings summarize the talks from the international conference “CLIMATIZATION OF HISTORIC BUILDINGS, STATE OF THE ART”, held at Linderhof Palace on December 2nd, 2010 deep in the snow of the Bavarian Alps as a dissemination activity of the European project Climate for Culture. In the book the reader will find ten self-consistent chapters dealing with several specific areas of preventive conservation, particularly with the techniques providing the indoor environment in historical buildings where artworks or historic exhibits are deposited and displayed.

The first chapter by *D. Camuffo* is devoted to the so-called “friendly heating” in churches, chapels and worship buildings at all. It shows the advantages of local and floor heating with low power demands focused primarily onto the visitors and leaving almost unaffected the building structure. Another low level heating strategy, based on a humidistat-controlled heating or the so-called “conservation heating” is described and discussed in the second chapter by *N. Blades* and *K. Rice*. Among other the authors demonstrate how the low level heating corresponds with reducing the moisture sorption and carbon dioxide emission. A similar type of heating is experimentally tested and investigated by a simulation study in the third chapter by *H. L. Schellen* and *E. Neuhaus* where the suitability of humidistat-controlled heating for the Dutch type of climate is investigated. A very comprehensive review on minimizing the invasiveness and energy demands in providing a stable and favourable climate in galleries and museums is presented in the fifth chapter by *J. Käferhaus*. The highlight of this part is the conclusion that sustainability and stability of the environment together with the energy savings is not a matter of “machinery” application but rather a result of deep understanding of the natural properties of the historic construction and putting them to good use in stabilizing the indoor environment. The potentials of dehumidification control of relative humidity as an energy efficient alternative to conservation heating are evaluated in sixth chapter by *P. K. Larsen* and *T. Broström*. The problems and experiences with preventive conservation in the Bavarian castles and palaces are reported in the seventh chapter by *T. Naumović*. And an investigating study on the impact of outdoor conditions on the interior environment in the Linderhof Palace is then presented in the eighth chapter by *S. Bichlmair* and *R. Kilian*. An original model-based microclimate control preventing the preserved artefacts from the harmful effects caused by the changes of moisture content in them is dealt with in the ninth chapter by *P. Zítek*, *T. Vyhlídal*, *O. Sládek*, *A. Sládek* and *G. Simeunović*. This environment control is applied to the Karlštejn Castle Chapel. The application of heating the walls of historic buildings by means of plaster-inlaid heating tubes to reduce the rising damp is examined with a hygrothermal 2D building model in the last chapter by *M. Krus* and *R. Kilian*. The impact of this technique on the diffusion flow of damp brings a novel view on this problem. The objective of the last chapter by *J. Holmberg*, *B. Kylsberg* and *K. Skeri* is to investigate the deterioration of selected objects correlated to outdoor climate over a 300 year period and to analyse the preservation strategy chosen at Skokloster.

The book is intended for whoever is culturally or professionally concerned with the preventive conservation or restoration and for all those interested in understanding the multidisciplinary problems in conservation of our tangible cultural heritage.

The editors want to thank all the parties that took part in the implementation of the conference and the proceeding. Especially, we thank to *Kristina Holl*, *Barbara Wehle* and *Stefan Bichlmair* (all from Fraunhofer IBP) for their great work in organising the conference. *Ivana Oswaldová* (CTU in Prague) deserves special thanks for finalizing the text and the layout of the papers. Next, we thank to *Prof. Klaus Sedlbauer* and *Prof. Pavel Zítek* for their introductory words. We are also grateful to all authors who wrote the papers that compose the proceedings.

Ralf Kilian
Tomáš Vyhlídal
Tor Broström

Acknowledgement

The conference, proceedings and the presented research are a part of the European large scale integrating project “**Climate for Culture**” – Damage risk assessment, economic impact and mitigation strategies for sustainable preservation of cultural heritage in the times of climate change”, financed by the European Commission under the Grant agreement no.: 226973. FP7-ENV-2008-1 Theme 6. Environment (including climate change).

TABLE OF CONTENTS

THE FRIENDLY HEATING PROJECT AND THE CONSERVATION OF THE CULTURAL HERITAGE PRESERVED IN CHURCHES

Dario Camuffo
National Research Council (CNR), Institute of Atmospheric Sciences and Climate (ISAC), Padua, Italy

Abstract: The buildings sector is receiving important attention in the development of sustainable energy efficiency policies. Historic buildings and churches constitute a problem because they have enormous volumes, the envelope has low efficiency and for their nature such buildings escape from the legislative framework. This paper discusses the main findings of the EU funded project Friendly-Heating. Heating only finalized to the thermal comfort of churchgoers is not compatible with conservation: the higher the comfort level, the stronger the departure from the historical climate and the higher the risk for conservation. The importance of keeping the unchanged the historical climate is stressed by the European standard EN 15757: 2010 *"Conservation of Cultural Property — Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials"*. A compromise should be necessarily found between different needs, i.e. thermal comfort, artwork conservation, energy saving and cost. Thermal comfort is negatively correlated with all other needs, the others going all in the same direction. An optimisation can be found by controlling the heat dispersion: instead to heating the whole building, it is convenient to keep heat localised around the congregation and reduce dispersions as far as possible. Instead of using systems that require continuous operation, it is more convenient to use only local, occasional heating. Artworks will safely remain in their historical climate; a small quantity of heat will reach and cross the envelope, thus reducing energy consumption and cost. Churchgoers may have some heat, especially on feet and legs and heavier clothing too may be helpful to optimise the balance towards a better advantage. The above concepts have inspired the European standard EN 15759: 2011 "*Conservation of cultural property – Specification and control of indoor environment – Part 1. Heating of churches, chapels and other worship buildings*".

Keywords: Church heating, heat dispersion control, artwork conservation, thermal comfort, energy efficiency

1. INTRODUCTION

In 2002, when the EU funded Friendly-Heating Project started, literature was specifically focused on a number of individual case studies and only one, although very nice general overview of all heating systems existed, i.e. Bodrass and Bemrose (1996). However, this overview was concerned on general aspects, safety and costs, without any consideration about the potential impact of heating on cultural heritage objects. In the past, the most common point of view was: "Church heating systems should be designed for economical running, the minimum of labour in servicing and maintenance, unobtrusive appearance and efficiency as a heating medium" (Mills, 1959). Cultural heritage was simply ignored.

The Friendly-Heating project, active 2002-2005, was aimed to carefully study the characteristics of all heating systems in order to evaluate pros and cons, and especially their potential impact on the various kinds of artworks in order to devise and test the best heating strategy to this aim. The goal was to preserve artworks in their natural, historical climate and, at the same time, to warm people at the highest thermal comfort compatible with conservation.

Objects live with continual interactions with their environment, especially governed by temperature (T) and relative humidity (RH), and their present-day state of conservation is determined by such interactions, including adaptation and acclimatization. This leads to the concept of natural climate experienced during the history of the objects, briefly, "historical climate". This concept was introduced in 1998 (Camuffo, 1998) and some twelve years later has been recognized as fundamental reference by the European Committee for Standardization (CEN) in the EN 15757 (2010) standard *"Conservation of Cultural Property — Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials"*.

In this paper we will make a short review of the main outcomes of the above European project in order to assist congregations in finding the most appropriate solution for the conservation of the cultural heritage preserved in their churches.

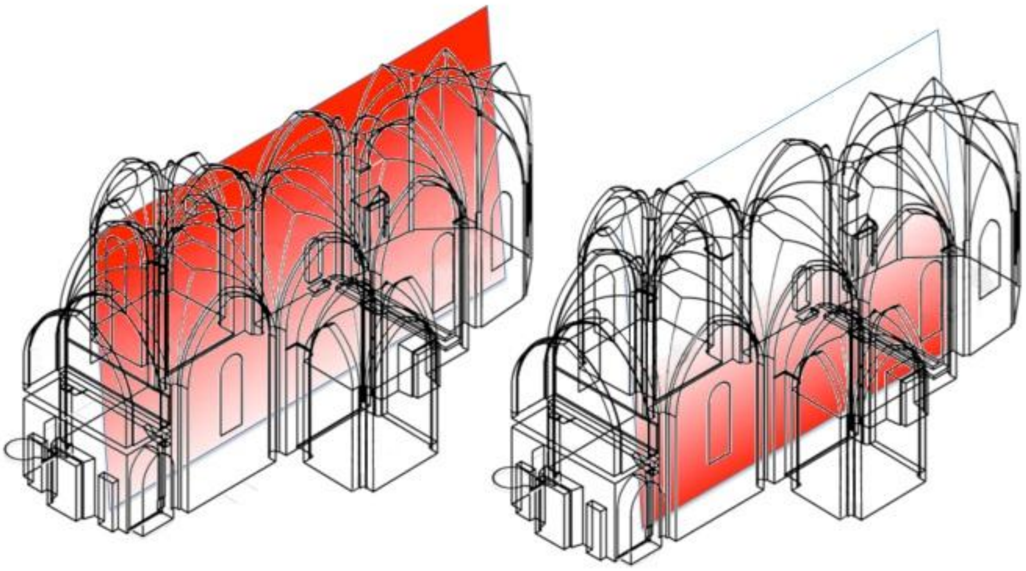


Figure1 The two heating strategies: (a) central heating, aimed to provide as far as possible homogeneous heat distribution within the whole building, at the same time supplying heat to the envelope. Most of the heat is accumulated in the upper part of the building. (b) Local heating, aimed to produce the best radiant temperature limitedly to the manned area, with some local increase in air temperature and minimum of draughts. The rest of the building remains almost unaffected and preserves its historical climate, or slightly departs from it.

2. REVERSIBILITY OF INSTALLATIONS

Keeping progress and limits of technology in mind, as well as the continually increasing demand for well being and safety, no heating system can operate for more than ten, twenty or thirty years. Inevitably, any installation requires works that mutilate the envelope. For example, with radiant floor heating the whole floor will be removed, and this is a serious problem in the presence of tombstones, tombs or archaeological remains; with warm air heating large ducts will be excavated to blow and extract air; with internal gas combustion piping for gas supply will be inserted and ventilation holes will be necessary; with hot water radiators large insulated pipes will be installed inside the masonry.

The problem of changing heating system is not sustainable, especially for old buildings, because mutilations cannot be repeated every one, two or three decades. Therefore, the choice of a heating system needs to prioritise the less invasive system and the reversibility of the installation, i.e. when the system will be obsolete and removed, the building should be the same as it was before the heating system was installed.

3. THE TWO MAIN HEATING STRATEGIES

3.1. Central heating

Central heating is aimed to provide as far as possible homogeneous heat distribution within the whole building, at the same time supplying heat to the envelope (Fig. 1a). It is used to reach the desired comfort level, or to provide some background heating to the building in order to avoid exceedingly low temperature and frost. The most common use is for large congregations and volumes, and the most popular systems are: underfloor heating, warm-air heating, natural or forced air convectors, radiators, electric or fuel stoves.

From the point of view of artwork conservation we should note that each heating operation forces the indoor climate to strongly depart from the historical climate, causing a potential harmful situation. Critical factors are: sharp peaks in air temperature (T) and drops in relative humidity (RH) for occasional use (e.g. warm air heating), or cycles of both T and RH for gentle operation or large inertia systems (e.g. underfloor heating), or excessively low RH for continuous heating in cold regions.

In no case the exceedingly low RH can be mitigated with the addition of moisture vaporized into the air. The problem is better explained considering separately the cases of intermittent and continuous operations. It should be thermodynamically explained in terms of dew point (strictly related to the moisture content in air) and surface temperature, but it can be also explained in terms of RH reached at the interface between the air and the object surface. We will follow the latter to be equally understandable to non-experts.

In the case of intermittent heating, when the system is operated, paintings on canvas, tapestry and the surface of wooden artefacts will closely follow the sharp increase in air temperature and the RH at the interface will be exceedingly low; as opposed, frescoes, marble statues, masonry and other items having large inertia will remain cold and the RH at the interface will be normal or exceedingly high for the additional moisture released from people and the evaporation from the ceiling and the upper masonry reached by warm air (Camuffo et al. 2010). As a consequence, any addition of moisture into the air will reduce the drops of RH in the air, and will be beneficial to objects having short-term inertia (i.e. too large surface overheating and too low RH at the interface), but it will have negative impact on objects having long-term inertia (i.e. no or low overheating, too high RH at the interface and risk for condensation).

In the case of continuous heating all surfaces will reach equilibrium with stationary, but different temperature levels determined by internal heat distribution, leakage, heat loss via conductivity etc. Once again, the addition of moisture into the dry air will be beneficial to the warmest surfaces, but will have negative impact on the coldest ones, where condensation may occur, with the result of generating moulds or affecting masonry with salt crystallization cycles.

Central heating requires a huge amount of energy, a large fraction of it being wasted trough thermal bridges, leakage and storage into the envelope. Historical churches have envelopes made with technologies not compatible with energy saving. They are typically non-energy-efficient buildings and the possibility of improvement is limited. The heat loss that derives from the heat supplied to the envelope depends, inter alia, on the temperature difference between indoor air and masonry. The heat loss through window panes, roof, etc. depends, inter alia, on the difference between both indoor and outdoor air temperatures. Being based on the dispersion of heat, central heating is hardly sustainable for non-energy-efficient historical buildings. With central heating people benefit from a small portion of the total power supply, i.e. the whole system has low efficiency.

3.2. Local heating

Local heating is aimed to produce the best radiant temperature limitedly to the manned area, with some local increase in air temperature and minimum of draughts (Fig. 1b). The rest of the church volume remains almost unaffected and preserves its historical climate, or slightly departs from it. The most common use is for small congregations and volumes, e.g. small churches or some specific parts of them, e.g. sacristy, baptistery, chapels, choir loft. The most popular systems are: radiant heating from infrared (IR) emitters located overhead, on the side or below; pew heating constituted of electric panels, tubular heaters, water pipes or radiators; heating carpets or footboards.

This heating strategy disperses a small amount of heat, leaving cold the rest of the church, i.e. the heat does not reach artworks and the envelope, or reaches them in a negligible fraction. Outside the moderately warmed manned area, the RH remains almost unaffected and the system is harmless to the conservation aims.

Reducing as far as possible any dispersion of heat, it is convenient for non-energy-efficient historical buildings thanks to the smaller loss of heat. Less energy/fuel is required. With local heating people benefit from a large portion of the total power supply, i.e. the system has high efficiency.

However, the thermal comfort is limited when the envelope is very cold, and churchgoers suffer from both radiant heat loss from their body and noisy cold air draughts generated by small thermal unbalances. Generally speaking, IR from incandescent emitters should be symmetrically distributed to the body and never IR heating should exceed 8 °C compensation; in addition, IR beams are shielded by the upper part of the people bodies and hardly reach legs and feet that remain in the cold shadow. Pew heating is based on only one heater per pew, which is insufficient to provide homogeneous warmth to feet, legs and hands. Finally, heating carpets and heating footboards cannot exceed 22 °C and are of little advantage compared to passive insulating layers, e.g. normal carpets or wooden platforms.

After this introduction, it is evident that the only sustainable heating strategy, at least in terms of both cultural heritage conservation and energy saving, is local heating.

4. THE FRIENDLY-HEATING PROJECT OUTCOMES

Generally speaking, the choice for a central or local heating system is based on a number of factors, where installation and operation costs and expected comfort lie in pole position. Only rarely the choice is based on conservation needs. In particular, the heating systems are generally installed on request of the congregation when it decides to reach a higher thermal comfort. However, thermal comfort and conservation are characterized by conflicting needs, e.g. comfort tends to raise ambient temperature and lower RH, whilst conservation requires no change in historical climate. As a consequence, any choice dictated by comfort as a main factor, risks being harmful to conservation.

The Friendly-Heating project recognized that local heating resulted to be the most convenient strategy, but it was necessary to further study how to reduce heat dispersion and how to improve comfort because in general local heating provides limited comfort because they have only one heater, sometimes located in a scarcely efficient position.

The best results were obtained with gentle IR radiation emitted from low-temperature sources, e.g. low-temperature heating foils, heating glass panes and heating carpets. Each of these emitters has its best application in some specific cases, not in all, as we will see later. The use of gentle emission of mild or warm air was soon excluded because warm air cannot be controlled for its buoyancy: it goes up quickly, escaping from the manned area and being dispersed aloft, with little advantage of churchgoers. In particular, churchgoers affected by warm-cold fluctuations feel a very unpleasant sensation and they may prefer no heating than warm-cold draughts, although generated from warm sources.

4.1. Heating solutions

The Friendly-Heating project individuated a number of different solutions, each of them for a specific use, e.g. the churchgoer assembly in the pew area typical of the Catholic Church, or the boxes popular in the Lutheran Church, or the standing congregation typical of the Orthodox Church, the altar area for the priest celebrating religious services, the choir loft, the organist and so on. Heating is conceived in modular form, i.e. divided into independent parts that can be operated separately, or together. For instance, in the case of a few people attending a celebration only a few front pews can be heated; or the choice can be made for a larger number of pews, or for the whole church. The modular mode reduces the heat dispersed into the church and, at the same time, lowers costs.

A very useful heater was the heating foil that was used for pew heating, or to obtain vertical heating panels adaptable to any surface for their flexibility, or under the altar-cloth. The heating foil (Fig. 2) is made of an electrically heated layer of graphite in microgranules deposited on a fibreglass support and then sealed between two plastic foils. When an electric current is passed through the conductive graphite layer, the electrical energy is converted into heat energy and the layer gets heated up. When the foil is heated, it expands and the increased width tends to increase the distance between granules. As a consequence, the electrical resistance increases with the foil temperature and reduces the current intensity. Consequently, the maximum temperature of the foil is self-regulated at specifically selected levels, established when the foil was built. This self-regulation provides a natural cut-out for the system and eliminates any risk of ignition or burning skin. A thermostat is added for further fine regulation and safety, but is not necessary.

Pew heating is in general not very comfortable, especially in the case of envelopes at very low temperature. Thermal comfort was improved with an ergonomic combination of heat sources distributed in the manned area below the kneeling pad, the seats, and on the back of seats (Fig. 3a). Feet are the most sensitive parts of the body exposed to cold, and the air in proximity of the floor is the coldest one, frequently renewed at each door opening. The heating foil band under the kneeling pad is conceived to heat feet from the upper part of the shoe, that is the most efficient solution. The churchgoer can slip shoes ahead and insert them below the under-kneeling heater, or withdraw them to reduce heating and stay in the preferred heating position. The heaters below the seats are aimed to heat the calf of the person sitting on that bench, and the legs of the person sitting on the next pew. The heating foil band placed back of seats is aimed to heat churchgoer hands when they are sitting and the chest when kneeling.

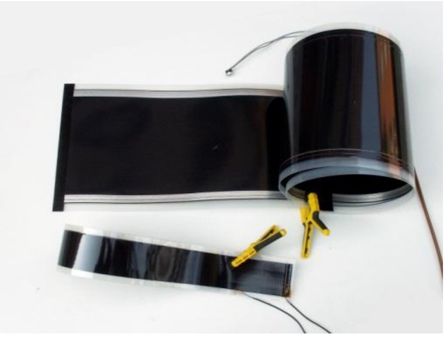


Figure 2 Heating foils, i.e. the basic heaters used for pew heating. The wide one has been used for the underseat leg-heater, the narrow one for the underkneeling foot-heater and the back hand-heater. Heating foils are constituted of a layer of graphite in microgranules deposited on a fibreglass support and then sealed between two plastic foils. When electric power is supplied across the conductive graphite band, heat is generated for the resistance opposed by the medium to the passage of current.

Heaters have been specifically designed to account for the physiological needs of the various parts of the body following the ergonomic needs, i.e. first feet, then legs and then considering that the body should be adequately covered with heavy cloths (Fig. 3b). In our case the range of temperature was between 40 ° and 70 °C.

All heating foils should be protected against accidents and vandalism. The preferred solution is a fine mesh stainless steel grid placed in front of the foil, and the back of the foil should have a reflecting aluminium foil and thermal insulation to avoid back dispersion. The steel grid will reflect most of the radiation impinging on it, having a very low IR absorbance (e.g. 7 %). The grid will assume an intermediate temperature between the heating foil and the air, and becomes mild, never hot. This avoids any risk for burning.

Heating glass panes can be used on the back of pews, or in front of cold windows, or forming a transparent band spaced from walls at the level of a sitting person. In such a case the heaters below the seats are not necessary and should be avoided. The heating glass panes are made of a very resistant tempered glass, with a transparent submicrometric layer of sputtered metal oxides inside. For the electrical resistance of the metal oxides, they are heated up when electric power is supplied. A thermostat maintains T at the desired level (e.g. 40 °C) and a second thermostat guarantees safety even in the case of failure of the first thermostat. The glass panes provide thermal comfort by means of IR radiation or direct contact with the back or the hands. In front of windows or walls they may counteract cold droughts falling along cold surfaces. The glass panes may reach an excellent safety standard and resistance, so that they don't need to be contoured by a support frame. In addition, they are "self cleaning", i.e. they are hardly soiled with dust, smoke or contact with hands.

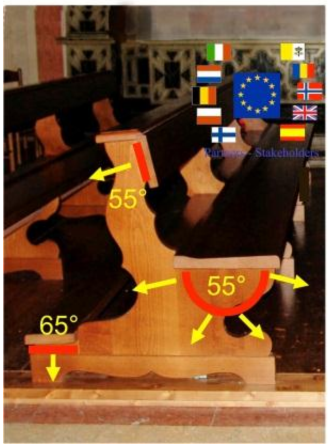


Figure 3a Location and temperature of the heaters fixed to pews in the EU Friendly-Heating project. The positions of the underseat leg-heater, the underkneeling foot-heater and the back hand-heater are indicated.

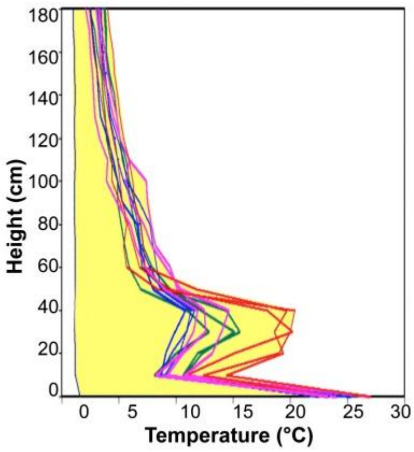


Figure 3b Temperature profiles generated by heaters. A number of profiles is reported, and the difference is justified by the position within the pew area, e.g. in the middle or on the borders. The increase in temperature corresponds to the coloured area.

The heating carpet is made of a heating foil or a heating wire placed between an insulating layer on the bottom to avoid heat dispersion to the floor and a carpet-like layer on the top. The top layer should protect the heating foil against mechanical damage by sharp objects, fire, water, etc. The surface temperature should be low (e.g. 20 °C) and provides comfort to feet but not the rest of the body, which should be heated with other sources, e.g. remote IR emitters. The area for the celebrant and the altar boys is warmed with heating carpets and remote IR emitters from both sides to make the heat distribution homogeneously.

More details about the above solutions can be found elsewhere (Camuffo et al., 2007; 2010).

4.2. Other general project outcomes

The Friendly-Heating project first recognized that the needs for cultural heritage and those for conservation are divergent. When heating is soft, the two needs are not necessarily conflicting, but when the environment becomes very cold, or the comfort level is kept too elevated, at this point they become conflicting, and a compromise between the two should be reached. The level at which the compromise stops depends on the vulnerability and value of the cultural heritage objects.

If conservation poses a limit to heating, this does not automatically mean that churchgoers should suffer for cold. Heaters should be helpful to mitigate cold environments, but churchgoers should be prepared to stay in a chilly or even cold building, and for this reason they should enter conveniently dressed and wear heavy cloths.

5. CONCLUSIONS

The Friendly-Heating project produced specific and general outcomes. Specific results concerned the analysis and evaluation of all kind of heaters from the point of view of the conservation of cultural heritage preserved in churches. Other specific results have been the optimization of existing methodologies and materials, the improvement and design of heaters and solutions to heat churchgoers without damaging artworks.

General results concerned the criteria that should be kept in mind when planning a heating system, as well as the limits that any heating system has, with a thorough analysis of pros and cons with reference to conservation.

Some basic concepts have been made clear or have been stressed, e.g.:

- reversibility of installation should be considered priority;
- conservation needs and energy saving are strictly linked together, and both are opposed to thermal comfort;
- a compromise between the opposite needs (i.e. conservation and comfort) is necessary; in the case of conflict conservation should have priority;
- local heating is preferable to central heating for conservation and energy saving purposes;
- improving envelope insulation, reducing heat leakage and using heavy cloths are the first form of heating. Only after this first step it is possible to consider any kind of other heating system.

The above basic concepts have been considered by the European Committee for Standardization (CEN), WG 4 (Environment) and have inspired the standard: EN 15759 (2011) "*Conservation of Cultural Property - Indoor Climate – Part 1: Heating Churches, Chapels and other Places of Worship*"

6. ACKNOWLEDGEMENTS

This paper reports findings of the EU funded research Friendly-Heating project (EVK4-CT-2001-00067) and disseminates the results of the activity of CEN/TC346 WG4 concerning the European standardization. Friendly Heating was conducted with: Emanuela Pagan, CNR-ISAC, Padua, Italy; Henk Schellen, Dionne Limpens-Neilen, Eindhoven University of Technology, The Neterlands; Roman Kozlowski, Lukasz Bratasz, Institute of Catalysis and Surface Chemistry, Polish Academy of Sciences, Kracow, Poland; Sirkka Rissanen; Finnish Institute of Occupational Health, Oulu, Finland; René Van Grieken, Zoya Spolnik, Laszlo Bencs; MITAC, Department of Chemistry University of Antwerp, Belgium; Joanna Zajaczkowska-Kloda, Piotr Kloda, Marcin Kozarzewski, Lodz, Poland; Marco Camuffo, Studio BOCA, Padua, Italy; Mons. Giancarlo Santi and Mons Stefano Russo, National Office for Ecclesiastic Cultural Heritage, Rome; Krzysztof Chmielewski, Central Office for the Preservation of Historical Monuments, Warsaw, Poland; Ton Jutte; Netherlands Institute for Cultural Heritage, Amsterdam, the Netherlands; Annika Haugen, Tone Olstad, Norsk Institutt for Bulturminneforskning, NINA NIKU Foundation for Nature Research and Cultural Heritage Research, Oslo, Norway; Dan Mohanu, Universitatea de Arte, Bucuresti, Romania; Brough Skingley, English Heritage, London, UK; Cesareo Sáiz-Jiménez, CSIC Instituto de Recursos Naturales y Agrobiologia, Sevilla, Spain.

7. REFERENCES

[1] Bordass, W. and Bemrose, C., 1996: Heating your Church. Council for the Care of Churches, Church House Publishing, London.

[2] Camuffo, D., 1998: Microclimate for Cultural Heritage. Developments in Atmospheric Science 23, Elsevier, Amsterdam, 415 pp.

[3] Camuffo, D., Pagan, E. Schellen, H., Limpens-Neilen, D., Kozlowski, R., Bratasz, L., Rissanen, S., Van Grieken, R., Spolnik, Z., Bencs, L., Zajaczkowska-Kloda, J., Kloda, P., Kozarzewski, M., Mons. Santi,G., Chmielewski, K., Jütte, T., Haugen, A., Olstad, T., Mohanu, D., Skingley, B., Sáiz-Jiménez, C., Bergsten, C.J., Don Russo, S., Bon Valsassina, C., Accardo, G., Cacace, C., Giani, E., Giovagnoli, A., Nugari, M.P. Pandolci, A.M., Rinaldi, R., Acidini, C., Danti, C., Aldrovandi, A., Boddi, R., Fassina, V., Dal Prà, L., Raffaelli, F., Bertoncello, R., Romagnoni, P., Camuffo, M. & Troi, A., 2007: Church heating and preservation of the cultural heritage: a practical guide to the pros and cons of various heating systems. Electa Mondadori, Milan.

[4] Camuffo, D., Pagan, E., Rissanen, S., Bratasz, Ł., Kozłowski, R., Camuffo, M., della Valle, A. 2010: An advanced church heating system favourable to artworks: a contribution to European standardisation Journal of Cultural Heritage 11, 205-219
Doi: 10.1016/j.culturher.2009.02.008.

[5] EN 15757, 2010: Conservation of Cultural Property — Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials. European Committee for Standardization, Brussels.

[6] Mills, E.D., 1959: The Modern Church. Architectural Press, Princeton.

[7] EN15759, 2011: Conservation of Cultural Property - Indoor Climate – Part 1: Heating Churches, Chapels and other Places of Worship. European Committee for Standardisation, Brussels.

CONSERVATION HEATING AND ENERGY EFFICIENCY AT THE NATIONAL TRUST: THEORY AND PRACTICE

Nigel Blades[1], Kirsty Rice[2]
[1]*Preventive Conservation Adviser (Environment) for the National Trust*
[2]*Energy Adviser for the National Trust*

Abstract: The National Trust uses conservation heating as its main method of environmental control for the care of collections in historic houses. This paper presents work the National Trust is undertaking to understand the energy use of its conservation heating systems and to operate them as energy-efficiently as possible, in the light of the National Trust's 2020 energy targets which seek to reduce overall energy consumption across the organisation by 20 % and to shift to 50 % renewable energy sources. The energy demand of conservation heating systems is analysed using degree days; measured energy consumption data are presented; and the reductions in fuel cost and CO_2 emissions achievable though switching from oil-fired to wood pellet fuel, demonstrated.

Keywords: Conservation heating, renewable energy, carbon emissions

1. INTRODUCTION

The National Trust is the UK's largest conservation charity, founded in 1895 to promote the permanent preservation of places of historic interest and natural beauty for the benefit of the nation. The Trust cares for some 300 historic buildings which it opens to the public. Many of these have historic collections of great significance. The types of object include furniture, paintings, textiles, books and works of art on paper, photographs, leather, metals and ceramics. Approximately 150 of the Trust's historic houses have UK accredited museum status, which requires them to demonstrate that suitable preventive conservation strategies are in place for the care of the collections.

2. ENVIRONMENTAL CONTROL AT THE NATIONAL TRUST

As illustrated by the example of Cragside, most of the National Trust's mansion houses contain historic collections of mixed organic materials that are vulnerable to the damaging effects of inappropriate relative humidity (RH). Shrinkage and desiccation can occur in excessively dry conditions (typically below 40 %) and swelling and attack by mould and wood boring insects when conditions are too damp (typically above 65 %).

In response to these risks, the National Trust has, over the last 30 years, developed an environmental control strategy based on humidistatically controlled ('conservation') heating for the care of collections on open display. RH is maintained in a band 40-65 %, by heating alone; the use of humidification is avoided by accepting the low winter temperatures that will be needed at times to keep RH above 40 %. This conservation heating approach [1] is especially suitable for historic houses because it can use existing building heating services such as radiators and pipework and relatively simple control technology, thus requiring minimal intervention and modification to historic building interiors.

Figure 1 Cragside, Northumberland, the former home of the 19th century industrialist, Lord Armstrong, is typical of the historic mansion houses owned and managed by the National Trust in England, Wales and Northern Ireland

In the past most National Trust houses closed to the public from the end of October until Easter and so there was no need for comfort heating in the winter. More recently, houses have started to open for winter events and begin their open season earlier in the year. Thus there is a need for heating for the comfort of visitors and volunteer room stewards. In order to accommodate this in the context of maintaining acceptable RH conditions for collections, the Trust has developed a comfort heating policy for showroom areas which allows for some additional heating provided the RH does not go below 40 %, the lower limit for our environmental control band of 40-65 % [2]. In practice this enables showrooms to be heated to around 15-16 °C. Whilst this is low by 21st century comfort standards, it is acceptable in the context of a historic house where staff, volunteers and visitors have lower comfort expectations than might be the case in a museum or gallery for instance.

Figure 2 Cragside's Drawing Room, showing the mix of fine and decorative arts collected by Lord Armstrong. Most of the objects are on open display with very few in their own microclimate boxes or display cases

The National Trust then has developed a low-level heating strategy for its historic houses that avoids the risk of excessive winter dryness and shrinkage of vulnerable organic materials without the need for humidification. Our experience of conservation heating has led to the observation that the heat input required for conservation purposes is about one third of that required for comfort heating.

The original sizing, number and location of radiators in a historic house heating system will rarely be adequate to deliver modern comfort temperatures, however such a system may be able to cope with the conservation heating demand, meaning that the historical radiator configuration can often be retained and reused. Nonetheless the actual energy use by conservation heating systems can still be considerable. Conservation heating is required 24 hours per day, 365 days per year in contrast to comfort heating which is only needed in the winter season and is usually run on a time clock setting so the heating is on for perhaps 8 or 12 hours per day.

Conservation heating is delivered in National Trust houses by either 'wet' or 'dry' systems. In a wet system low pressure hot water is circulated through a series of radiators with the heat provided by a boiler fuelled by mains gas, liquid petroleum gas (LPG), oil, or biomass. Dry heating systems mainly use electric heaters such as water or oil-filled radiators, or convectors, which can either be fixed or portable devices. A few properties have warm air systems, where heated air is delivered through floor or wall ducts. Electric heating has a number of advantages from the building/collection conservation perspective – it is very easily controllable

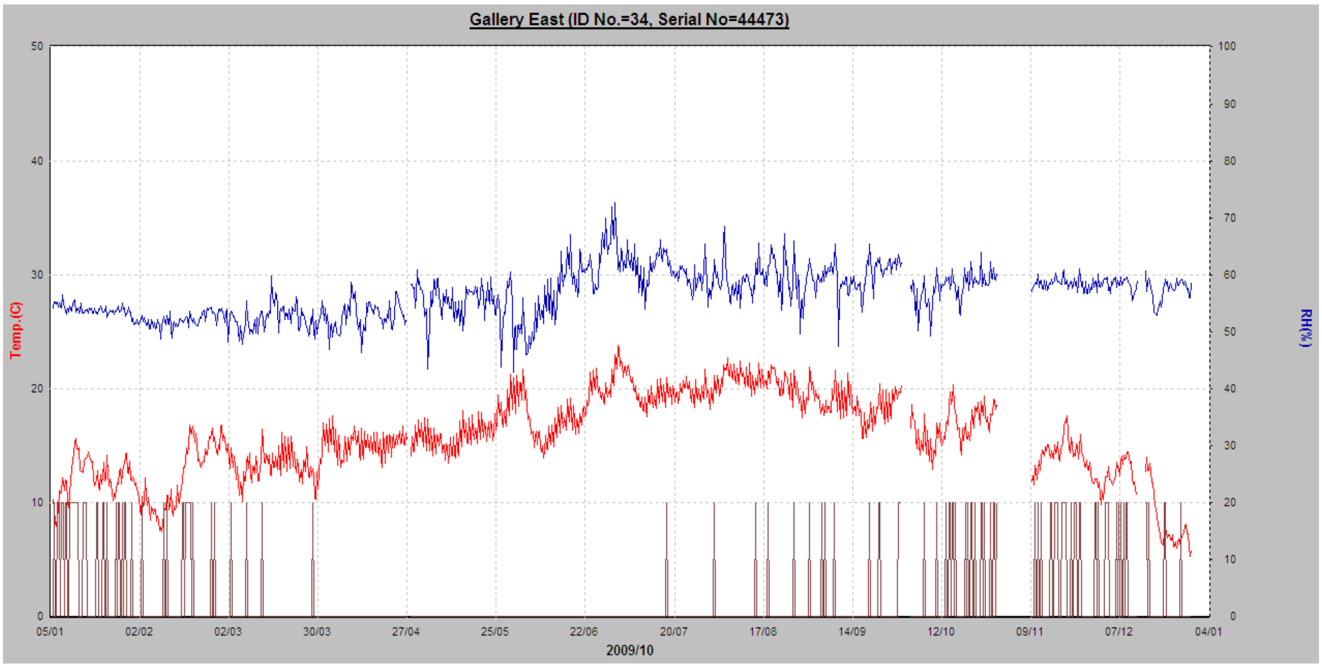


Figure 3 Annual RH and temperature conditions in the East Gallery at Cragside. The RH in the East Gallery is controlled by an electric conservation heating system operating around a set point of 58 %. RH is in range 40-65 % for 98 % of the year, though there is a small excursion above 65 % in mid-summer. Note that in early January the temperature is allowed to fall as low as 6 °C in order to maintain RH in the desired band.

and groups of rooms can be more easily zoned than with pipework. The risk of flooding from a pipe leak is eliminated. However national grid electricity is the most expensive heating fuel in the UK and has the highest carbon emissions per delivered KWh of any fuel. Taking a wider environmental perspective in terms of climate change and the Trust's own energy efficiency targets, discussed, in the next section, our preference is far as possible to use wet systems and to reduce the use of electric heating.

As well as considering the heat input needed for conservation heating, it is worth noting that historic buildings can have very significant heat loss through the building fabric, single glazed windows and from draughts and ventilation associated with windows, chimneys, suspended floors and voids in the building structure. In the damp UK climate a certain level of ventilation is necessary to disperse indoor moisture, e.g. moisture evaporating from the inside of a wall that has become temporarily damp from rainfall. It is likely that there is scope to reduce heat loss by reducing ventilation, though this must be carefully applied in historic showrooms in order to maintain a healthy building and the historical integrity of the interior.

3. ENERGY EFFICIENCY AND THE NATIONAL TRUST

The National Trust is committed to the conservation of its buildings and collections but recognises the need to do this in the wider context of conservation, taking into account the impact of our activities on landscape, the natural world, its resources and climate. In response to the threat of climate change and increasing energy prices, the Trust has introduced challenging targets to reduce its energy and carbon footprint. By 2020, the Trust is committed to:

- Operate existing systems more efficiently
- Reduce our energy usage by a fifth
- Become less reliant on fossil fuel
- Generate half of our energy through our own renewable or low carbon systems

Energy usage in 2009 is the baseline year, against which progress towards the 2020 targets will be measured.

In 2009, the Trust used 84 GWh of energy to provide heating and power to our buildings, excluding tenanted properties. As can be seen from Figure 4, imported grid electricity and oil represented just over three-quarters of this. These fuel types are also the most significant with respect to total cost and carbon content. Even if the UK electricity grid becomes "low-carbon" (through increase in nuclear and renewables within the energy mix), the grid itself is rife with inefficiencies as it relies on centralised power generation, with significant embedded losses within the distribution network. Oil has other complications, particularly the environmental hazards associated with extraction and local pollution hazards from poor storage or pipe leaks. The Trust's energy strategy has identified electricity and oil as the priority fuels for reduction or replacement [3]. Table 1 shows the rationale for these priorities in terms of the carbon emissions associated with each delivered KWh and current UK cost per KWh for different fuels.

In 2009, National Trust buildings used 2 million litres of oil for heating. Historic mansion properties used most of this at 1.7 million litres. The remainder was used in countryside properties and offices. Heating systems which use oil are being prioritised for replacement with biomass (wood) boilers or heat pump systems. The challenge for the Trust has been to implement alternative technologies so that they are suitable for delivery of both comfort heating to offices and staff accommodation and conservation heating for showrooms.

When installing biomass systems wood fuel from National Trust estates, as chip or log is used wherever possible. This wood is a natural by-product of good woodland management, where regular coppicing is required to provide a suitable environment for new and sustained growth. Where this is not an option, pellets or chip from sustainable sources are purchased.

Mansion houses with high electricity consumption are being prioritised for efficiency measures such as low energy lighting and equipment and modifications to conservation heating strategy, as described in the next section. Those using electric night-storage heating are being reviewed for replacement by wet systems where feasible and improvements to building structure, such as insulation and draught-proofing, have been initiated. The National Trust is also assessing the potential for renewable electricity to be generated at our properties, primarily through hydro-electric and solar photovoltaic installations.

To encourage local responsibility for meeting energy targets, the Trust has developed its own in-house metering and monitoring system which is accessible to all properties. This enables properties to enter energy data, such as meter readings and fuel deliveries and to compare their energy use with previous years or with other properties. Advanced metering is to be installed on high energy use properties to identify energy wastage and enable better energy management by the property staff. This metering will also enable managers to understand the effects that increased visitor numbers or extended winter opening hours might have on energy usage, particularly if these factors lead to increased demand on comfort heating or lighting requirements in mansion buildings.

4. ENERGY USE OF CONSERVATION HEATING SYSTEMS

As part of the work to meet our 2020 energy targets, the Trust is looking closely at the energy consumption of its conservation heating systems. It has developed a method of predicting and modelling conservation heating energy demand using degree day theory. This is described in detail elsewhere [4] but the following section will show some of the outcomes of the application of the method.

4.1. Modelling of energy demand using degree days

Heating degree days quantify the heating demand of a particular heating strategy, based on the difference between external temperatures specific to a particular locality or year and the expected or required indoor temperature. Degree days are normally calculated for comfort heating but can also be derived for humidistatically controlled heating because this will also require a calculable indoor temperature, though this will vary with relative humidity. The degree day method can be used to show the different heating demand profiles for comfort and conservation. Figure 5 below compares the degree days for comfort heating to 20 °C with those for conservation heating to 58 % RH, for Cragside, a 19th century house in Northumberland in the North East of England (figures 1 and 2).

From figure 5 the different demand heating characteristics of comfort and conservation heating are evident. Whilst comfort heating demand is concentrated in the winter months, the conservation heating demand is at a steady but lower level throughout the year. The overall heating demand of comfort heating is 2714 degree days compared with 982 for conservation, in line with our experience that conservation demand is about one third comfort heating demand.

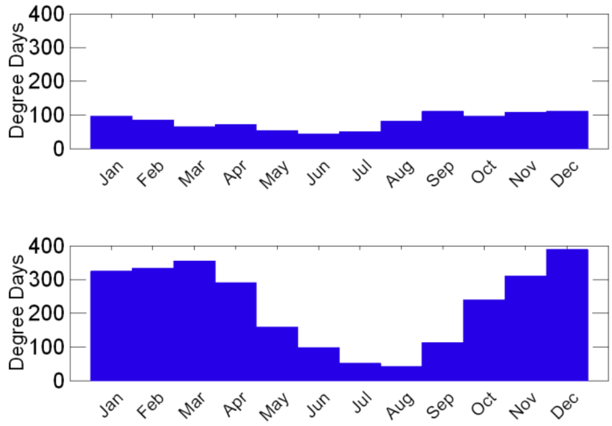


Figure 5 Heating degree days for Cragside, Northumberland, based on 2008 data. Top: comfort heating to 20 °C, total degree days = 2714. Bottom: conservation heating to 58 % RH, total degree days = 982.

A key parameter for conservation heating is the RH set point – the value above which the heating is switched on

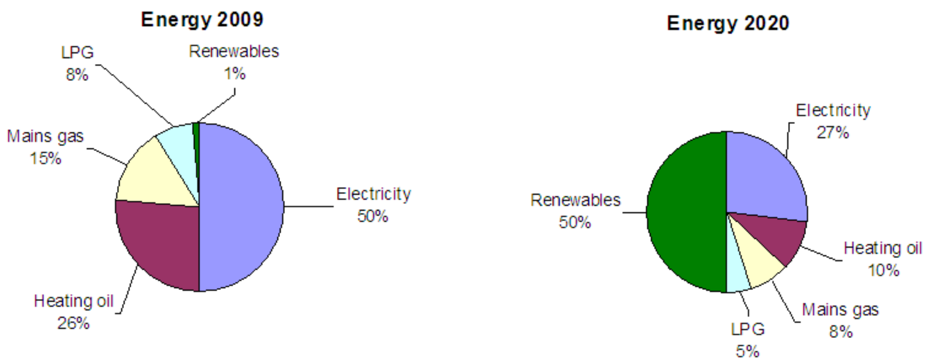


Figure 4 National Trust baseline energy use and 2020 target [3]. Total ener gy usage at 100 % baseline in 2009 with total energy usage reducing to 80 % in 2020, with half of this coming from renewable energy or low carbon systems.

Table 1 Indicative fuel CO_2 emissions and costs

	$kgCO_2$/kWh [1]	£/kWh [2]	Notes
Electricity (UK Grid)	0.527	0.09	Day rate
Electricity (UK Grid)	0.527	0.06	Night rate
Oil/kerosene	0.265	0.06	
LPG	0.225	0.06	
Mains gas	0.206	0.015	
Wood Pellet	0.06	0.035	

[1] Data from UK Dept Environment, Food and Rural Affairs; wood pellet from Carbon Trust

[2] Indicative cost, National Trust

and below which the heating is switched off. The standard National Trust set point has been 58 %, a higher value than might be typical for museum control systems, but reflecting the cooler damper conditions that have existed in UK historic houses over the centuries. The degree day method can be used to model the energy demand of conservation heating to different RH set points, with the results shown in figure 6.

As can be seen in figure 6, changing the RH set point has a considerable effect on the heat demand. A 2 % increase in the RH set point can reduce energy demand by approximately 12 %.

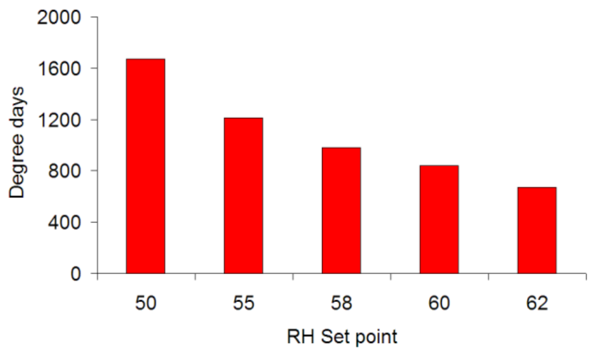


Figure 6 The annual conservation heating energy demand, as shown from degree days, at different RH set points. Data for Cragside, 2008.

As an energy-efficiency measure the Trust has begun reviewing RH set points for its conservation systems. A key conservation aim is that the RH is reliably maintained below 65 % for the prevention of mould growth. With conservation heating systems that deliver good, stable RH control, particularly electric heating, it is possible to operate at a higher set point and still keep RH below 65 %. Thus in some houses it is safe to operate at set points of 60 or 62 % RH. Conversely, in houses with less powerful heating systems there may be significant excursions above 65 % RH with a higher set point and thus it is sensible to operate these at the standard 58 % set point.

4.2. Measured energy use of National Trust conservation heating systems

Until the recent improvements in energy metering at National Trust buildings, it has not been easy to measure the actual energy use of conservation heating systems. Metering of energy has historically been at the point of supply to the property rather than for a particular use or area within the property. However several properties have had metering installed that is specific to the conservation heating system. This has enabled us to begin quantifying their actual energy use.

A study [4] of three smaller National Trust properties with electric conservation heating suggests annual energy use of 110–150 kWh/m^2 (40–50 kWh/m^3). If we look more closely at one of these properties, Canons Ashby a 17th century house in the English midlands (figure 7) we can estimate the energy cost and carbon emissions of its conservation heating system (table 2).

Figure 7 Canons Ashby House, Northamptonshire.

It would be desirable on wider environmental grounds for this conservation heating to be delivered with lower carbon emissions and at lower cost to the Trust. Therefore the RH set points at Canons Ashby have been adjusted from 58 to 60 % with an estimated annual energy saving of 12 %, and reduction in carbon emissions of 3241 kgCO$_2$ per year (table 2). In the future it may be possible to replace grid electric heating with lower carbon emission wet heating systems, but this must be done with care. A larger capital project would be required and the impact on the historic building fabric must be taken into account. Some properties have never had any heating pipework or radiators and their installation would be a significant impact on their historic fabric.

However many properties do have existing wet heating systems and the Trust's approach with these buildings is typically to divide the building up into a number of separately controlled heating zones, using existing and additional pipework runs, with the heat supplied by an externally located biomass boiler.

Table 2 Energy use and carbon emissions for electric conservation heating system at Canons Ashby. Data for 12 months, April 2009 – April 2010.

Energy Used (kWh)	Controlled area (m^2)	kWh/m^2	Controlled volume (m^3)	kWh/m^3	Estimated energy cost (£)	Carbon emissions (kgCO$_2$)
51246	347	148	1304	39	4612	27007

Table 3 Comparison of fuel costs, KWh demand and CO_2 emissions for the oil and pellet boilers

Year and fuel type	Annual fuel cost £	Annual thermal demand kWh	Annual CO_2 emissions (kg)	Degree days Northern Ireland	kWh per degree day
2008 oil boiler	5.390	94.684	25.091	2.255	42
2010 pellet boiler	3.726	69.380	4.163	2.682	26

5. USE OF ALTERNATIVE TECHNOLOGIES TO PROVIDE CONSERVATION HEATING

As discussed in the previous sections, the National Trust is prioritising the replacement of fossil fuel energy with renewable energy. For house heating systems heat pumps, which have been shown to work well with conservation heating [5], are being used at some properties, where there is a suitable water or ground source. However, the main type of renewable heating being installed at National Trust properties is the biomass boiler. An example of this is Ardress House, Northern Ireland, where the oil boiler was replaced by a wood pellet one to provide conservation heating, comfort heating and domestic hot water.

Figure 8 Ardress House, Northern Ireland

Figure 9 KWB Multifire 60KW wood pellet boiler installed at Ardress House in 2009.

Ardress House is a 17th century farmhouse, open to the public from March to September and on some school and national holidays. A resident managing tenant occupies part of the property not open to the public, though their demand for hot water and heating is minimal. Installed in 1994, the previous oil boiler was inefficient and the heating system badly setup. It was controlled by room humidistats linked to temperature controls, which called for heating for the whole house if one control was activated. The new boiler was installed in July 2009, new hot water storage and new RH controls installed in January 2010.

As demonstrated by Table 3, substantial savings have been achieved by replacing the inefficient boiler and improving the controls. It is clear that switching from oil to pellet has resulted in financial savings of one third of the 2008 fuel cost[1]. The more efficient boiler and control setup have reduced the energy demand by more than a quarter, and the 2010 attributed CO_2 is only a tenth of what it was in 2008. When the heating demands of the two years are compared, using heating degree days, performance is even more impressive because, in Northern Ireland, 2010 was a significantly colder year than 2008. In 2008, 42 kWh of energy was required per degree day of heating demand, but with the new wood pellet boiler and controls this fell by 38 % to 26 kWh per degree day.

The new heating system is managed by a building management system (BMS), which provides more intelligent control of the conservation heating and new boiler. Another improvement has been the use of a hot water accumulator tank, which acts as a "buffer" to the heat supply. The boiler does not need to run continuously, rather it only needs to bring the tank temperature up to a preset temperature and the call for supplemental heat or further running of the boiler is then determined by the BMS. Biomass boilers work more efficiently when operating at or near full load, whereas fossil fuel boilers can efficiently operated at lower loads, so do not need an accumulator tank.

[1] It should be noted that pellet prices are subject to increase – the initial cost per tonne in July 2009 for the Ardress supply was £129, now it is £165. However, oil has also seen an increase over the same timeframe – in 2009 it was around 45p per litre, at the time of writing it is 65p for National Trust properties in Northern Ireland.

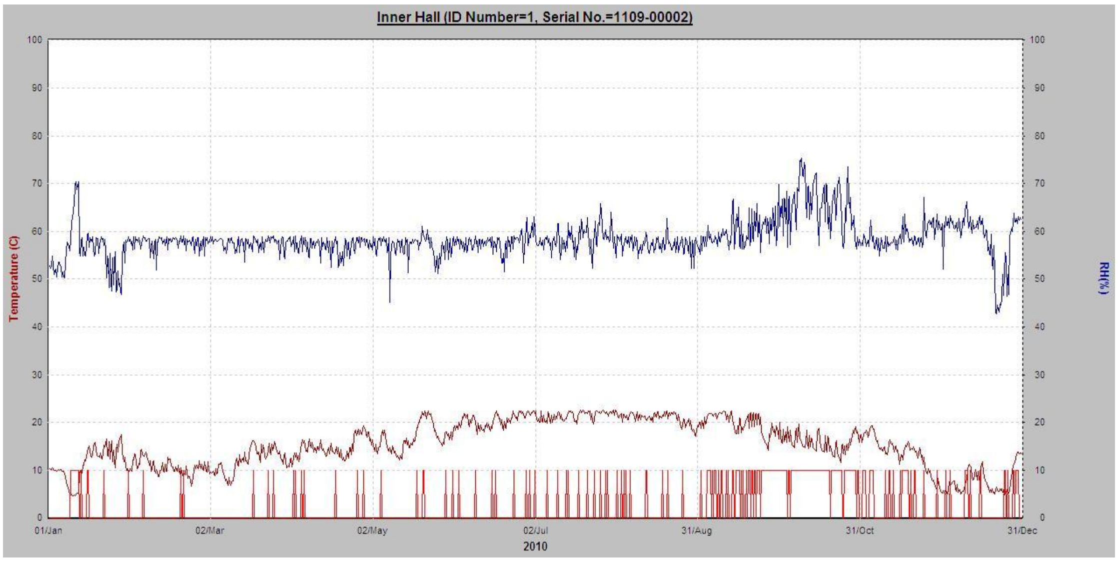


Figure 10 Environmental conditions maintained in the Inner Hall, Ardress by the biomass conservation heating system. RH was within the National Trust 40-65 % control band for 94 % of the time in 2010. The target specification is for 40-65 % RH to be achieved for 90 % of the time or better.

At Ardress the accumulator tank enables the operating characteristics of the wood pellet boiler to be matched to the 'little and often' demand that is characteristic of conservation heating. There is a quick response to heating demand for RH control, and at the same time unnecessary wear and tear on the pellet boiler is avoided.

Data from the first year of operation at Ardress, 2010, show that the new conservation heating and biomass boiler system is working very effectively. RH was maintained in the 40-65 % band across all of the showrooms 89-99 % of the time. Analysis of the data from the new system and the reliability of the boiler has enabled the RH set point to be increased from 58 % to 62 % in well controlled rooms, leading to further energy savings.

6. CONCLUSIONS

In this paper we have shown how the National Trust is using conservation heating as an effective environmental control strategy in its historic houses and at the same time seeking to reduce energy use and carbon emissions. By choosing appropriate technologies for generating heat and making efficiency savings based on detailed analysis of system operation, we hope we have demonstrated that these are not mutually exclusive goals, but can instead be achieved simultaneously.

7. REFERENCES

[1] Staniforth, Sarah et al.: Appropriate technologies for relative humidity control for museums housed in historic buildings. In: Preventive Conservation, Practice, Theory and Research, Preprints of the Ottawa Congress, 12-16 October 1994, Eds. Perry Smith and Ashok Roy (London: IIC, 1994), 123-128.

[2] Specification for Environmental Control, National Trust internal technical specification, (2010).

[3] National Trust 'Energy – Grow your own', (2010). www.nationaltrust.org.uk/main/w-energy-report-2010.pdf

[4] Blades, Nigel et al.: Analysing the energy consumption of conservation heating systems at the National Trust. Journal of the Institute of Conservation, 34(1), 16-27, (2011). http://www.tandfonline.com/doi/full/10.1080/19455224.2011.556912

[5] Brostrom, T and Leijohufvud, G. Heat pumps for conservation heating. Nordic Symposium on Building Physics, Copenhagen, (June 2008).

CONSERVATION HEATING IN A HISTORICAL BUILDING: RESULTS FROM AN EXPERIMENTAL AND SIMULATION STUDY

Henk L. Schellen, Edgar Neuhaus
Unit Building Physics and Systems
Faculty of Architecture Building and Planning
Tel: +31 40 247 2651
H.L.Schellen@bwk.tue.nl
Eindhoven University of Technology
Vertigo 6.29
P.O. Box 513
5600 MB Eindhoven

Abstract: For the conservation of an important museum collection in a historic building a better controlled indoor climate may be necessary. One of the most important factors is controlling relative humidity. Museum collections often are part of the interior of a historic building. In most cases the installation of an expensive air-conditioning system may cause damage to the building and its historic authenticity. Furthermore humidifying may lead to dramatic indoor air conditions with mould and condensation effects on the cold indoor surfaces or even internal condensation in the construction. One way to overcome this problem is to make use of so-called 'conservation heating'. A humidistat to limit relative humidity controls the heating system. Conservation heating control was tested in an experimental set-up in the laboratory and experience was gained in a historic building in the Netherlands. Control strategies and regimes were tested both by experiment and by simulation. The simulation model was validated by measurements. In the historic building the indoor climate was monitored during a long period. The preservation conditions of the indoor climate on the collection and the monumental building were evaluated. The indoor climate for preservation of a monumental building and its monumental interior may be improved by conservation heating. The human comfort however may decline. Furthermore it is a simple and energy efficient system which requires low maintenance.

Keywords: Conservation heating, microclimate control, building simulation

1. INTRODUCTION

Originally, historic buildings did not have any other heating system than an open fire or some kind of local heating system. Sometimes a central heating system was installed afterwards. Measurements in one of the most valuable historic buildings prove again that heating during the cold period leads to low indoor RH, causing damage to interior and objects (Neuhaus et al. 2004). Outside the heating season high RH often occurs, also causing risk for damage to interior and objects e.g. by mould growth (Erhardt et al. 1994). In most cases the possibilities to fully control relative humidity in a historic building, e.g. by installing a full air-conditioning system, is limited. Installing mechanical systems and ducts always will cause damage to the building and its historic authenticity. The high installation, maintenance and running costs are not even mentioned. Furthermore humidifying devices may lead to dramatic indoor air conditions with high surface humidity and condensation effects on the cold indoor surfaces of the exterior walls, single glazing and roofs, or even condensation in the inner parts of the construction (Schellen 2002).

The principle of conservation heating is controlling the heating system using a humidistat device (Staniforth et al. 1994). Literature on conservation shows that control of relative humidity is more important than control of temperature (Michalski 1998). With conservation heating, relative humidity is stabilized by selective heating. High relative humidity is prevented by starting heating. Reaching low relative humidity during the cold season is prevented by limiting heating to maintain a certain lower temperature setpoint. The use of this control however is restricted. In summer it may be necessary to start heating and during wintertime it may be necessary to limit heating, causing thermal discomfort of occupants. In the Netherlands there is little experience with conservation heating.

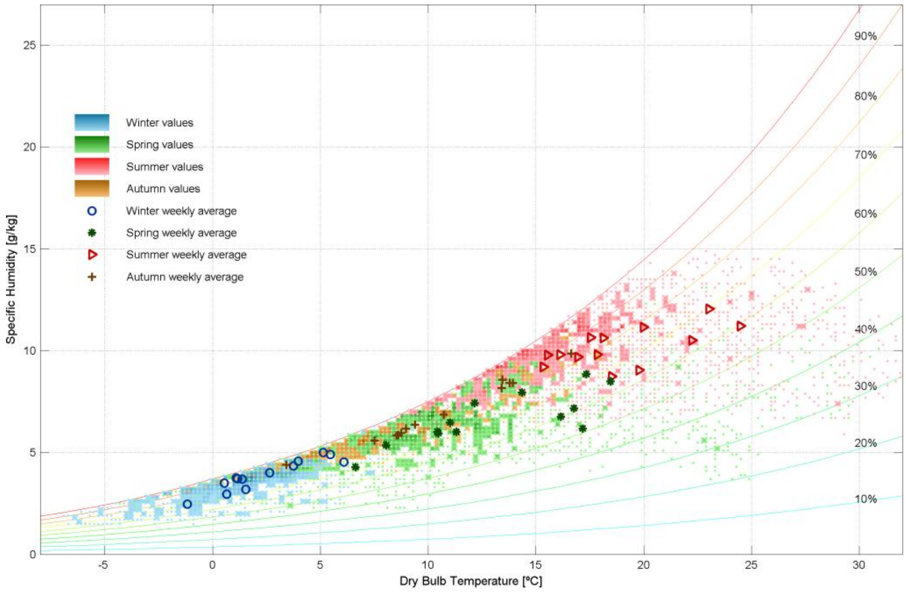


Figure 1 Dutch outdoor climate data plotted in the psychrometric chart for the year 2006

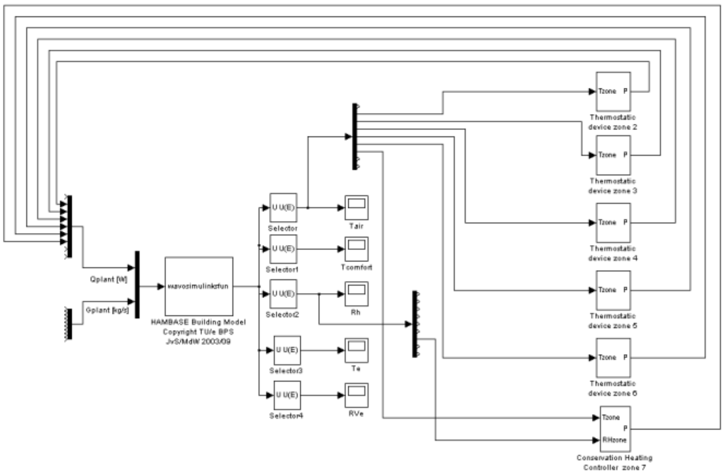


Figure 2 Simulink Block diagram of simulation model

2. OBJECTIVES

The main objective of this research was to determine the suitability of humidistat-controlled heating in the Dutch climate. The Netherlands have a maritime temperate climate with a cool winter, warm summer and a uniform precipitation distribution, *Cfb* according to the Köppen climate classification system (Köppen 1931). In Figure 1 the Dutch outdoor climate for the year 2006 as measured in De Bilt is plotted in the psychrometric chart.

Prior to testing on site in a historic building comprehensive laboratory testing was performed. First objective of this pre-testing was to develop a general validated simulation model for conservation heating to gain insight on the effect on the indoor climate, control strategies, needed heating capacities and optimal setpoints. An additional objective was to investigate how to provide limited comfort during the use of conservation heating.

Second objective was to gain experience using the needed materials and instruments for the experimental set-up in the real monument by building a set-up in the test-site on the campus.

Third objective in the research was to construct a heat and moisture simulation model for this particular historic building to predict the suitability of conservation heating for this specific case. This building model is validated with measurements.

Fourth objective is testing with an experimental set-up in the real monument. Testing started during the cold winter months and will be continued for a full annual cycle. During these tests valuable data and more experience on the interaction between climate and building physics are gained.

3. METHODS

3.1. Modeling conservation heating

Simulations of the indoor climate were performed using the heat and moisture model HAMBASE (Wit 2006) coupled to Matlab Simulink (The Mathworks 2006). The Simulink block representation is presented in Figure 2.

Table 1 Setpoints for the controller devices in the model

Thermostat-controlled room		Humidistat-controlled room	
Start daytime	8 a.m.	Tmin	10 °C
Start nighttime	10 p.m.	Tmax	25 °C
Tday	17 °C	Tset	17 °C
Tnight	17 °C	RHmin	45 %
		RHmax	55 %

The largest block contains the HAMBASE building model. The blocks at the right side are the conservation heating controller and conventional thermostatic devices of the different zones of the model. The inputs of this block are temperature and RH of the zone to be controlled. For the thermostatic controlled room during day the temperature was controlled at T_{day} and during night at T_{night}. The period of the day started at *start daytime* and ended at *start nighttime*. The control strategy in the humidistat-controlled room is based on the flowchart as given by Figure 3 and modeled using Simulink (Schijndel et al. 2003). First it is checked if the room temperature is higher than the set minimum temperature Tmin. If not so, the heater is switched on. Next it is checked if the temperature is below the set maximum temperature. If not so the heater stays off regardless of RH conditions. It is important to limit Tmax in order to avoid overheating of the room, e.g. during summertime. If temperature is between the setpoints of minimum and maximum temperature, the controller continues to check if correction of RH is acquired by checking if the current RH is higher than the set maximum RH. If so, the controller switches the heater on until the relative humidity is below RHmax or the temperature Tmax is reached. In historic buildings where human comfort is needed, the possible provision of limited thermal comfort by slightly expanding the controller is investigated. If RH is between RHmin and RHmax, heating is possible to raise indoor temperature and increase thermal comfort. The heater will stay switched on until RHmin or the desired comfort temperature Tset is reached.

Dependent on the input values the condition is checked if heating is required according to the conditions as given in Figure 3. The output of the controller is zero or, if heating is required, the set heating capacity for this zone.

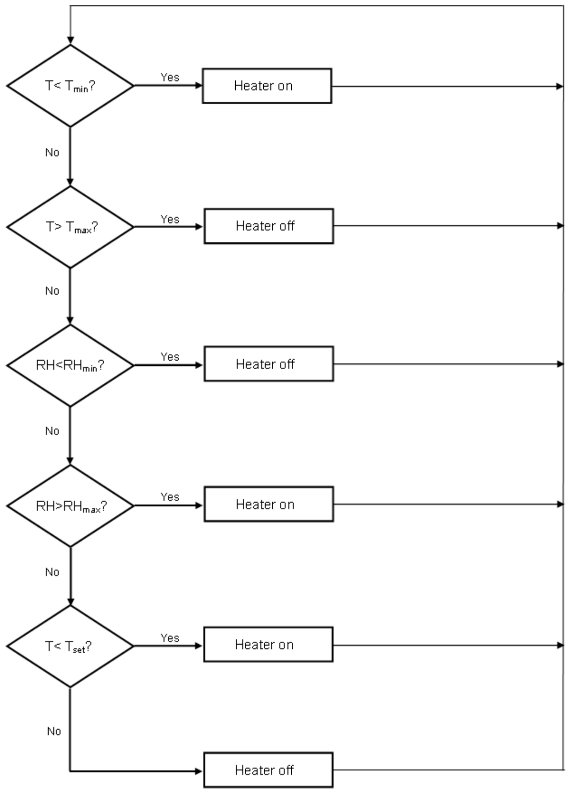


Figure 3 Flowchart of conservation heating with limited comfort function

Setpoints of both controllers are given in Table 1. RH boundaries of the humidistat-controlled room are set to 45 % and 55 %. These values are chosen to maintain indoor climate conditions between 40-60 % RH, which gives a moderate risk of mechanical damage to high-vulnerability artifacts (Kelter 2003). Settings of the thermostat-controlled room are set to a constant temperature of 17 °C to avoid fluctuations. Air exchange rate in the rooms is not measured and is set to an estimated value of 0.8 times per hour.

3.2. Experimental set-up

For an experimental set-up two rooms in the historic building were selected on the first floor. The building is T-shaped and made out of masonry with concrete floors and single glazing. During testing this part of the building was unused and doors and windows remained closed. There were no known moisture sources in this part of the building. Sun blinds were closed for about 60 % of the window area during testing (Figure 4). The configuration used for the experimental set-up consisted in each room of a laptop computer for control, three electric oil-filled radiators of 1 kW each and a combined T/RH-sensor. The radiators were placed 1 meters off the outside wall. T/RH sensors were mounted on a tripod

Table 2 Accuracy of the used sensors for measurement and control

T/RH sensor type	Accuracy	
	Temperature [˚C]	Relative humidity [RH]
Eltek GenII GC-10 (measurement)	± 0.15	± 1.4 %
Vaisala HMD70Y (control)	± 0.4	± 2.0 %

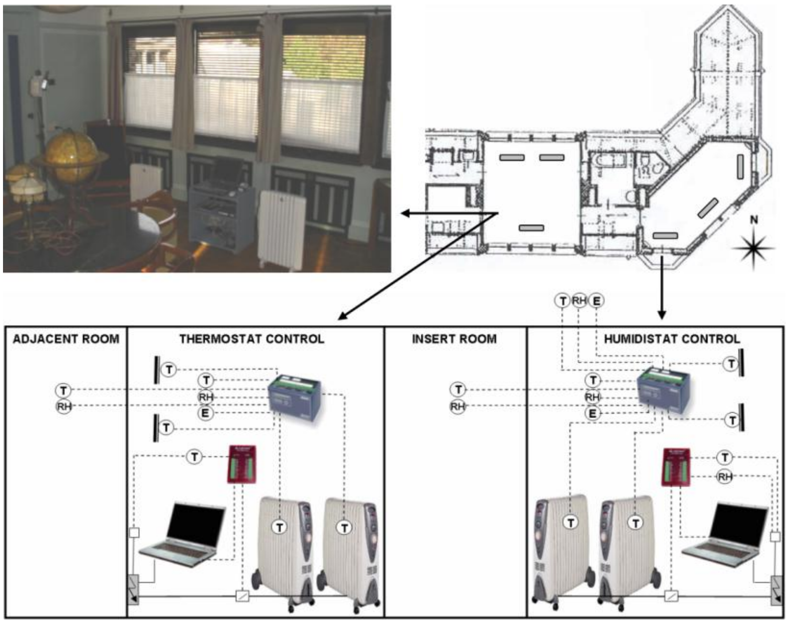


Figure 4 The upper left image shows the set-up in the thermostat-controlled room. A floor plan of the two rooms where the set-ups were installed in is given by the upper right image. This floor plan also shows the locations of the heaters. Schematic representations of the configuration of the test set-ups are also given

about 1.50 m high, in the middle of the room. The existing central heating system was switched off for these rooms. In one room the set-up was installed to heat the room according to conservation heating. The software was programmed according to the flowchart as shown in Figure 3. Every 10 seconds the software ran a loop with current temperature and relative humidity as input.

In another room the set-up was installed to thermostatically heat the room. Setpoints of both controllers were likewise as shown in Table 1. At first, the settings for the thermostat-controlled room were set to a day temperature of 20 °C and 15 °C during the night. After one week of testing, measurements showed high daily RH fluctuations up to 15 % RH caused by the temperature setback at night. Therefore the thermostat-controlled room day temperature is set to the same value as the night temperature after one week. This is done to avoid deliberate fluctuations of RH in the valuable historic interior and thereby limiting the risk of any damage done to the interior during the experiment. The electric radiators were controlled by a simple on/off switch. Additional heat production was limited by using only one laptop computer per room to control the heaters. In the rooms under investigation indoor air temperature, surface temperature of window and wall, relative humidity and incoming solar radiation were monitored. In adjacent rooms air temperature and relative humidity was measured. Outdoor temperature, relative humidity and solar radiation were also monitored.

4. RESULTS

4.1. Conservation heating model

Figure 5 shows simulation results of relative humidity from January 14th to February 14th 2006 of the humidistat-controlled room in the historic building. In this figure one month period is zoomed in to make the control strategy visible. Simulation results are validated with measurements. Minor discrepancies occur possibly due to the estimated air exchange rate of 0.8. Furthermore sensor accuracy plays a role. The accuracy of the used T/RH sensors is given in Table 2.

It is visible that with a Tmin set to 10 ˚C it is not possible to maintain a minimum of 45 % RH due to the low specific humidity of the outdoor air, which mostly occurs during wintertime (Figure 5: 22/01–04/02). Over the simulated period Tmin has to be lowered to about 4 ˚C to maintain 45 % RH in the Dutch climate. In Figure 6 simulation results of RH and temperature are shown if the room is humidistatically heated with (simulation 1) and without (simulation 2) the limited comfort function. Without using the comfort function heating is only necessary to obtain the lower temperature limit or to limit high RH.

During times that RH is between limits (Figure 6: 17/01–23/01 and 04/02-14/02), heating is started to reach the set value of 17 ˚C to provide limited comfort. The temperature level to which the indoor air temperature can be raised is strongly dependent on the conditions of the outdoor climate however. If no comfort is desired heating is only necessary to maintain the lower temperature boundary or to lower RH. This results in a reduction of the use of energy and installation components which promotes longevity.

In Table 3 annual energy expenditure of three different heating strategies in an identical room is compared. Values are obtained by simulation using the outdoor climate data of the year 2005. Results show that conservation heating without limited comfort function uses about 30 % less energy in comparison to a conventional thermostat control.

In Figure 7 temperature and RH of the test set-up and simulation are plotted in a psychrometric chart. This is done both for the thermostat- controlled room as for the humidistat-controlled room. The different colors represent the seasons. The symbols represent the weekly averaged values.

In the thermostat-controlled room (upper figures) low RH occurred during periods of low specific humidity (winter time and early spring time). The blue winter weekly averaged RH reached values downto 20 % RH. In the same periods RH in the humidistat-controlled room (lower figures) is clearly higher due to a lower indoor temperature. The lowest winter time values reached were about 35 % RH. When we compare the measured results (left figures) to the simulated results (right figures), the results look very similar. Both the lowest and highest temperatures and RH's were predicted well. In the matrices the percentage of pixels within and outside the guidelines (blue area) are presented. The middle of the matrix presents the values within the guidelines. Also these values are very comparable for measured and simulated results.

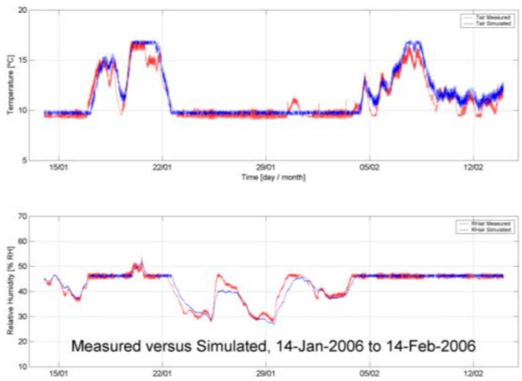


Figure 5 Simulation results of temperature and relative humidity in the humidistatically heated room over the period from January 14th to February 14th 2006

Table 3 Estimation of the annual energy use in 2005 by HAMBASE considering the same room

Heating Strategy	Annual energy use [kWh]
Conservation heating without limited comfort function	4329
Conservation heating with limited comfort function	5431
Conventionally thermostat-control*	6133

*day temperature 20˚C with 5 K setback between 10 p.m and 8 a.m.

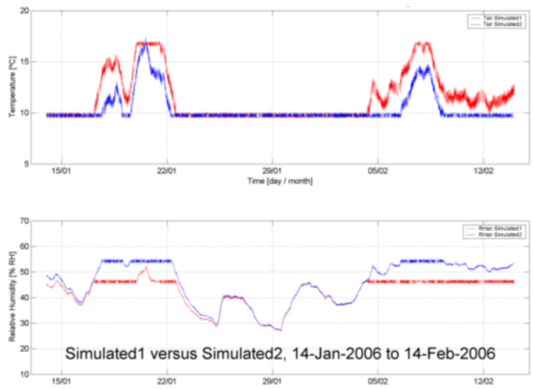


Figure 6 Simulation results of RH when limited comfort is provided and when not

5. CONCLUSIONS

Conservation heating is an efficient technique to create preservation conditions in historic buildings in the Dutch climate. The largest benefit is elimination of extremes in indoor RH. Fluctuations in temperature and RH also are lower compared to a conventional thermostat-control with a night setback. Apart from providing improved conservation conditions energy expenditure is far lower compared to conventional heating to provide thermal comfort. Improved comfort can be provided by limited heating when RH is between desired boundaries. This possibility is strongly dependent on the specific humidity (kg/kg) of the outdoor air.

Conservation heating is ideal for historic buildings that are closed for the winter season and do not accommodate highly sensitive artifacts. The choice for the use of conservation heating depends on what is forwarded as being the most important: the comfort of visitors or the value of furnishing and artifacts. If conservation heating is applied in countries with a temperate maritime climate like the Netherlands, thermal comfort during the heating season is low. But if humidistat-controlled rooms are part of a tour, visitors are relatively active and could leave their coats on. If visitors in addition are informed about the system, Tmin can be set to a lower value of e.g. 10 ˚C without causing large comfort problems.

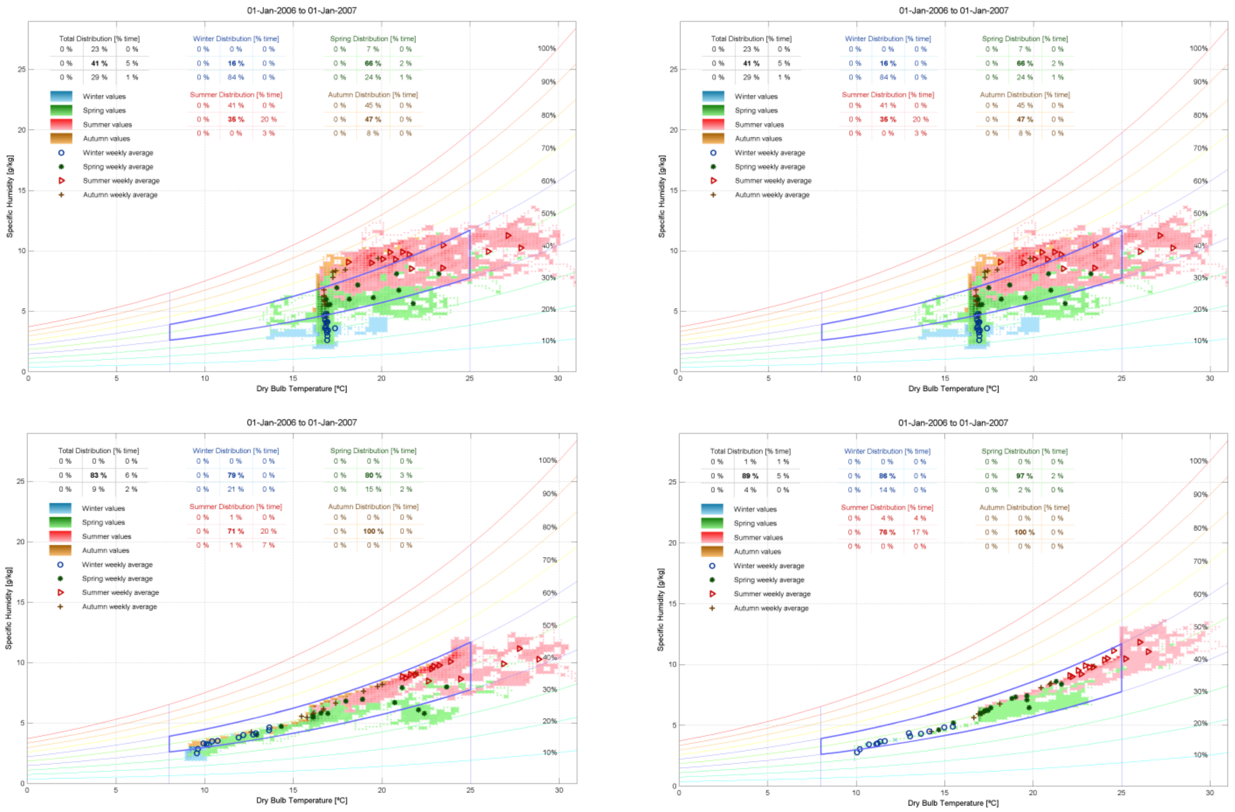


Figure 7 Measured (left) and simulated (right) indoor climate for both the thermostat (upper) and the humidistat-controlled room (lower) over the period from January 1st 2006 to January 1st 2007

If no thermal comfort is desired, values of the controller have to be selected for minimum use of the heaters, to be energy efficient and promote longevity of the system. Settings can differ per project and depend on both building physics and collection. The lower temperature setting has to be determined by assessing the temperature sensitivity of the collection, the presence of water filled pipework and the function of the room. Simulation results show that Tmin can be set to a lower value of about 4 ˚C to obtain a lower RH limit of around 45 % in the Dutch climate. When comfort is required during specific times, the limited comfort function can be used during conservation heating. By expanding the conservation heating controller with a timer it is possible to only heat during times thermal comfort is desired. In this case it is important to use a limiter to prevent quick heating of the room. The use of a limiter in the control is also recommended for situations that the installation restarts after e.g. a malfunction. Furthermore modeling is useful to determine optimal controller settings and gain insight in energy expenditure.

Our experimental set-up showed a side effect when having a room with humidistat control next to a room with thermostat control. This resulted in a wooden door that bend due to the difference in temperature and related RH. It is recommended to reduce these differences. Also literature shows that heating may run out of control in rooms with a small air exchange rate and many hygroscopic materials due to the release of moisture (Padfield 1996).

Future work consists of identifying in which climate conditions conservation heating is feasible and where not. Furthermore the effect of indoor moisture sources on the stability of the control will be researched using modeling and an air exchange rate measurement of the building where the test set-up was installed in will be performed.

6. ACKNOWLEDGEMENTS

The authors wish to thank the staff of the Dutch Government Buildings Agency, the Netherlands Institute for Cultural Heritage and Park De Hoge Veluwe for their contribution in this research.

7. REFERENCES

[1] Erhardt, D. and Mecklenburg, M. (1994). Relative humidity re-examined. Preventive Conservation: Practice, Theory and Research. Preprints of the Contributions to the Ottawa Congress, September 12-16 1994, 32-38.

[2] Kelter, S.L. et al. (2003), Museums, libraries and archives, Chapter 21, ASHRAE Applications Handbook SI Edition.

[3] Köppen, W. (1931). Grundriss der Klimakunde (Zweite, verbesserte Auflage der Klimate der Erde), Walter de Gruyter & Co., Berlin, Leipzig.

[4] Michalski, S. (1998). Climate Control Priorities and Solutions for Collections in Historic Buildings. Historic Preservation Forum 12(4): 8-14.

[5] Neuhaus, E. and Schellen, H.L. (2004). Hunting lodge St.Hubertus of Hoenderloo, analysis of the indoor climate, Eindhoven University of Technology, Unit BPS, 04.94.K (internal report in Dutch)

[6] Padfield, T. (1996). 'Low Energy Climate Control in Museum Stores - a postscript. Proceedings of the ICOM-CC Conference Edinburgh, September 1996, vol 1, 68-71

[7] Schellen, H.L. (2002). Heating Monumental Churches, Indoor Climate and Preservation of Cultural Heritage, Dissertation, Eindhoven University of Technology, Unit Building and Physics

[8] Schijndel, A.W.M. van, Wit, M.H. de (2003). Advanced simulation of building systems and control with Simulink, 8th IBPSA Conference Eindhoven, August 11-14 2003, 1185-1192

[9] Staniforth, S., Hayes, B. and Bullock, L. (1994). Appropriate technologies for relative humidity control for museum collections housed in historic buildings, The International Institute for Conservation of Historic and Artistic Works (IIC), London, 123-128

[10] The MathWorks (2006). Simulink, Simulation and Model-Based Design, version 6, Natick, Massachusetts, USA

[11] Wit, M.H. de (2006). HAMBASE, Heat, Air and Moisture Model for Building and Systems Evaluation, Eindhoven University of Technology, Unit BPS, ISBN 90-6814-601-7

HISTORIC BUILDINGS AS MUSEUMS
Sustainability and energy saving in museums, depots, churches and historic buildings

Jochen Kaeferhaus
Technisches Büro Käferhaus GmbH, Vienna,
kaeferhaus@aon.at

Abstract: The mostly too strong limits of recommendations or museums standards (for example British Standard BS 5454:2000) often provoke too much machinery in museums and depots with the result of contradictory output. Huge air conditioning systems, big energy bills and measuring results with short term peaks endanger the artefacts. Consequences may be that in the future we cannot any longer afford our museums or depots, especially when energy is getting more and more expensive, not mentioning the totally unsolved situation of what might happen in those strongly air conditioned museums when there is a failure in energy supply, for example when no gas is delivered.There are many museums however, with none or a minimum of building services, which shelter very delicate artefacts as the “Stift Klosterneuburg” with its “altar of Verdun” of the year 1180. Climate control was never installed, but the altar has no damages at all.

Keywords: energy saving, micro climate, sustainability in historic buildings, comfort, stability in climate, humidity, radiation heat, tempering

1. INTRODUCTION

The upcoming discussion of sustainability is more than a fashion. It is a severe necessity – especially in historic buildings. That means it is “very simple” to build on the “green meadow” a passive house, but it needs a lot of brain to transform an ancient building into a sustainable, energy saving building. This is the problem with our museums and depots, often hosted in historic buildings, to refurbish these historic buildings with a bunch of necessary activities – building services included.

2. DISCUSSION ABOUT STANDARDS OF MICRO CLIMATE VALUES

The discussion about “right and wrong” micro climate and the limits is endless.The quoted articles in the annex are exemplary. Fortunately critical voices as from Tim Padfield and the “Fraunhofer Institute”, Holzkirchen, Germany, stress again and again the bigger importance of slow movement of the micro climate according to seasonal outdoor changes, buffered through big building masses, instead of narrow limits for the micro climate with peaks.

The “classic” demand for 50 % rel. humidity and ± 5% limit and room temperature of 20 °C ± 2 K never was proven or is a result of thorough research, but is a phantom figure, one scientist copies from the other.

These limits – depending of the kind of artefacts - are far too narrow and often have the consequence of too big machinery with centralized humidifier and complex control units, which costs a lot of money to buy, to run and to maintain. Often those air conditionings and control units are far too complicated and difficult to run. Often they are a source of mistakes and create peaks which damage to the artefacts. The leading value for the micro climate always is the relative humidity and not the temperature, which should oscillate very, very slow from 40 % to 60 %, depending of the artefacts, with an hourly change of RH of maximal 5 % and a daily change of about 10 % .

3. HOW TO REACH BEST CLIMATE STABILITY

According to the long-term experience, the following recommendations can be formulated:

- Integrated planning
- Intelligent use of big masses of the building to reach thermo stability
- Improvement of the thermal quality of the building, if possible
- Ensure air tightness and create buffer rooms
- Using best possible, intelligent shading systems to minimize external loads
- Reducing internal loads (light, machinery) to 15 W/m² maximum.
- Heating exclusively by radiation with warm walls to avoid mould; convective heat transports dust
- Simple controlled ventilation with minimum air exchange rate to 0.5, if possible
- Humidification, if possible, decentralized

- Simple technologies for building services and control systems as thermostat valves.

4. EXAMPLES

Art Gallery in the Academy of Fine Arts, Vienna

Figure 1 Academy of Fine Arts, Vienna

The Art Gallery in the Academy of Fine Arts (Fig. 1), Vienna, is a building of Theophil Hansen of 1877 and is primarily a University of Art.

The existing gallery was refurbished in the late 80ies and consists in a size of about 800 + 400 m² with very famous paintings as “Das jüngste Gericht” of Hyronimus Bosch and others like Lukas Cranach the younger and elder.

In addition to the existing paintings gallery a new gallery for contemporary art, “xhibit” was created and integrated in the same part of the building with new entrance room, shop and cashier.

The picture in Fig. 2 shows the situation before the refurbishment with old radiators and bad shading systems and isolating glass of bad thermal quality.

Figure 2 Existing situation in the former painting gallery before the refurbishment with radiators, which transported dust and dried the gallery air and the decentralized humidifiers, which were used later on

Principally the values of the indoor climate were rather stable, in winter too dry and in summer sometimes too hot. Due to the lack of a closed entrance room as a buffer zone, the indoor climate often was influenced of bad climate situations in the stair case. For that reason a new buffer room as shop and cashier was planned. Also ventilation with cooling system with possibilities of dehumidifying was planned.

The following measures as an integrated planning were taken:

(Thermal improvement or insulation was not necessary due to the fact, that this story of the art gallery is situated in the middle of the building with heated rooms below and above.)

- Air tightness of the rooms and especially of the windows were planned as well as the improvement of the thermal quality of the windows, which are historic metal case or box windows which are not allowed to change in any form. An improvement of the window only was possible by changing the glass and sealing the joints of the inner layer of the windows. The inner window got an insolating glass with an u-value of 1.1 W/m²K with a coating against heat losses from inside. The outer glass is a single pane also with a coating against sun rays but with no change in color so the outer appearance of the historic building wasguaranteed. To get the best thermal results, several glass and coating qualities were dynamically simulated.
- As a shading system a new screen was chosen after long discussions and dynamic simulations (trnssys), since the conservators asked for a maximum light intensity of about 220 lux and the dean of the academy asked for a shading system with view contact to outside, assuming the neighborhood of the academy. Furthermore the outer layer of the window got 2 little Swedish slit ventilation openings (Fig. 3), which are closed in winter and opened in summer in order to ventilate the inner case of the window in summer. Measurements of the inner glass temperature in summer have proven about 10 K less temperature of the surface of the window, compared to a window, which was not ventilated. That means with such a sophisticated shading and ventilating system the external loads are remarkable less despite the huge size of the windows (3,5 x 2,5 m).
- Also the internal loads of the gallery were remarkable reduced due to led light, which was partly chosen for the gallery. Also the general room light towards the ceiling is automatically dimmed upon intensity of the daylight.
- A very important item of the refurbishment is the creation of a vestibule with compartments where the shop and the cashier is situated (Fig. 5), in order to control the air exchange from the stair case into the two galleries which is no longer possible as it was before the refurbishment.

Figure 3 Summer ventilation system of the shading in the box window with Swedish slit openings in the frame which were closed in winter in the Art Gallery in the Academy of Fine Arts.

Figure 4 View into the painting gallery during works without convective radiators but with the new wallheating, which shows the pure beauty of this large exhibition room

Figure 5 View into the buffer room, which avoids air ventilation from the corridor to the art galleries, coming from the entrance hall with the cashier going to the painting gallery to the left hand side and to the “exhibit”, which is a gallery for modern art on the right hand side

Figure 6 Copper tubes for pure radiation heat in the walls (tempering), later embedded in plaster above metal channel for electric wiring, which was later covered with wooden baseboard

Figure 7 New copper convectors, earthened by electric wire in plugs to avoid dust transport, under the historic windows, since wall heating before wood is not possible

- The installed building services are very simple as for the heating. The existing radiators were dismounted and a pure radiation heat as a tempering system was mounted instead– which meant, that only two copper tubes were put into the plaster of the outer wall, not as a register but only two lines parallel to the bottom (Fig. 6).
- Warm outer walls with simple thermostat valves help to have a constant room temperature in winter of about 18-19 °C. So there is absolutely no danger of mould growth since there is never a condensation since we do not reach dew point with humidity on the walls, which is necessary for the mould spores to grow, since the walls are all warm. The “comfort” of warm walls for the paintings and artefacts is very important, as it is also important for the guardsmen. With the warm walls it is easily possible and comfortable to reduce room temperature below 20 °C, which helps to avoid winter dryness without humidifying. As known from physics lessons, 1 K more room temperature not only means about 6-10 % more

energy consumption, but also about 3 % less rel. humidity.

- For cooling and ventilation a cooling unit of 27 kW was placed as one single unit on top of the lift shaft on the roof. Whereas inside the house on top of the lift shaft, under the cooling unit, in a very small technical room the ventilation unit of 6000 m³/h, which means an air exchange rate of 0.5-2 was installed. Also a heat recovery system of a rotating wheel was build to reach best possible heat recovery (90 %) and also humidity recovery (enthalpy wheel).
- In the part of the modern gallery, the "xhibit", an own air handling unit (AHU) was installed with a capacity of 2.000 m³/h, also with best possible heat recovery systems, but without a cooling system, since this gallery is headed towards north and in summer not really hot, due to the big building masses. An existing chimney was used to have a clandestine air intake and exhaust opening which is not be seen from outside. The Austrian monument authorities asked for these details, in order not to destroy the historic ambiance of the building through building services. The air of the 6000 m³/h AHU (air handling unit) is taken through a historic tunnel in the earth, surrounding the building to keep the foundation dry. The size of this tunnel is about 1,70 m high and about 1m large and is made of bricks. This air intake through the tunnel cuts extreme temperature and humidity peaks in summer and in winter.
- The existing historic vertical chimneys were used for the distribution of the air in the building and far distance jet nozzles bring the air in the gallery, totally without any visible ducts.
- The ventilation is activated, when the air quality sensor exceeds a CO_2 concentration of more than 1.200 ppm, which very rarely occurs, due to the great air volume of the rooms. Generally the AHU is activated, as a first priority, when the air quality is bad. Further, the AHU will be activated, when outside, there are favorite conditions for the microclimate in the gallery, by comparison of absolute humidity and temperature inside and outside. When ventilating, it is very important to start ventilation very, very slow until the necessary rpm, to avoid peaks in the microclimate. Cooling will be activated in summer, when room temperature exceeds 26 °C, which was not necessary last summer 2010. Therefore the energy needs for cooling and ventilation were almost zero. Only for heating in winter a specific amount of about 50 kWh/m² was necessary.
- The rest of the housing services is standard and known. Good and cold light and best possible security.
- The last item is an interesting point of view: internal air quality and internal pollution. A subject, often forgotten, especially during refurbishments, since lots of paint and chemistry is used during work. Therefore the walls on which the paintings are mounted, were filled with lambs wool and small, silent and very slow working ventilators circulating room air through the keratin fibers, which have purifying effect, above all against formaldehyde.
- Finally the question of centralized or decentralized humidification was really thoroughly discussed. Fortunately the existing decentralized humidifiers were accepted and no centralized system with the AHU was asked for, since these systems mostly create problems and they are always a source of germs and mould. In additions they cost energy because they make the ventilation working all the time.

Depot in the ground floor of the Academy

The next example is a very sustainable depot with high climate stability in the ground floor of the same building, which was necessary to host all the precious paintings during refurbishment. It was a very bad and humid room of about 300 m² which was improved in a very short period.

With few time and few money with new concrete floor and new storage racks, new simple light and new doors this depot was ready within three month, in the beginning even with more humidity due to the new concrete floor.

For heating, drying of the walls and stability of micro climate a wall heating system (tempering) was installed (Fig. 8), which helped to reduce the humidity in the room due to the humid walls and the new concrete floor with lots of water.

Figure 8 Installation of simple wall heating with only two copper tubes in the plaster of the wall in the depot against humidity and for climate stability

For the ventilation in the depot a 400m³/h air handling unit (Fig. 9), normally used in passive houses with 90 % heat recovery was installed.

Figure 9 Depot ventilation with an ahu build for passive houses and the central heating system with the distributing device

The control of the ventilation follows the same rules as in the "Art Gallery" three stories above.

The results were astonishing: The stability of the micro climate in the depot was unique, only in summer, sometimes the limits of rel. humidity exceeded the 65 %. So a dehumidifier was installed.

The investing costs as well as the running costs of the depot are minimal.

The "Ciesa San Colombano", Bologna

Figure 10 View into the "Chiesa San Colombano"

Next example for an integrated, sustainable refurbishment was the transformation of the Church St. Colombano in Bologna (Fig. 10) with roman roots into a museum of harp cords of the world famous collection of Maestro Tagliavini.

The principles for climate stability are the same: Airtight shell, (heavy) insulation of the roof, shading, buffer room at the entrance, wall heating and controlled ventilation.

In the first floor, the installation of the heating was most difficult, due to the wooden covers of walls, seats and even floorand paintings on the wall. Therefore the radiation heating system was installed invisible beneath the wooden benches (Fig. 11).

Figure 11 View into a room in the 1. Floor richly decorated with paintings and wood, even on the floor with copper heating coils under the wooden bench

Despite the ambitious planning, the last corrections of the heating control are not possible, since in some rooms it is far too warm, which means also far too dry, less than 40 % rel. humidity, which is unacceptable for wooden instruments. Instead reducing the heating from 24 °C to 16 °C, humidifiers should be bought, what makes no sense.

Also the control unit for the AHU was not set right, so cooling effect of night cooling in summer could not be achieved. A situation, which often happens, that control units are not installed the right way.

The Stift Klosterneuburg

Figure 12 View to the "SalaTerrena" of Stift Klosterneuburg

StiftKlosterneuburg (Fig. 12) is unique for its rich early medieval art as the "altar of Verdun" (a very rich email work, see Fig. 13) and the painted wooden wings from the same altar (Fig. 14).

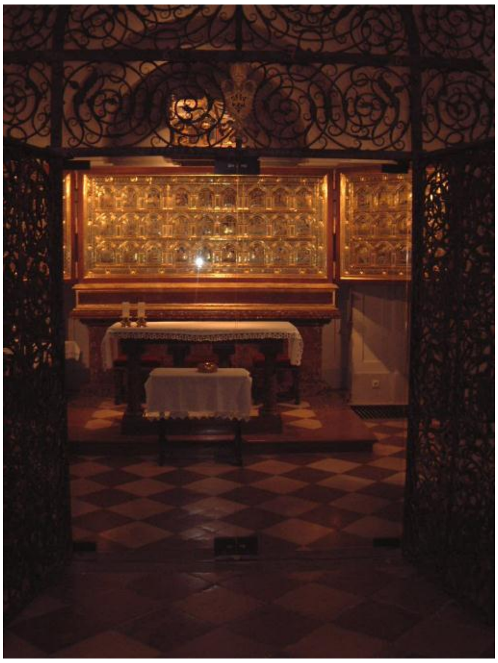


Figure 13 View to the unique "altar of Verdun" made in 1018 out of email

During the refurbishment in 2008 pure radiating heat as wall heating was installed, where possible with small ventilation.

Since near the altar absolutely no dust was allowed, for more comfort one wall was covered with clean, dry plasterboard with integrated tubes for heating, which served as source of radiation heat. A little ventilator in the wall with filter brings fresh air, when favorable, through comparison of absolute humidity and temperature, inside and outside.

Figure 14 View to the wooden wings, the rear sides of the "altar of Verdun"

The medieval room got a wall heating and a controlled ventilation from the ground floor.

The underground *book depot* in the Monastery of Einsiedeln, CH

Figure 15 Front view to the Monastery of Einsiedeln

For the numerous and precious books of the monastery of Einsiedeln (Fig. 15) an underground depot (500 m²) (Fig. 16-17) is built and the existing historic building will be transformed into a library.

Various dynamic simulations with trnssys have proved that cooling of such an underground depot with continuous temperature of the earth about 10-13 °C is not necessary.

Different insulation keeps the balance of heat losses and gains in the depot and tempering in the walls, which got a clay plaster for humidity exchange, avoid mould and keep a minimal temperature between 18 and 22 °C.

Ventilation of 0.5 to 2 air exchange rate is planned. For heating the depot waste heat from the IT trough a heat pump is used.

Figure 17 View to the depot in the ground and the future library with humid walls on the left hand side, which will be refurbished

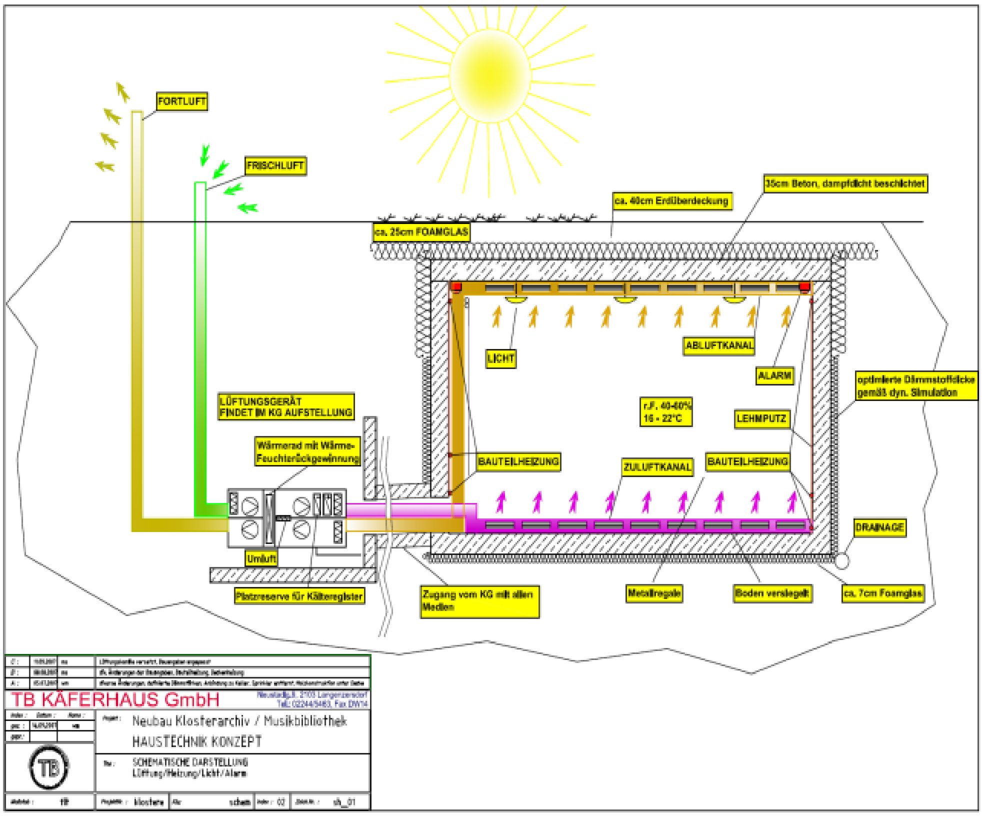


Figure 16 Principle of the book depot in Einsiedeln after dynamic simulation with trnssys

The Museum of Fine Arts, Vienna

Figure 18 View to the Museum of Fine Arts, Vienna with gallery IV with the cold wall problems

The museum of Fine Arts, Vienna, hosts very famous paintings.

Due to insufficient thermal quality of an outer wall towards the court yard (Fig. 19) in combination with a wrong convective heating system, mould was found at the back side of the paintings and on the drapery of the wall (Fig. 20-21).

Figure 19 View to the cold outer walls to the court yard, showing the thermal weak points of the lacking window, which are filled with thin walls with skrafitti

As known, mould spores are everywhere. The moment they find humidity like in our case because of condensation, they begin to live and grow.

In the middle of all show rooms seats with integrated convectors and steam humidifiers circulate room air, dust and humidity towards the ceiling as shown in Fig. 22. Near the cold outer walls the chilled room air falls down, leaves humidity and damaging the paintings with mould.

Figure 20 View to the cold, outer wall, covered with cloth and affected with dust, humidity and mould

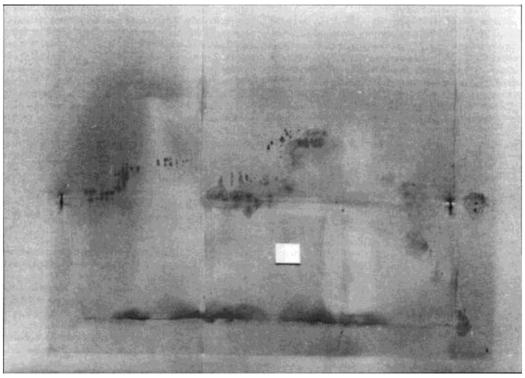


Figure 21 Mould, dust and humidity on the back of paintingswhich hung in front of cold walls

This situation occurs very often.

Figure 22 Wrong convective heating system with radiators in the middle of the benches with ultra sonic atomizer for humidification, driving humid, heated air towards the ceiling and falling down, cooled in front of the cold outer walls

To solve this critical situation, only heat to the wall brings a solution, which was done by a tempering system on the wall (Fig. 23), under the drapery, where the paintings were hung upon.

To be sure not causing any harm to the precious paintings, numerous sensors were installed and the energy consumption was counted, after the convectors in the middle of the room we put off, as well as the humidifiers. Both were no longer needed.

The most fascinating result was the reduction of the specific energy consumption of this room, which was about 140 kWh/m² before and 70 kWh after the refurbishment.

There was no more need neither for the convectors in the middle of the room nor for the humidifiers, which had deteriorated most this situation.

Figure 23 Wall heating on the cold outer wall

5. RESULTS

- We cannot afford any longer costs and bad micro climate in museums due to complex machinery
- History has shown, that stability of indoor climate is not a question of big housing services.
- Passive methods of climate control are sustainable, more affordable and sure
- We have to discuss the reasonable limits of micro climate, especially of rel. humidity
- The slow change of rel. humidity is more important than the discussion about figures

6. CONCLUSIONS

Sustanability, energy saving and stability of climate is not a question of machinery or building services. It is the result of integrated, intelligent planning including using the masses of the building.

Best shading, air tightness, buffer rooms, minimal internal and external loads, small ventilation, radiation heat, decentralized humidification are the colons on which sustainable planning is base on.

7. REFERENCES

[1] KAEFERHAUS, J. Nachhaltige Renovierung museum aktuel, München, (2010), Seite 25-28

[2] KAEFERHAUS, J. Quo vadis Austria museum aktuel, München, (2005), Seite 62-66

[3] F. BOODY, H. GROSSESCHMIDT, W. KIPPES, M. KOTTERER, Editors, Climate in Museums and Historical Buildings: Temperierung, (wissenschafliche Reihe Schönbrunn, Bd.9) Vienna (2004), as a main compendium about preventive conservation with long bibliography

[4] A. HUBER, A. KORJENIC, T. BEDNAR, Auf der Suche nach der richtien Entscheidung, Vienna (2010), Technologische Studien, Kunsthistorisches Museum

[5] J. KÄFERHAUS, A. HUBER, Symptome bekämpfen oder Ursachen vermeiden? Vienna (2010),TechnologischeStudien, Kunsthistorisches Museum

[6] J.KÄFERHAUS, Können wir uns unsere Museen auf Dauer noch leisten? Restauro Lindau (2011)

CLIMATE CONTROL IN CULTURAL HERITAGE BUILDINGS IN DENMARK

Poul Klenz Larsen[1*], Tor Broström[2]
[1] *Department of Conservation, The National Museum, Copenhagen, Denmark*
[2] *Gotland University, Visby, Sweden*
* *Corresponding author. Tel: +45 33473533, Fax: +45 33473327,*
E-mail: poul.klenz.larsen@natmus.dk

Abstract: Conservation heating has been used for decades to control the RH in cultural heritage buildings. But if the building is not used for living or working, heating is not needed for human comfort. The chemical decay of organic materials depends mainly on temperature, so it is better for preservation to reduce heating. The air exchange rate is related to the design of the building envelope. With rising energy prices humidity control by dehumidification may be an attractive alternative. The potential for energy efficient RH control was examined for a generic building exposed to the monthly average outside temperature and RH in Denmark. The indoor temperature was allowed to follow the outside average, whereas the indoor RH was controlled to 40 % 50 % 60 % or 70 %. Dehumidificationwas implemented in three different buildings: A recent museum store, a medieval church, and an 18thcentury country mansion. The energy consumption depends on the RH set point, the
air exchange rate and the source of liquid moisture to the building. The air exchange rate related to the design of the building envelope. Single glazed windows and doors are the most important sources of leakage to buildings. Lack of maintenance may lead to poor performance of the dehumidifier and waste energy.

Keywords: humidity control, energy efficiency, air exchange rate, case studies

1. INTRODUCTION

Conservation heating is a well established practice to control the relative humidity for preservation purposes [1]. It is a simple and robust method, but the stability of RH depends on the air infiltration rate and the temperature control. A peculiar aspect of conservation heating is that it is required also in summer to maintain a moderate RH. As energy conservation becomes more important, heating all year is less appropriate for climate control. Dehumidification is an attractive alternative for heritage buildings, where heating is not needed for human comfort. There are two methods for dehumidification of atmospheric air; absorption and condensing. The condensing dehumidifier contains the same elements as a refrigerator, but in a different combination: A fan drags the air through the cooling unit to extract the moisture, which drips into a bucket or to a drain. The cooled air then passes through the heating unit and back into the room a little warmer than before. This method works well in heated buildings but is less efficient below 8 ˚C. The absorption dehumidifier passes the air through a desiccant, usually silica gel, which absorbs the water vapour from the air. When the desiccant is full, a supply of warm air removes the moisture to the outside. The advantage of this method is that it works at low temperatures, even below zero degrees. The humidity is not transformed into a liquid, so the device does not need a drain or a bucked to be emptied. However, the device requires ducts for the release of the warm humid air to the outside. The energy consumption for dehumidification is dealt with through energy calculation of a generic building and a case study of three Danish buildings: A recent museum store, a medieval church and a an 18thcentury country mansion.

The question is how heating and dehumidification affects preservation. Any chemical process depends on the activation energy, and the speed of reaction increases exponentially with absolute temperature, as stated by the Arrhenius equation. For chemical processes involving water, the reaction rate also depend on the relative humidity. The effect of hydrolysis wasquantified by Sebera [3] to predict the durability of paper. He defined the isoperm as a relative measure of equal permanence for different combinations of constant temperature and relative humidity. The isoperm was set to 1 for the combination of 18 ˚C and 50 %. Lower T and RH would give higher permanence or longer lifetime and vice versa. The isoperm concept was not able to cope with variations in T or RH. Reilly [4] defined the Time Weighted Preservation Index (TWPI) as a measure of the lifetime of any object subjected to a given climate. The TWPI does not take into consideration the difference in durability for different materials and techniques. Padfield [5] proposed the decay index as an indicator of the relative damage to any object by any combination of T and RH. He designed a new diagram, which combined Seberas isoperm with the water vapour diagram (fig 1). The diagram has two sets of lines, one of equal decay rate (called isoburn) and one of equal water vapour content in the air. By combining the two it is straight forward to predict the effect of different climate control strategies on preservation. Starting at 8 ˚C and 75 % RH the decay rate is 0.3. If the RH is reduced to 40 % by dehumidification, the decay rate is only 0.15. If instead the RH is reduced by heating to 17 ˚C, the decay rate becomes twice as high. It is evident that conservation heating is less attractive than dehumidification because most objects degrade faster at higher temperatures.

2. CALCULATIONS

A model building was used for the calculation of energy demand. The size and shape of the building need not to be defined, because solar gain and heat radiation to the open sky was not considered. The building was empty and had no internal sources of heat, so the inside temperature would follow the outside. The main source of humidity into or out of the building was the outside air, which would enter at a constant rate, defined by the AER. The RH was maintained constant at 60 % all year by dehumidification. The calculation used the monthly averages of temperature and relative humidity in Denmark. For every month the excess moisture to be removed by a dehumidifier was determined. These data are presented in table 1. The energy needed for dehumidification to different levels of RH as a function of the Air Exchange Rate (AER) is shown in fig. 1. The energy was used to heat up the air stream that evaporated the moisture from the adsorbent. The heat of evaporation for water is 0.67 kWh/kg, but some additional energy was used heat up the cold outside air. The fan for recirculating the process air also needed a little power. It was assumed that an absorption dehumidifier would use 1 kWh to remove one kg of water from the air, regardless of the air temperature. The result of the calculations is presented in figure 2.

The energy consumption for dehumidification is proportional to the Air Exchange Rate for any RH setpoint. If the building is airtight there will not be any need of dehumidification, soall lines intersect in (0.0). It takes twice as much energy to keep 40 % RH as 60 % RH, and fourtimes as much energy to keep 40 % RH as 70 % RH. The question is if a low RH is efficientfrom a preservation point of view. The benefit of keeping a low RH is shown in fig. 1. By reducing the RH from 70 % to 40 % at 8 ˚C the decay index is lowered from 0.3 to 0.15. This improvement in preservation has a high price in terms of energy conservation. It appears that only very humidity sensitive objects like acetate film archives or salt contaminated iron wouldrequire a low H. For all other materials the most energy efficient setpoint of RH is 60 %.

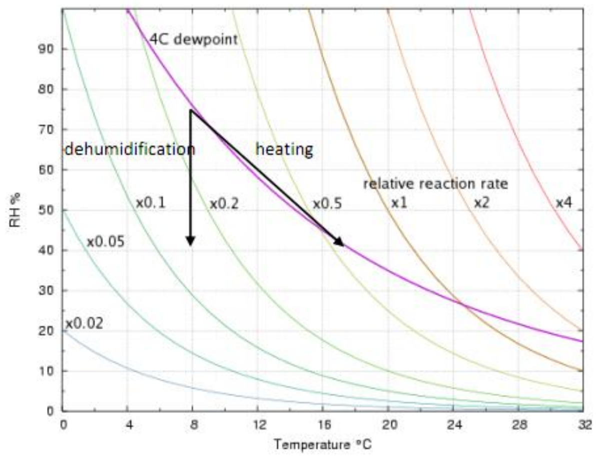


Figure 1 The relative decay rate by hydrolysis for organic materials and the saturation water vapour content of the air as a function of temperature and relative humidity (from [5]). Dehumidification reduces decay whereas conservation heating increases decay.

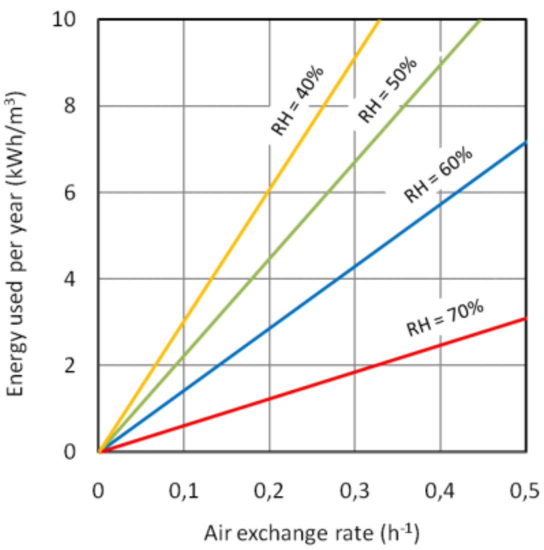


Figure 2 The annual energy consumption for dehumidification to a particular RH (solid lines) and conservation heating with a heat pump (dotted lines). The diagram is only valid for climatic conditions similar to those in Denmark.

Figure 3 View of an abandoned shelter for fighter airplanes, now used as a temporary museum store for a collection of furniture.

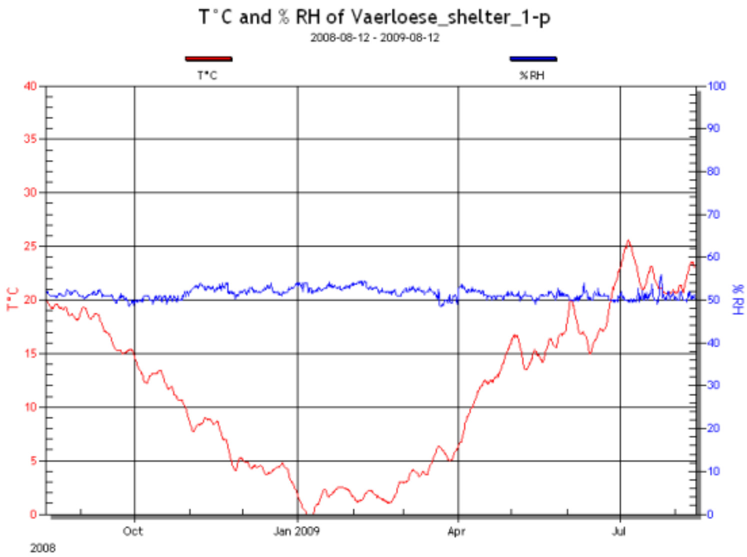


Figure 4 Indoor climate records from the värlöse shelter in one year. The Rh was controlled to 50 % by absorption dehumidifiers

3. CASE STUDIES

An abandoned shelter for fighter airplanes is located at Värlöse airfield north of Copenhagen (fig. 3). It is used as temporary museum store for at collection of furniture. The shelter was designed with a 50 cm thick concrete roof to resist a nuclear attack. The large steel gate is well sealed, so there is very little natural air infiltration. The AER was measured to 0.05 $h^{-1}$by carbon dioxide and the RH was controlled to 50 % by absorption dehumidifiers. The temperature was drifting from 0 ˚C in winter to 22 ˚C, so the summer temperature was higher than the 18 ˚C used for the calculations (fig. 4). This was probably due to heat accumulation, when the uninsulated roof was heated up by the sun. The need for dehumidification in summer was therefore probably less than calculated. According to the diagram in fig. 2, the annual energy demand would be around 1 kWh/m3, but the actual consumption was 5 kWh/m3. The poor performance of the dehumidifier was due to lack of maintenance. If the filters are not cleaned at regular intervals, the silicagel will be filled with fine particles whichreduces the ability to absorb water vapour. Neclectance is a potential source of energy waste for any mechanical climate control system.

The medival church in Kippinge is located on the island Falster in a rural area (fig 5). It has 1 m thick solid brick masonry walls and a tiled roof. It is used for services only once in the week, so it has intermittent electrical heating. The church is heated to 18 ˚C for a few hours and is left with only little heat most of the time (fig. 6). The winter temperature is therefore a few degress higher than assumed for the calculations, so the need for dehumidification is less in winter. The RH was controlled to 70 % by a condensing dehumidifier. The AER was measured by the PerFlourcarbon Tracergas method [2] to be 0.1 h^{-1}. The annual energy consumption was 1900 kWh or 1.5 kWh/m^3 which is more than predicted from fig.2. This may be due to evaporation from the walls into the church. The amount of water removed by the dehumidifier was measured when the bucket was emptied. A total of 1500 liters was removed in one year. The energy cost for the condensing dehumidifier was therefore around 1.3 kWh/liter. However the energy was not lost, but released back into the church from the heating coil. The heat gain is of minor importance compared to the direct electrical heating, which used 17 MWh in one year.

Figure 5 View of Kippinge Church from the southeast. The building is located in a rural area onthe island Falster.

Table 1 Monthly average for outside temperature (Out T), outside relative humidity (Out RH) and outside absolute humidity (Out AH) for Denmark. Estimated difference in absolute humidity for dehumidification to a constant RH.

	Meteorological data			**Dehumidification**			
Month	**Out T (°C)**	**Out RH (%)**	**Out AH (g/m^3)**	**40% RH (g/m^3)**	**50%RH (g/m^3)**	**60%RH (g/m^3)**	**70%RH (g/m^3)**
Jan	**0**	**87**	**4.2**	**1.95**	**2.4**	**2.9**	**3.4**
Feb	**0**	**85**	**4.1**	**1.95**	**2.4**	**2.9**	**3.4**
Mar	**2**	**83**	**4.6**	**2.25**	**2.8**	**3.4**	**3.9**
Apr	**7**	**76**	**5.9**	**3.1**	**3.9**	**4.7**	**5.4**
May	**12**	**68**	**7.2**	**4.25**	**5.3**	**6.4**	**7.5**
Jun	**16**	**68**	**9.2**	**5.4**	**6.8**	**8.2**	**9.5**
Jul	**18**	**71**	**10.8**	**6.1**	**7.6**	**9.1**	**10.7**
Aug	**17**	**74**	**12**	**5.8**	**7.3**	**8.7**	**10.1**
Sep	**14**	**78**	**9.4**	**4.8**	**6.0**	**7.2**	**8.4**
Oct	**9**	**83**	**7.3**	**3.5**	**4.4**	**5.3**	**6.2**
Nov	**5**	**87**	**5.9**	**2.7**	**3.4**	**4.1**	**4.75**
Dec	**3**	**88**	**5.2**	**2.4**	**2.9**	**3.6**	**4.15**

Table 2 The results of the different case studies with dehumidification in a museum store, a medieval church and a historic mansion.

	Värlöse shelter	Kippinge Church	Liselund Mansion
Dehumidifier	Absorption	Condensing	Absorption
Set point	50 % RH	70 % RH	60 % RH
AER	$0.05\ h^{-1}$	$0.1\ h^{-1}$	$\approx 1.0\ h^{-1}$
Energy consumption	$5\ kWh/m^3$	$1.5\ kWh/m^3$	$20\ kWh/m^3$

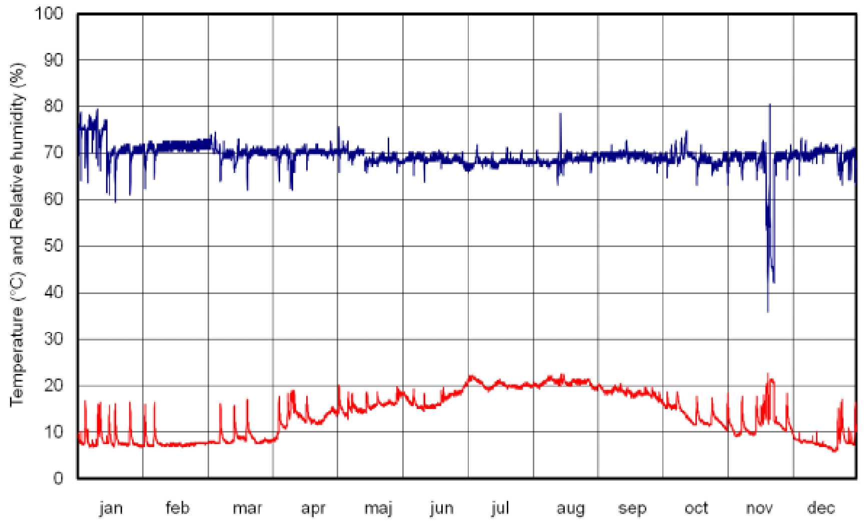


Figure 6. Indoor climate records from Kippinge Church in 2009. The relative humidity was controlled to 70 % RH by dehumidification. The indoor temperature variation was 5–22 °C due to the intermittent heating in winter

Figure 7 View of Liselund Mansion from the southwest. The building is located in a pleasure garden on the island of Møn close to the Baltic Sea.

The country mansion in Liselund dates back to 1800. The building is situated at a small pond in a romantic park on the island Møn at the Baltic Sea (fig. 5). The walls are 50 cm solid masonry and the roof is thatched. The building has large single glazed windows and doors, which take up 25 % of the wall surface area. In summer there are guided tours, but apart from that it remains closed all year. The RH is controlled by an absorption dehumidifier (Munters) located in the basement. The dry air is distributed with ducts into each room through small grills in the floor. The air is returned though the staircase to the basement. The RH was 55-65 % all year, whereas the temperature was rifting from around 0 ˚C in winter to 20 ˚C in summer (fig. 6). The annual energy consumption for dehumidification was 13 MWh or 20 kWh per m^3 per year. The Air Exchange Rate was not measured, but is probably large. The doors and windows are indeed rather leaky, and much energy would be saved by improving the air tightness of these components. Another reason for the high energy consumption might be an internal source of moisture from the basement. The floor is only slightly above the water level in the small pond, and flooding occur regulary.

4. CONCLUSION

Dehumidification is an energy efficient way to control the relative humidity in cultural heritage, where heating is not needed for human comfort. The energy use depends on the setpoint of the RH. The higher the acceptable RH, the less energy is used. The energy consumption also depends on the air exchange rate, which may be large if the building has many single glazed windows. This is often the case for historic buildings where double glazing is not permitted for antiquarian reasons. In modern buildings designed for the purpose the air exchange rate can be very low, and the need for energy will in theory be less than 1 kWh/m^3. But the dehumidifier needs proper maintenance to achieve this target. An absorption dehumidifier is more sensitive to corrosion and congestion by particles than a condensing dehumidifier. As a rule of thump absorption dehumidifier uses 1 kWh to remove 1 liter of water vapour from the air, and a condensing dehumidifier uses a little more. If the building has an internal source of moisture the energy demand will be larger than predicted, but this is usually difficult to quantify.

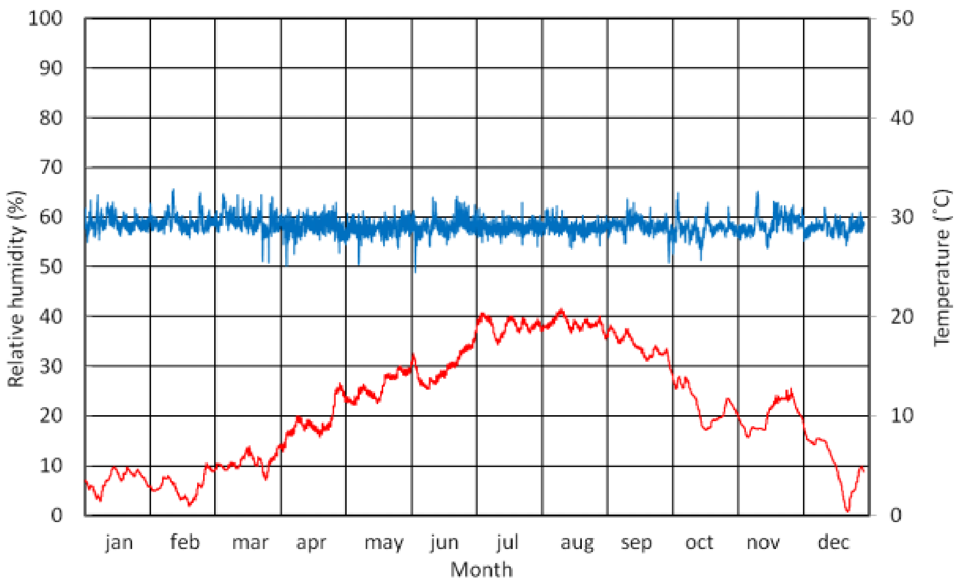


Figure 8 Indoor climate records from Liselund Mansion in 2009. The relative humidity (RH) was controlled to 55- 65 %RH by dehumidification. The indoor natural temperature variation was 0–20 °C due to the influence of the outside temperature

5. REFERENCES

[1] S. Staniforth, B. Haves and L. Bullock, Appropriate Technologies for Relative Humidity Control for Museum Collections Housed in Historic Buildings, Preventive Conservation: Practice, Theory and Research, Preprints of the contributions to the Ottowa Congress. London, The International Institute for Conservation of Historic and Artistic Works (IIC), 1994, pp. 123 – 128

[2] N.C. Bergsöe, Passive tracer gas method for ventilation investigations. Description and analysis of the PFT-method, SBI report 227, Danish Building Research Institute, Hörsholm, 199

[3] http://palimpsest.stanford.edu/byauth/sebera/isoperm/

[4] James M. Reilly, Douglas W. Nishimura, Edward Zinn, 'New Tools for Preservation, assessing long-term environmental effects on library and archives collections' The Commission on Preservation and Access, Washington DC, 1995, ISBN: 1-887334-46-7.

[5] Tim Padfield, The isoperm and the isoburn. 2004. http://www.conservationphysics.org/twpi/twpi_03.php

[6] http://www.conservationphysics.org/twpi/twpi_01.ph

PREVENTIVE CONSERVATION IN THE PROPERTIES OF THE BAVARIAN DEPARTMENT OF STATE-OWNED PALACES, GARDENS AND LAKES

Tina Naumović
Preventive Conservation, Bavarian Department of State-owned Palaces, Gardens and Lakes, Munich
(with special thanks to Klaudia Pontz for help in translation)

Abstract: The diversity of the buildings in care of the Bavarian Palace Department in location, building structure, history, use and state of modernization influencing the indoor climate is very wide. Preventive conservation starts to play a significant role and has become a “cross-over discipline” concerning various sections within the Palace Department. Three examples of the Preventive Conservation in the Palace Department show real-life problems and illustrate the team work among the various professional disciplines in solving them.

Keywords: Preventive conservation, indoor climate, mould growth, light problems, case studies

1. HISTORY AND PROPERTY OF THE PALACE DEPARTMENT

The Bavarian Department of State-owned Palaces, Gardens and Lakes**,** otherwise known as the Palace Department was created as part of the administration at the court of the electors and kings of Bavaria.

After the end of the monarchy in Bavaria in 1918 the palaces and residences and their court gardens became state property, and since 1932 the department has been officially known as the "Bavarian Department of State-owned Palaces, Gardens and Lakes".

Today the palace department with a staff of around 850 is the largest public institution responsible for historic houses and museums in Germany, managing 45 palaces, castles and residences, which attract over five million visitors per year.

The buildings in the care of the Palace Department vary greatly in dimension, structure and environmental conditions. Most of the sites are castles and palaces within a wide range of dates of origin: medieval castles, renaissance and baroque residences, garden palaces and the famous castles of Ludwig II dating to the late 19th century. In addition to the palaces, churches and monuments such as the statue of Bavaria are also part of the property of the Palace Department. Even some small country houses, former studios of famous local artists, are in the possessions of the Palace Department which inherited them from the artists’ families.

2. DIVERSITY OF THE BUILDINGS IN STRUCTURE, LOCATION, USE AND STATE OF MODERNIZATION INFLUENCING THE INDOOR CLIMATE

The diversity of the buildings in location, building structure, history, use and state of modernization influencing the indoor climate is very wide.

The location and surrounding area of a building and accordingly the out-door climate always has a strong influence on the indoor climate. Many castles and palaces are very exposed to wind and rain being situated on a hill (or even mountain like the “King’s house” – Ludwig’s II mountain hut - on the Schachen). Some buildings are close to lakes or actually built on islands or in parks and gardens, where the out-door humidity is very high. Others are near groundwater or even close to subterranean water streams like the palace of Linderhof.

Some of the castles have been used as museums for a very long time. For example the Prunn Castel can be visited since 1827, and all the “King’s Castles” of Ludwig II were opened to the public in 1886, only a few weeks after his death. Today the museums can be visited either with guided tours or individually. The amount of visitors differs from castle to castle. The numbers range from about 10.000 to 1.6 millions per year; obviously a large number of visitors have a direct impact on the indoor climate.

The amount and type of events taking place in the palaces and castles are also very varied. In general these are concerts or weddings where only seats are needed and drinks are served. There are, however, also seated dinners with full catering service.

The technical devices used for heating and air conditioning in these historical buildings have a wide range of time of origin. Especially the time since World War II offers an historic overview over the then up-to-date air condition model of every decade. Some of the buildings are unheated. If there is a heating system installed it can either be wall heating, under-floor heating, central heating or conservation heating. The climatization systems range from no climatization, to mobile equipment like humidifiers or dehumidifiers and air-ventilation systems and full air-condition systems. Climate monitoring, if any, is mostly carried out using thermohygrographs. Only a few palaces are equipped with data loggers.

The air-tightness of the building's apertures is highly affecting the indoor climate. In the Palace department you can find all types of windows and doors, from original historic ones (not air-tight at all) to modern standards (mostly too air-tight).

One "specialty" of the Palace Administration influencing the indoor-climate is the high level of fire-protection: There was a big fire at the Trausnitz castle in Landshut in 1961. Most of the main castle was destroyed, three firemen died in the fire. It transpired afterwards that the fire could spread so fast because it was moving through the historic chimneys. In consequence, all un-used chimneys in every castle and palace were bricked up. This point has to be mentioned as there is the suspicion that the indoor climate is badly influenced by this closure; a re-opening of the chimneys in Linderhof Castle is under discussion.

3. HISTORY OF PREVENTIVE CONSERVATION AT THE BAVARIAN PALACES

Preventive conservation being carried out in Bavarian castles clearly did not start with the installation of a preventive conservator. The necessity to protect delicate and expensive artwork from damaging environmental conditions, to avoid fast decay and simply to save money was clearly realized by and almost a matter of course for the people who built and paid for a palace.

With the change of the palaces from noble domestic homes to museums, a lot of preventive measures were cut. During royal times many rooms and halls were only used once a year. In the interim the window shutters were closed and the furniture protected with sheets. Nowadays, thousands of visitors are moving through these precious and delicate interiors. In consequence, doors and windows are open for airing, allowing access to sunlight, and in winter, for a greater visitor-comfort, the central heating is turned on. The visitors bring in dust, and most of them cannot refrain from touching the art pieces.

This modern use as museums is the greatest challenge for all those concerned in the protection of our cultural heritage

4. PREVENTIVE CONSERVATION AT THE PALACE DEPARTMENT

In 2006 the position of a "preventive conservator" was established at the Conservation Centre of the Palace Department, followed by the post of a technical assistant in 2007. The professional background for the position of the preventive conservator is a diploma in conservation.

Before the position of a preventive conservator was created, various conservator-restores of the Conservation Department carried out preventive conservation measures, depending on what type of art was affected.

Now, the preventive conservation section is in charge of such tasks as, among others, climate monitoring and control, light protection, emergency plans and indoor pollution. The technical equipment for light and climate measurements and the mobile equipment for climate control (humidifier and dehumidifier) are also concentrated in this small department, being periodically serviced and calibrated.

Preventive Conservation
(ger.: Präventive Konservierung-PK) monitors climate conditions; collecting and evaluating climate data. The climate data are collected by various technical devices, ranging from classic thermohygrographs to data loggers which have to be read on-site and real time climate curves to be checked via internet.

Based on the acquired data (and unfortunately quite often based on obvious damage) the PK carries out risk and damage assessment and then suggests measures to improve the climate, frequently helping out with its equipment.

The preventive conservation section is testing light-protection materials and develops light-protection systems. It also develops emergency kits for the on-site administrations, organises in-house training for our front of house staff concerning conservation matters (for example the handling of climatization equipment, cleaning, first aid for art in the case of emergency). PK tests and suggests materials for showcases in temporary and permanent exhibitions or art stores. Working closely together with the colleagues from textile and wood conservation workshops, integrated pest management is implemented.

With the establishment of "Preventive Conservation" at the conservation centre, the collaboration with other departments in such a large institution has become much easier. The various departments and the on-site staff at our palaces need to contact only one person for all issues of preventive conservation.

Preventive conservation in general has become a "cross-over discipline" concerning various sections within the Palace Department.

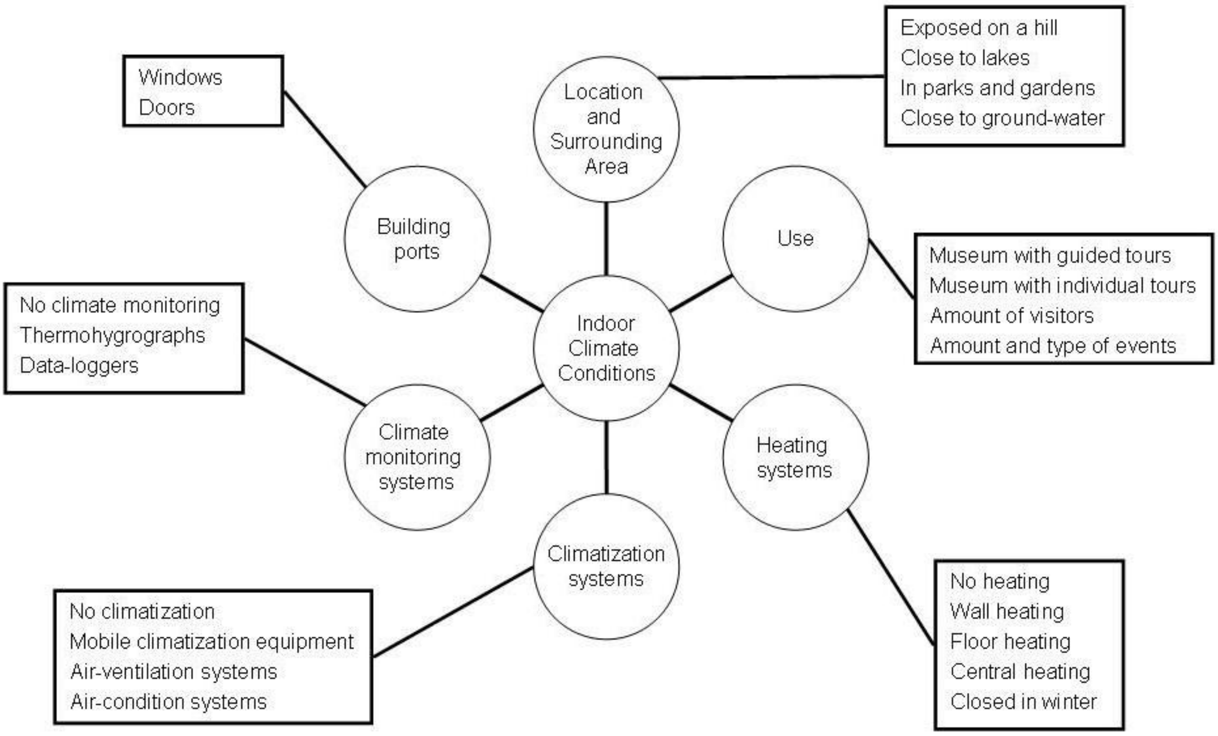


Figure 1 Diversity of the buildings in structure, location, use and state of modernization influencing the indoor climate.

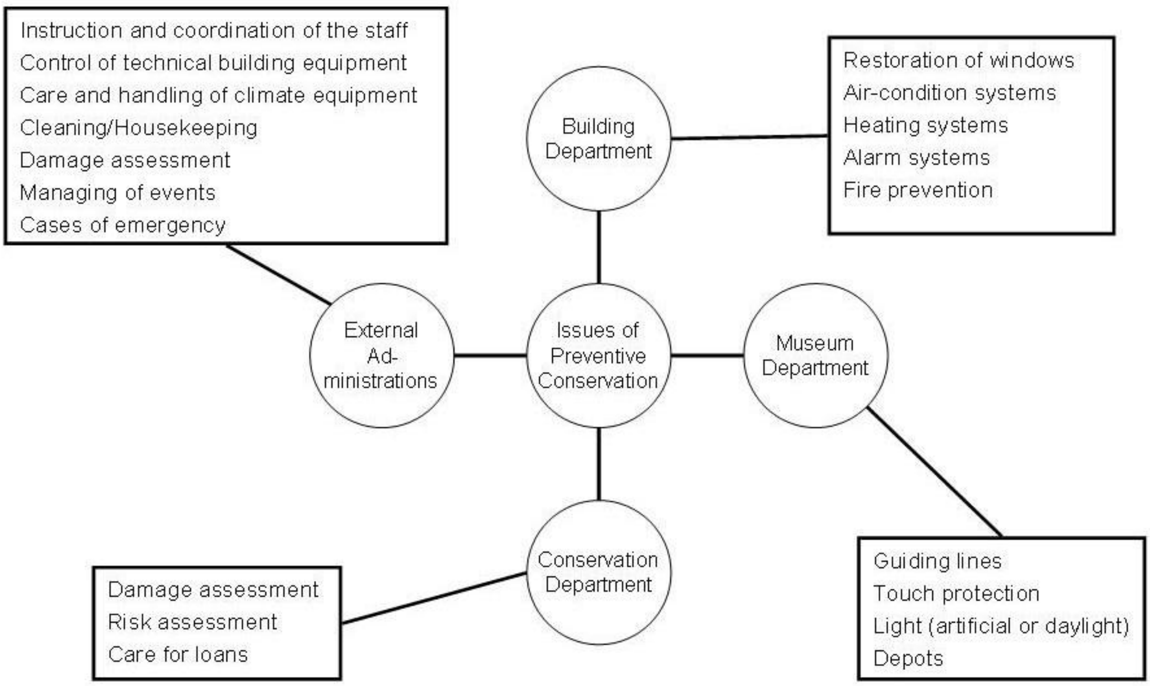


Figure 2 Administrative units and their responsibilities affecting the aims of preventive conservation.

Responsible for the preservation, conservation and modernization of the palaces and castles are three special divisions based at the headquarters of the

Bavarian Palace Department at Nymphenburg Palace in Munich. The museum department is responsible for the mobile interior, the building department is in charge of the buildings and the non-mobile interior, and the conservation centre carries out conservation measures. Each palace is managed by the so-called external administration which takes care of the "daily business" on site.

The activities of the various departments and of the external administrations are strongly affecting the aims of preventive conservation.

The museum department is in charge of the art treasures and the structure and design of museums and special exhibitions. Consequently the arrangement of the visitors' route, the design of the touch protection, and the light management affect issues of the preventive conservation. The museum department also manages the art storage.

The building department is responsible for the planning, implementation and supervision of building works: for example the restoration of windows, the planning of air-conditioning and heating systems, the installing of burglar alarms and fire prevention.

The conservation department is responsible for planning, implementing and supervising conservation campaigns, and all conservator-restorers carry out damage and risk assessments. They also handle loans for and from other museums.

The external administrations are responsible for the management of the "daily business": the instruction and coordination of the guides and guards, the control of the technical equipment (heating, air-ventilation, air-condition), the care and handling of climate equipment (humidifier, dehumidifier, climate –monitoring systems) and the management of events (setting up seats, catering, heating). Of course they are the first to notice any damage to the works of art. They inform the conservation department when, for example, parts have broken off, or when pests or mould are found. The on-site-staff is also responsible for cleaning and housekeeping, and in cases of emergency obviously they are the first to fight bigger damages.

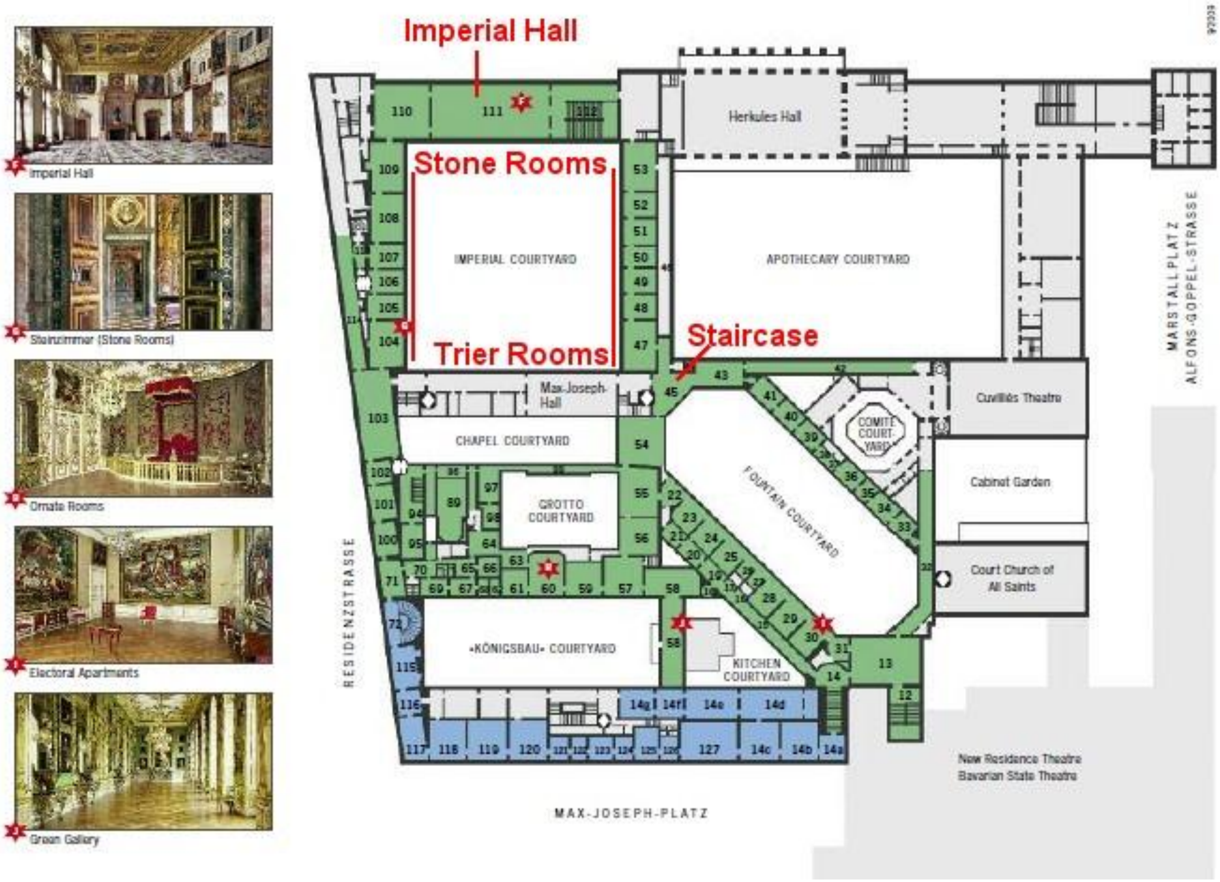


Figure 3 Munich Residence, ground plan, first floor. [3]

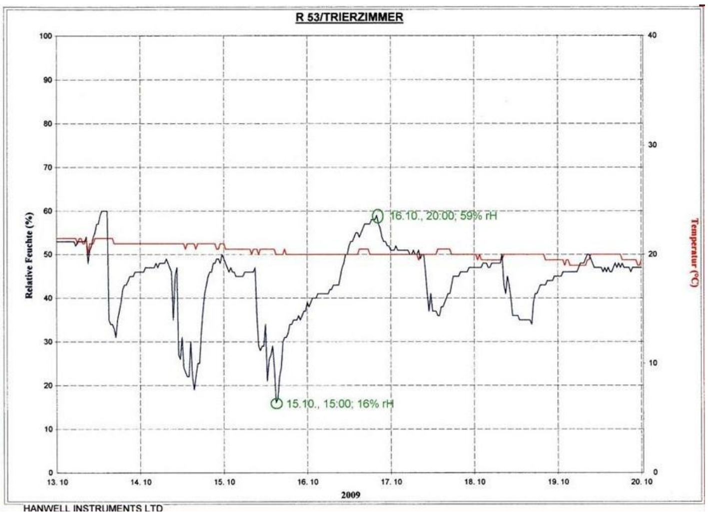


Figure 4 Climate curve, Munich Residence, Trierzimmer, Room 53, 13.10.2009 - 20.10.2009. The relative humidity fluctuates extremely on all days except on 16.10.2009, the day of the large event in the Imperial Hall.

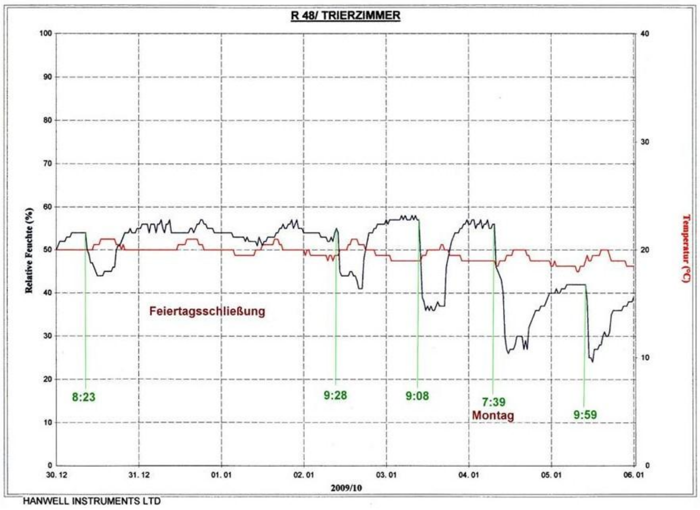


Figure 5 Climate curve, Munich Residence, Trierzimmer, Room 48, 30.12.2009 - 06.01.2010. During the closing days (“Feiertagsschließung”) the climate is very stable. With the re-opening of the museum the relative humidity fluctuates again due to cleaning activities every morning.

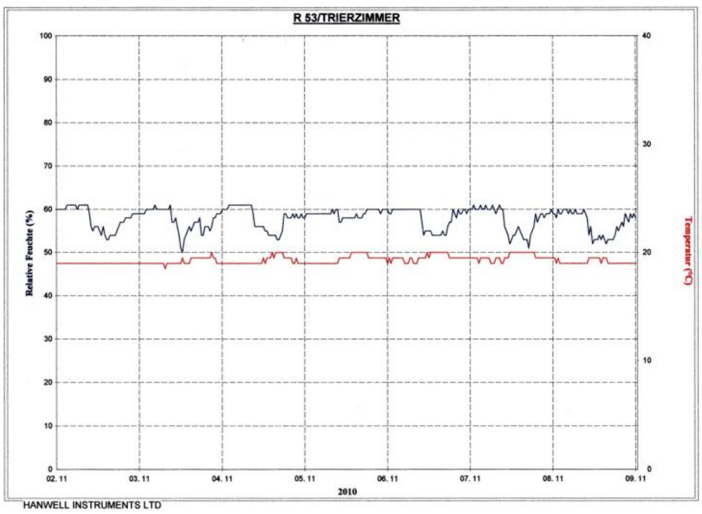


Figure 6 Climate curve, Munich Residence, Trierzimmer, Room 53, 02.11.2010 - 09.11.2010. Climate situation in the Trier Rooms after the installation of more humidifiers in the rooms and in the staircase nearby.

5. EXAMPLES OF PREVENTIVE CONSERVATION AT THE PALACE DEPARTMENT IN PRACTICE

5.1. Climate problems in the Munich Residence

Most of the town residences of the Palace Administration have one mutual problem. Due to their central position in large cities and because of their large function rooms they are much in demand for events such as concerts, conferences and parties. For example, the Munich Residence is used for more than 1000 events per year. Like most of the historic house museums managed by the Palace Department the Munich residence is closed to visitors on only three days a year.

Many events held at the Munich Residence take place in the Kaisersaal (imperial hall). Close to this hall apartments called the Stein- and Trierzimmer (stone and Trier rooms) are located (Fig. 3). The climate in these apartments, especially in winter, was much too dry and showed big fluctuations. The lowest RH measured was under 20 %. The humidity level fluctuated almost daily by 30 % (Fig. 4). The ideal climatic condition for furniture should be stable around 50 % RH. Unfortunately the most precious and most delicate furniture are exhibited in these apartments and many are already damaged due to the adverse climatic condition.

The apartments are equipped with central heating from the 1950s, and the temperature even in deepest winter was around 20 °C. In the Trier- and Steinzimmer 15 mobile humidifiers are installed.

Fortunately we can check the climate in the residence via internet. For this reason, we noticed the dryness in these rooms. We suspected that the preparation of the Kaisersaal for events could be the cause of the low humidity. The outer doors at the bottom of the staircase were left wide open whilst chairs and catering equipment were set up. Due to the fact that the whole interior of the Kaisersaal dates from the 1980s being the last part of the building to be reconstructed after World War II, the hall is not really in the focus of protection and climate monitoring is not being carried out.

Following up on our suspicion, we evaluated the climate data collected from the adjoining apartments. Surprisingly the climate before and during the big event on the 16th October 2009 was better than in the normal use of the museum (Fig. 4). The external administration realised the need for the protection of the historic rooms. Therefore, during the preparation of the Kaisersaal the doors to the hall were closed and so the visiting line interrupted. The Stein- and Trierzimmer became “dead-ends”. The air-draft circulating through the enfilades was cut off; the air exchange was lower and therefore the climate more stable.

To find out how the daily use affects the climate we took a close look at the climate curves on one of the few closing days and realized that the climate readings were most irritatingly stable (Fig. 5).

The changes in relative humidity always occur with the opening and closing of the museum doors. Unfortunately the most low-end solution to this problem - simply keeping the doors closed - is not possible; the doors must remain open for an efficient visitor flow.

Therefore more humidifiers were set up in the apartments and even in the staircase nearby, and now climate conditions for the objects of art are much better (Fig. 6). Fortunately this was also made possible by the head of the external administration, who provided enough staff to clean and refill the humidifiers.

5.2. Mould problems in the church of St. Bartolomä

In case a conservator notices any damage and suspects that it could be a climate problem, he or she informs the department of preventive conservation. PK, then, either starts monitoring the climate or looks at existing data to find out if the climate can be the reason for the damage.

In the church of St. Bartholomä, for example, there were severe mould problems. As the shore of the Königssee (“King’s Lake”) is very close high humidity levels in the church are not really surprising (Fig. 7). Nevertheless the interior was in quite a good condition.

Figure 7 Königssee, St. Bartholomä, view from the lake.

In 2008 some windows were destroyed in a hailstorm. Due to the rain water damage there was a kind of mould explosion on the walls and altarpieces. The mould was removed from the walls and plasterwork in the same year. A conservation of the altar is planned, but in this climate conditions the altar will obviously deteriorate quickly. In fact, the mould on the walls is growing back even now.

The first action was to put two data-loggers in, in order to have at least some climate monitoring. In the first three weeks of September 2009 the relative humidity measured behind the altarpiece on the north side of the church was more than 85 %. The likely reason of this high level of humidity is that the rain infiltrating the walls during the hail storm had not dried off yet. Additionally, there is the problem of summer condensation. In the summer season (May to October) the outside door is always kept open, and so condensation on the cold walls inside the church is inevitable.

Fortunately there is a meteorological station close to the church and all the outside climate data was available. Even in September the absolute humidity measured inside the church was a lot higher than outside.

As a “first-aid campaign” against the mould an automatic door-closing device and two dehumidifiers were installed. In order to prevent salt crystals forming on the walls the dehumidifier was set at 65 % RH, so that the humidity on the walls reached about 75 %.

For the future the installation of a low-level wall heating system and/or a humidity-controlled air-ventilation system is in discussion. In May 2011 as part of the Climate for Culture-Project, an extended climate monitoring programme will start. Based on the acquired data we can hopefully find on the right solution to this problem.

5.3. Light problems in Neuschwanstein castle

Sadly, in Neuschwanstein all textiles are badly light damaged. Parts of the upholstery and the curtains are almost completely destroyed. The original colour and structure of the textiles only survive in areas which were protected from light.

The extensive light damage is due to the fact that during visiting hours the windows are wide open to meet the need for fresh air. In summer the castle receives up to 7000 visitors a day (and 1.6 millions per year) and the air in the small rooms gets stuffy very quickly.

In 2009 a campaign was launched to conserve the textiles in the king’s bedroom. To prevent further damage, protection from light obviously had to play a major part in the conservation programme. Otherwise any remedial conservation treatment would have been in vain.

Working closely together, the museum department, the building department and the conservation department developed a new lighting system. Daylight is excluded by screens fitted to the windows and the room is lit by strategically placed artificial lights. A glass screen prevents visitors touching the fragile pieces of art. (Fig. 8)

It is now possible to exhibit, in addition to the conserved textiles, some original curtains that were kept in the store in the past, because they could so easily have been damaged by the exposure to light and visitors.

Installing light protection screens throughout the castle would be necessary. However, in order to guaranty sufficient air exchange we have to find an alternative to open windows.

Figure 8 Neuschwanstein Castel, King’s Bedroom. Light protection and touch protection. (Source: BSV, Bauabteilung, Heiko Oehme, 2010)

Just the fact, that the windows in three rooms now must remain closed, caused severe criticism. All colleagues involved in the planning and implementation of the new protection system have to face the charge that there is more condensation occurring on the windows and that the climate in the castle is generally getting worse because of the slower air exchange.

Due to the fact, that Neuschwanstein takes part in the Climate for Culture Project, hopefully climate monitoring can help to prove, that open windows are not the only means of climate control. Various alternatives for a sufficient air exchange will be investigated.

These examples demonstrate that damage prevention/damage assessment in historic buildings has to start with the analysis of the building and its surroundings, and the actual conditions of the historic interiors. Monitoring the climate can be one way to understand the characteristics and interrelations within the building. As a next step, the relationship between the existing climate and the damage or, as the case may be, the risk of damage has to be assessed, and finally adverse climate conditions should be improved. All this constitutes is a great challenge for all the disciplines involved. Only a well-functioning cooperation of architects, scientist and conservator-restorers guaranties the future preservation of our cultural heritage.

6. REFERENCES

[1] URL:http://www.schloesser.bayern.de/deutsch/ueberuns/index.htm [Stand: 10.05.2011]

[2] URL:http://www.burg-trausnitz.de/deutsch/burg/brand.htm [Stand: 10.05.2011]

[3] URL:http://www.schloesser.bayern.de/deutsch/service/infomat/screen-pdf/mu-residenz_engl.pdf [Stand: 10.05.2011]

ROOM CLIMATE IN LINDERHOF PALACE
Impact of ambient climate and visitors on room climate with a special focus on the bedchamber of King Ludwig II.

Stefan Bichlmair, Ralf Kilian
Fraunhofer IBP

Abstract: This report is part of the European research project "Climate for Culture" of the Fraunhofer Institute for Building Physics IBP at Holzkirchen on preventive conservation of cultural heritage. Within this project the influence and behaviour of the room climate in Linderhof palace of the Bavarian King Ludwig II. will be investigated by measurement and building simulation. The outer climate, the impact on the room climate of the King's Bedroom and the room climate itself will be introduced. To get a better understanding of the impact of the outer climate to the room climate a short overview is given to building history and construction of the unheated historic building. The room climate is very important for the preservation of art. Especially high fluctuations in relative humidity are of interest, as they can cause damages. Up to 3000 and more visitors are coming to Linderhof palace (Figure 1) per day in summertime. Therefore a special view on visitors comfort will be given due to room climate conditions.

Keywords: structure component, room climate, cultural heritage, preventive conservation

1. INTRODUCTION

In the years 2008 to 2011 the influence and behaviour of the room climate in Linderhof palace of the Bavarian King Ludwig II has been investigated by measurement and building simulation with a special focus on the connection between the outer climate, the room climate and other influences, like visitors. A short overview is given to building history and construction of the unheated historic building, with a special focus on the room climate of the King's Bedroom. The room climate is very important for the preservation of art. Especially high fluctuations in relative humidity are of interest, as they can cause damages. Up to 3000 and more visitors are coming to Linderhof palace (Figure 1) per day in summertime. Therefore a special view on visitors comfort will be given due to room climate conditions.

Figure 1 The picture shows the front view with entrance of Linderhof Palace. (Source: Bayerische Schlösserverwaltung BSV).

2. BUILDING

2.1. Building history

Linderhof palace was mainly build up from 1868 to 1876 from the Bavarian King Ludwig II. in the Bavarian alps in Graswang Valley. The forested park where the castle is located is about 940 m above sea level between mountain ridges up to 2185 high. The valley is west-east oriented. The last building phase was built in 1886 with enlarging the king´s bedchamber. Some weeks after death of the King the bedchamber has been accomplished and opened to the public. Since this time the palace has been stayed unheated. In Figure 2 the different building phases are coloured illustrated.

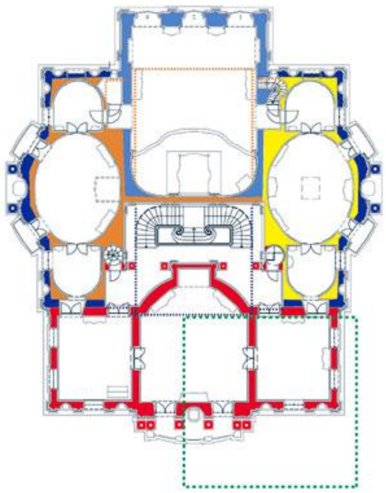


Figure 2 Upper floor of Linderhof palace with six building phases. The King´s bedchamber is the biggest room and was accomplished in the very last building phase after death of King Ludwig II in 1886 (light blue room). (Source: BSV).

2.2. Building components

The outer and inner walls of the building are made of bricks. On the inner side in every room a special construction made of wooden panels is assembled on the wall with a certain distance of a few centimetres to the wall. Gilded carvings, paintings and decorations are fixed on these wooden panels. The windows in the palace are still the original wooden single glazed windows of the construction period. All of them are in a good condition. The joinery work is well performed, all joints are closed and gaps are narrow. All windows in the ground floor are always closed. The windows in the upper floor are also all single framed. Only in the bedchamber there are boxed windows with two single glazed frames. Every day when the palace is shut down additional inner shutters on the windows are closed. This may improve the air tightness of the windows considerably. A construction detail of the outer wall and window of the bedchamber is shown in Figure 3.

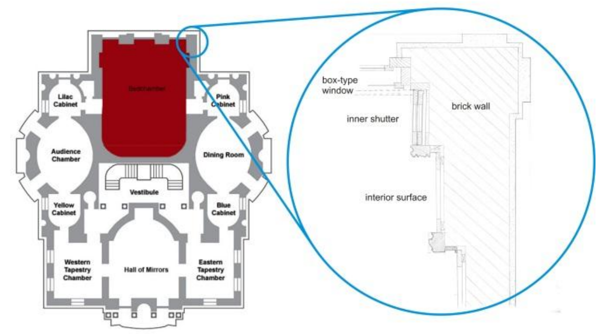


Figure 3 Detail of wall construction with interior surface consisting mainly of framed wood gilded or painted. The opened inner shutter is hidden in a lateral box.

2.3. Ventilation of the Building

During opening hours the windows are opened by the tour guides. If the weather is not too bad the guides open the windows as required. This means during summer almost all windows are open during opening hours in the upper floor, where the showrooms are. Only in the bedchamber the windows are always closed. The palace is opened in summer period from 7.00 a.m. starting ventilation with opening of all windows in the upper floor due to odour and cleaning until 8.00 a.m. The guided tours lead only to the upper floor and the royal rooms with rich furnishing on interior surface. The king´s bedchamber is partly shown in Figure 4.

3. GENERAL VIEW ON AMBIENT CLIMATE

First measurements have started in February 2008. Here, the one year period from 21.06.2009 to 20.06.2010 will be introduced and analysed. A one year period consists of 8760 hours. In this period 8586 data out of 8760 had been recorded. This is to consider in interpreting the statistical figures. The data have been measured in a 5-minute interval. The hourly data is the mean value of every 5-minute measured data of one hour. The sensors for relative humidity and temperature are placed on the north side of the castle on a balcony. Additional measurements have been made at the “Grotte”, about some hundred meters in distance to the castle. Due to partly faults in measurement the data have been combined.

Figure 4 The pictures show the bedchamber, the biggest room in the castle with a volume of ca. 805 m³. In the middle of the upper picture the royal bed can be seen. The visitors cross the room in front of the balustrade. The lower picture shows the windows without curtains and on the right the window and wall corner details shown in figure 3.

Relative Humidity of ambient climate

The relative humidity is in average very high with 95.1 % RH. This may be due to special conditions of the mountain valley. The relative humidity goes down in daily cycles, especially in the warm summer period, up to 24 % RH. A weak seasonal cycle can be observed with a monthly moving average (MA) of the hourly data, depicted in Figure 5.

Temperature of ambient climate

Figure 6 shows the ambient temperature with seasonal cycle. The average temperature in this year period is 5.46 °C with a maximum of 29.2 degree and a minimum of -17.3. The monthly moving average (MA) gives damped figures with maximum of 15.1 °C in summer (05.08.2009) and minimum in winter (17.01.2010) with -5.6 °C. Based on this data a sine function can be calculated, describing the idealized seasonal cycle:

$$T(x) = 5.50 - 10.322 * sin(((2*\pi)/365) * (x-35)) \qquad (1)$$

Where T is temperature and x denotes time in days from the beginning of year.

Absolute Humidity of ambient climate

Absolute humidity has to be calculated from temperature and relative humidity. This parameter gives the water content per m³ air. This becomes important for comparing ambient water content and water content of inside air of the castle. In average there is 7.25 gram water per m³ air enclosed. A maximum is given of 16.5 g/m³ without a peak in June which is probably a measurement fault. The hourly measured minimum water content is in winter with 1.13 g/m³. The monthly moving average (MA) is in maximum 12.51 g/m³ and minimum 3.13 g/m³, see Figure 7.

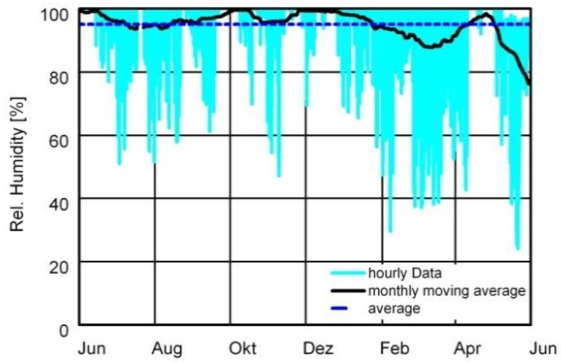


Figure 5 Relative humidity of ambient climate with monthly moving average and average of whole period, from 06/2009 until 06/2010.

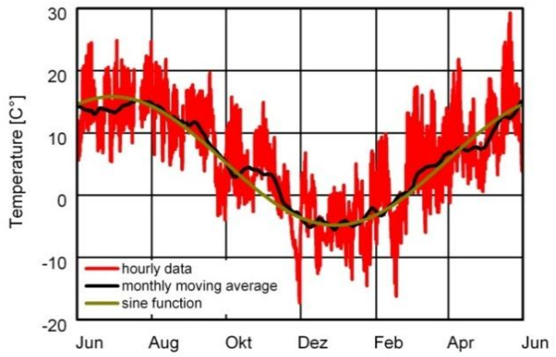


Figure 6 Ambient climate temperature with monthly moving average and sine function, from 06/2009 until 06/2010.

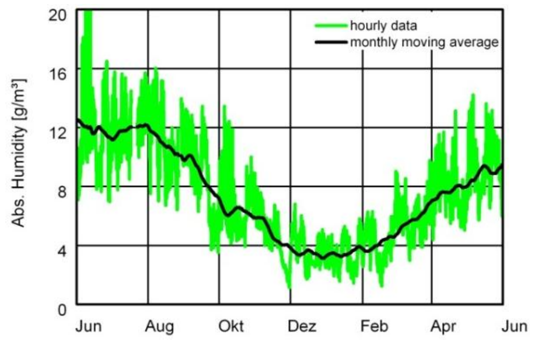


Figure 7 Absolute humidity of ambient climate with monthly moving average, from 06/2009 until 06/2010.

4. ROOM CLIMATE OF KING´S BEDCHAMBER

The data consists of 8181 hourly values (from 8760 hours of a year), obtained as a mean value from 5-minute measured data. In the bedchamber two sensors for relative humidity are placed to secure the measurements. The accuracy of these sensors is ± 0.3 Kelvin and ± 3 % point relative humidity. The used sensor types are sensors transforming the analogue signal in a digital signal, type SHT 15 and HIH 4000.

4.1. Relative Humidity

The average for this year period is 72.4 % RH which is on very high level. Figure 8 shows the course of the graph. In June 2010 there can be observed some downward trend. This trend turns in July (not shown). There is a maximum of 96 % RH and a minimum of 46 % RH. The seasonal cycle of the RH of the bedchamber is in maximum in monthly moving average (MA) 80.1 % RH and minimum 63.8 % RH (without figures in June 2010). The annual monthly moving average cycle of RH in the bedchamber follows the RH cycle of the ambient climate. This is also due to the annual temperature cycle. Mean difference in RH between bedchamber climate and ambient climate is 22.7 % point RH. Figure 9 shows the distribution of relative humidity in class width of 1 % point RH. The very high values are rare and barely to see, but exist.

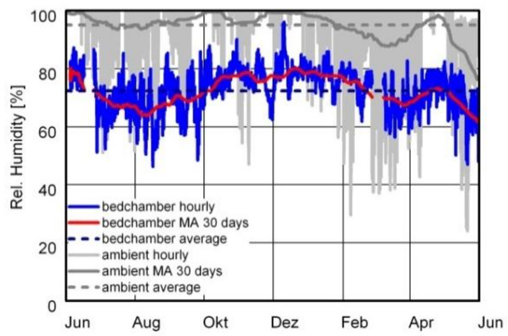


Figure 8 Relative humidity of bedchamber with monthly moving average, from 06/2009 until 06/2010 and ambient climate in background.

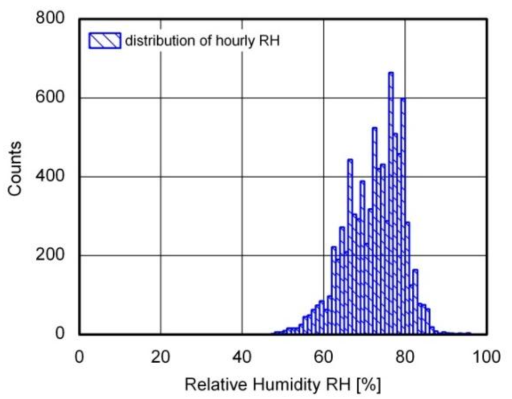


Figure 9 Distribution of RH in bedchamber with class width of 1 % RH, from 06/2009 until 06/2010

Daily fluctuation

The daily fluctuation is a common figure to evaluate the climate in a room. This information can be compared to figures given by means of preventive conservation. Holmberg [1] gives a limit of 15 % RH points for a daily acceptable range in unheated buildings. Burmester [2] gives for a museum climate 5 % RH points as acceptable limit. Due to ASHRAE [3] museum climate with a limit of daily fluctuations of 5% RH points is considered as a Class A museum. These are some examples for ongoing international discussions. Here it stands for some figures to get an idea of the climate situation in the bedchamber of Linderhof palace. In Figure 10 the daily fluctuations are shown with a daily maximum (blue line) and minimum (light blue line) value based on 5 minute measured data. The difference of daily maximum and minimum gives us the maximum daily fluctuation, depicted as dark blue graph. Some boarder lines indicate the bad climate situation with many fluctuations over 15 % RH points up to 25 % RH points.

A constant climate or RH level is not given in Linderhof palace. The RH follows an annual cycle as shown. In Figure 11 further examples for recommended room climates or possibilities for evaluation are given. The fluctuations of relative humidity are centred on the monthly moving average according to the "acclimatisation concept" of Bratasz [4]. A boarder line of ± 10 % RH points gives the limit of a museums climate of Class B according to ASHRAE [3].

4.2. Temperature

The graph of the air temperature in the bedchamber is shown in the Figure 12. The maximum of the hourly data is 24.8 °C and minimum - 1.4 °C. There seems to be some measurement fault at 0 °C. Comparing these values to additional measurements in adjacent rooms shows that lower temperatures could be possible in this period. The room temperature follows strongly the seasonal cycle of the ambient climate. The daily up and down is damped compared to ambient temperature. Average temperature of this year period is 11.67 °C.

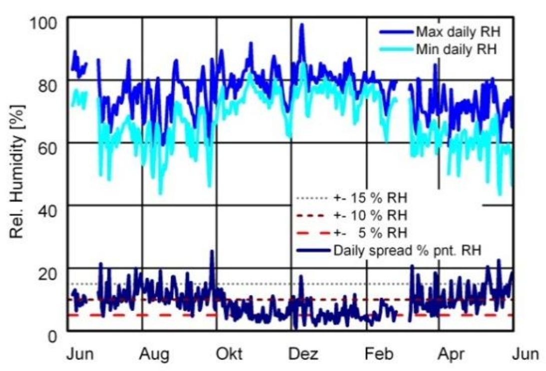


Figure 10 The blue line shows the daily maximum measured value, the light blue line the daily minimum measured value. The dark blue line shows the maximum daily difference (difference between blue und light blue lines) in RH from 06/2009 to 06/2010.

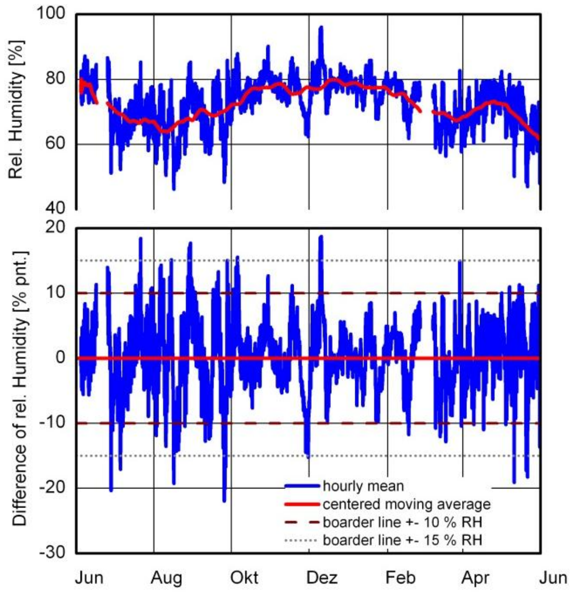


Figure 11 The upper graph shows with the blue line the measured room climate in RH of the bedchamber. The red line shows the monthly moving average. The graph below shows the fluctuation of relative humidity of the upper shown data centred on monthly moving average from 06/2009 to 06/2010.

In summer the maximum of monthly moving average is at 22.3 °C and the minimum in winter at 0.4 °C.

Calculating the difference of mean ambient and bedchamber temperature gives an offset of plus 6.2 Kelvin for the bedchamber. In summer the offset is a little bit higher at 7.2 K, in winter slightly lower at 6.0 K.

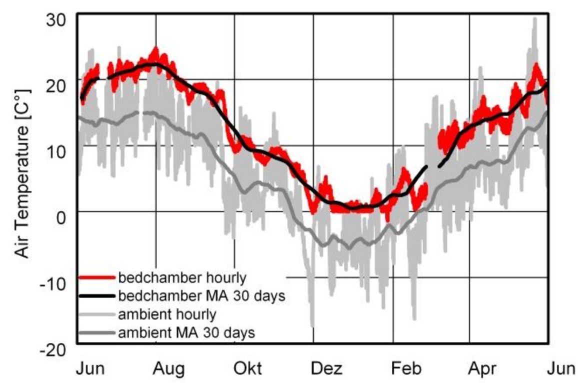


Figure 12 The red graph shows the air temperature with hourly data of the bedchamber, the black line is the monthly moving average. The grey lines show the data of the ambient climate analogue. Time from 06/2009 until 06/2010**.**

4.3. Absolute Humidity

Figure 13 shows the absolute humidity in the bedchamber in context to the ambient climate. Without water vapour sources and adequate airing the water content inside should be the same as outside. Visitors are the only known source of water vapour. This indicates the influence of the visitors to the room climate. A distribution of the visitors is given in Figure 15. Examining the water content of the calculated hourly data gives an average value of 8.12 g/m³. The maximum is given in summer with 17.27 g/m³ and a minimum with 2.98 g/m³. The monthly moving average (MA) gives the maximum of 13.49 g/m³ and the minimum of 3.92 g/m³. Calculating the difference between bedchamber and ambient water content gives inside a plus of 0.87 g/m³. In detail we can calculate a plus of water content in the bedchamber compared to ambient climate in summer (max) with 0.98 g/m³and in winter (min) with 0.79 g/m³.

Sultriness

Warm and humid air is referred to as uncomfortable climate conditions to humans and is called sultriness. There are some different definitions when sultriness starts. Scharlau [7] refers sultriness to the curve of Lancester-Castens, starting at a water vapour pressure of 1878 Pascal. A newer definition gives Steadman [5] with beginning of sultriness at 1600 Pa. Fiedler [6] combines Temperature with Humidity for his definition. For further considerations the definition of Steadman is used. A water vapour pressure of 1600 Pa corresponds to 12.07 g absolute water content per m³ air. Figure 14 depicts the three definitions of sultriness in context of hourly data of relative humidity and temperature in a scatter plot. Conducting the data gives in total 1295 hours of sultry conditions in this period of one year. During opening hours there are 630 hours with uncomfortable conditions of sultriness. In total there are 80 days with hours of sultry conditions. Figure 15 shows these days with the ratio of sultry hours to opening hours.

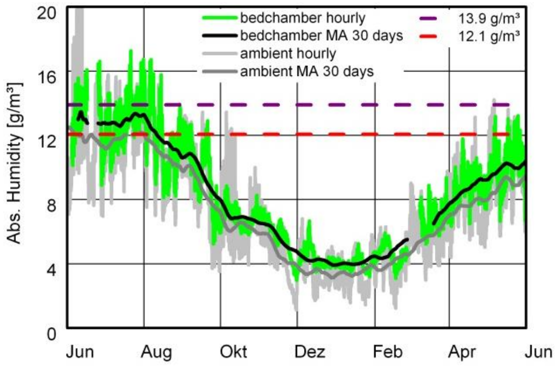


Figure 13 The green line shows the absolute humidity with hourly data of the bedchamber, the black line is the monthly moving average. The grey lines show the data of the ambient climate analogue. Time from 06/2009 until 06/2010.

5. BUILDING SIMULATION OF KING´S BEDCHAMBER

Conducting a building simulation is complex and time-consuming. For correct calculation all necessary boarder conditions have to be examined and determined thoroughly. The following chapter gives a short insight in first calculation results of dependencies of visitor influence, outer climate, and air change rate. The whole building model with boarder conditions will be highlighted in a further paper.

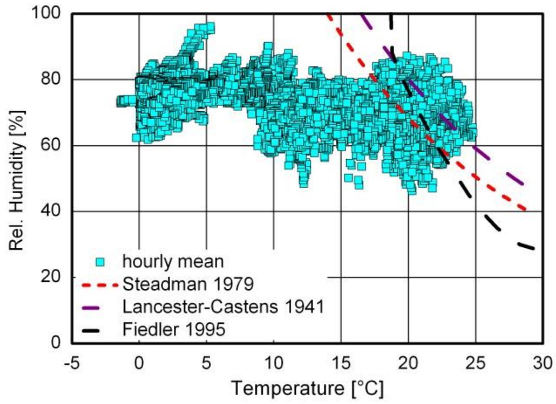


Figure 14 Scatterplot of the measured data of the bedchamber. Temperature and relative humidity of the hourly data is shown in this plot as a squared box. The measured data is related to the border lines of sultriness due to absolute humidity and temperature. Time from 06/2009 until 06/2010.

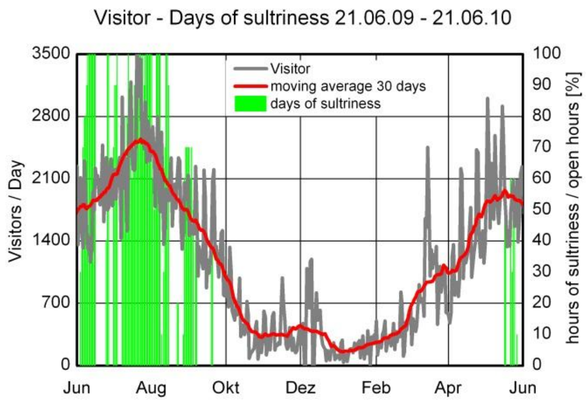


Figure 15 Days of sultriness in context of daily figures of visitors, from 06/2009 until 06/2010. Overall 80 days with definition of sultriness occur. The hours of sultriness are given in ratio to opening hours.

5.1. Simulation model

The building simulation model is based on the real building components partly introduced in this paper. Due to software limitations and to lower the work load some simplifications have been made in modelling the bedchamber. For example the round areas on ceiling and two room corners are implemented as areas without bending. Figure 16 shows the building model implanted in the software. For calculation purposes the single building components are allocated to single areas with same assembling respectively similar climate conditions.

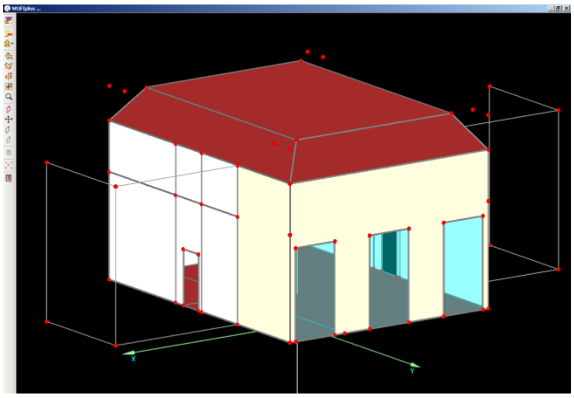


Figure 16 Building model of King´s bedchamber implemented in simulation software WUFI® Plus. The windows on north facade are imaged as light blue areas.

5.2. Simulation of visitors and air change rate

Investigations on the room climate in Castel Schönbrunn at Wien, conducted by KIPPES [8] shows that the air change rate has much more influence on room climate than the emissions of visitors. A new airing concept has been developed based on this thesis. The proposed measures contained a better sealing of the windows to reduce the influence of the outer climate.

As a first step a building simulation calculation was done with changed air tightness of the bedchamber in assumption of closed windows throughout the year. Due to this measure a maximum reduction of airing with outer climate should be reached. The air change rate was set to 0.13 h^{-1} in accordance to the lowest measured value of air change rate in winter time. The result of this simulation set up will be compared to the same simulation set up only distinguished between constant and as real assumed air change rate conditions.

The building simulation shows in Figure 17 the same relative humidity where the ACR are almost equal. During summer and autumn a rise of RH can be observed due to the reduce ACR.The absolute humidity also rises with the RH. Figure 18 shows the absolute water content. In this graph the boarder line for sultriness due to STEADMAN [5] is added. The already bad air conditions for the visitors are going worse. The hours and days of sultriness are doubling as figures in Table 1 show.

Also the concentration of carbon dioxide was measured and compared in building simulation. The results are depicted in Figure 19. The values of measured data and simulation data show a good accordance. The values of carbon dioxide are rising up to 4000 ppm in simulation results with reduced air change rate. The air quality is decreasing with rising carbon dioxide. Due to DIN EN 13799 [9] the air quality beyond the green line of 1400 ppm is bad.

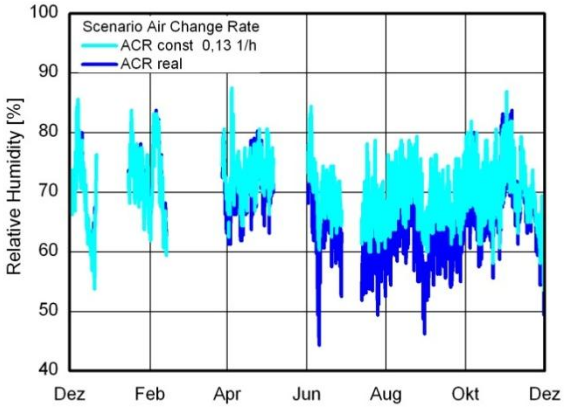


Figure 17 Relative humidity in room air of the bedchamber with results of building simulation under real conditions and scenario with constant air change. Time from 12/2009 to 12/2010. With the reduced ACR in summer and autumn the RH rises.

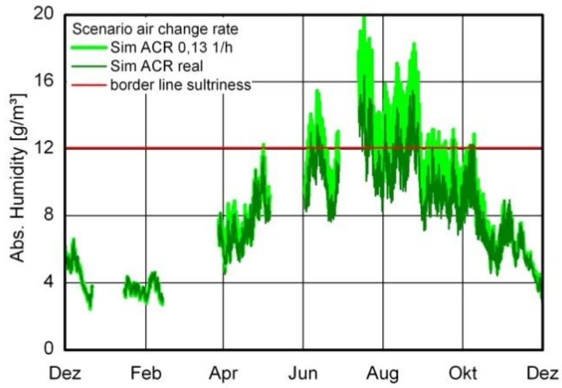


Figure 18 Absolute humidity of the bedchamber with results of building simulation under real conditions and scenario with constant air change. Time from 12/2009 to 12/2010. With the reduced ACR in summer and autumn the RH rises.

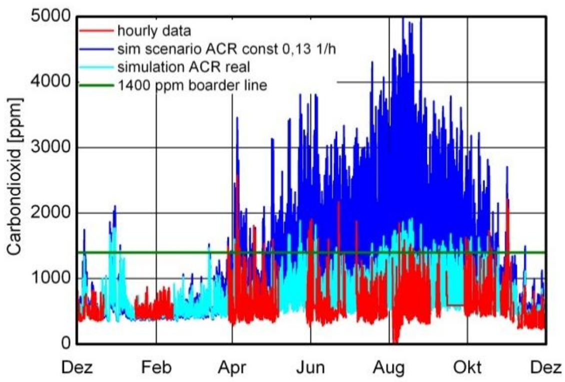


Figure 19 Carbon dioxide in room air of bedchamber, with results of building simulation under real conditions and scenario with constant air change rate compared to measured data. Time from 12/2009 to 12/2010.

Table 1 Days of sultriness as results of building simulation with real conditions compared to a reduced air change rate for the period from 12/2009 to 12/2010.

	Simulation real ACR	Sim ACR constant	Change [%]
Hours total	**782**	**1511**	**193**
Hours during opening	**372**	**790**	**212**
Days with sultriness	**55**	**108**	**196**

6. SUMMERY AND OUTLOOK

Knowledge about the building history and construction details is vital for understanding a building and its own special climate. In case of Linderhof palace the thorough construction is partly responsible for the considerable offset of about 6 Kelvin of the room temperature without any heating, beside visitors and lightning. The fluctuations of relative humidity were shown and set in context to internationally discussed values.

Very important to tourism in comfort (sultriness) and to the castle in preservation is the much higher absolute water content compared to the ambient climate. A precisely measurement is necessary to get true information to distinguish the influence of visitors in an offset of water content of air.

The real measured room climate of the King’s Bedroom is replicated by computing a building simulation based on the adjacent room climates. First results illustrate the interrelationship of visitors and air change rate compared with the measured data of the King´s bedchamber room.

In order to adjust the simulation model to the real room climate further investigations are necessary. In order to proof the input parameters and adjust the model to the measured data of the room climate, sensitivity analysis will be made and their conformity will be compared with the real data. Further investigations on room climate and possible airing methods are necessary to improve the momentarily situation. With this generated building simulation model it will be possible to investigate different airing methods and their regulation and automatic control.

7. REFERENCES

[1] Holmberg Jan G. 1997. Technical Classification of Museum Buildings ICOM-ICAMT 1989, in: EUROCARE Eureka Project EU 140, EU 1378 PREVENT, Preventive Conservation, Report No. 7 from Swedish Partners

[2] Burmester, Andreas: Die Beteiligung des Nutzers bei Museumsneubau und –sanierung. Risiko oder Notwendigkeit oder welche Klimawerte sind die richtigen? in: Raumklima in Museen und historischen Gebäuden. Bietigheim-Bissingen, 2000, p. 9-24

[3] ASHRAE Handbook – HVAC Application (SI), Chapter 21: Museums, Galleries, Archives and Libraries, American Society of Heating, Refrigerating and Air-Conditioning Engineers. 2007.

[4] Bratasz, Lucasz: Acceptable and non-acceptable micorclimate variability: the case of wood, in: Camuffo, D.; et.al. (Editors): Basic Environmental mechanisms affecting cultural heritage. P. 49–58, Cost Action D42, Nardini Editore, Firenze, 2010

[5] Steadman, R.G..: The assessment of sultriness, Journal of Applied Meteorology, Volume 18, p. 861–885, 1979

[6] Fiedler, Klaus: Hygiene, Präventivmedizin, Umweltmedizin systematisch, Uni-Med Verlag, 1. Auflage, Bremen 1995

[7] Scharlau, K.: Schwüle und Behaglichkeit als Klimagrößen, Medical Microbiology and Immunology, B 123, V 4, p. 511-530, Berlin 1941.

[8] Kippes, Wolfgang: Raumklima in historischer Bausubstanz. Ein Beitrag zur material-wissenschaftlichen Begründung der Denkmalpflege. Dissertation, Wien 1999.

[9] DIN EN 13779: Lüftung von Nichtwohngebäuden - Allgemeine Grundlagen und Anforderungen für Lüftungs- und Klimaanlagen und Raumkühlsysteme, Beuth-Verlag GmbH, Berlin 2007

EQUAL-SORPTION MICROCLIMATE CONTROL APPLIED TO THE HOLY CROSS CHAPEL AT KARLŠTEJN CASTLE

Pavel Zítek[1], Tomáš Vyhlídal[1], Oto Sládek[2], Aleš Sládek[2], Goran Simeunovic[1]
[1]*Centre for Applied Cybernetics, and Department of instrumentation and Control Engineering, Faculty of Mechanical Engineering, Czech Technical University in Prague, Technická 4, 16607 - Prague 6, Czech Republic,*
tel: +420 224 352 564
Pavel.Zitek@fs.cvut.cz
[2]*Kybertec, s.r.o., Tovární 1112, 537 01 – Chrudim, Czech Republic*
tel: +420 469 659 147
sladek@kybertec.com

Abstract: The paper deals with a scheme of the microclimate control developed for preventive conservation purposes to inhibiting the undesirable moisture sorption phenomena in historical exposition rooms. The proposed microenvironment control of this kind was applied for the first time in the Holy Cross Chapel at Karlštejn Castle, Czech Republic. The harmful exposure, namely the strain in the deposited art works produced by the variations of moisture sorption is inhibited by a specific control of interior air humidity. The original idea of air humidity control compensating for this harmful impact has been further investigated to achieve a more precise maintenance of acceptable variation of moisture content. The paper presents the recent results of this research leading to a proposal for modification of the first application of this method in Karlštejn Castle. The control leaves the interior temperature to run almost its spontaneous year cycle while a non-linear model-based control provides adequate adjustments of interior temperature and air humidity just compensating for the moisture sorption variations due to the ambient condition changes. This compensation prevents the exhibits from the harmful variations of the moisture content changes and from their harmful effects. The air handling device and control was implemented in the chapel already in 1999 and the proposed modification of microclimate control is to achieve a more precise maintaining permanently the desirable moisture content in the organic or porous materials of art works inside the Chapel.

Keywords: Equilibrium moisture sorption, humidity control, preventive conservation

1. INTRODUCTION, STATE OF THE ART KARLŠTEJN CASTLE

Originally the research of microclimate control reported below was initiated by the occasion of re-housing the precious collection of 129 medieval paintings of Master Theodoricus back into the Holy Cross Chapel at the Karlštejn Castle. The paintings suffered serious moisture originated damage and had to undergo a costly restoration. Before their returning back to the castle the Chapel interior was restored and equipped with a special local air-handling system adjusting the internal microclimate to prevent the paintings and other exhibits from further endangering by moisture impact. Already since 1999 the system has been in successful operation.

Karlštejn, Fig. 1, is a large Gothic castle, about 30 km southwest of Prague, founded 1348 by Charles IV, the Holy Roman Emperor and the most famous King of Bohemia. It was built up to serve for safekeeping the Imperial and Bohemian Crown Jewels and a precious collection of holy reliquaries. Charles IV himself personally supervised the construction works and interior decoration and already in 1365 the construction was finished when the Holy Cross Chapel, as the "heart" of the treasury, was consecrated. Karlštejn is one of the most famous and most frequently visited castles in the Czech Republic.

The Holy Cross Chapel is conceived as the most dominant centre of the castle and takes up the entire second floor of the Castle's Great Tower. It is accessible by a four-flight staircase where the walls are covered with murals depicting scenes from the Legend of St Wenceslas and St Ludmila, the most famous Czech Saints. The chapel itself is vaulted by two fields of groined cross arches and lit by four windows with traceries in which semi-precious stones were set instead of glass discs. The inferior parts of walls are decorated by colour inlays with predominantly red and polished semi-precious stones. On the Chapel's walls there is a precious collection of outstanding wood panel paintings by Master Theodoricus from the period from 1360 to 1365, see Fig. 2 for a part of the paintings on the wall behind the altar. The paintings are the portraits of apostles, knights, sovereigns, dignitaries, prophets and angels, authorities entrusted by the Emperor with safeguarding the Imperial sacraments. Master Theodoricus, the court painter to Charles IV., presented himself as a painter who succeeded in connecting realism and individuality of pictured figures with the former conception endorsing rather primitive Christian or Byzantine traditions. The set is one of the most notable collections of medieval art and also the biggest collection of one artist from 14th century in the whole Europe. This style is also preferred in the overall decoration of the chapel.

Figure 1 Karlštejn Castle, The Holy Cross Chapel is located in the second floor of the Great tower.

Figure 2 Interior of the Holy Cross chapel with wood paintings by Master Theodoricus

1.1. Natural microclimate in the Holy Cross Chapel

The region around the castle is typical with rather rough character of weather conditions during the year seasons. On the other hand for the interior environment in the Chapel the heavy masonry of the Great Tower plays the decisive role. The thickness of the walls around the Chapel from three point six to six metres reduces the interior temperature variations narrow in amplitude. Due to the thermal capacity and resistance of the walls the leaking windows represented the main input influencing the indoor environment of the Chapel before its reconstruction. There is an advantage for the present study that there exist long-term records of the indoor environment in the Chapel which may be used as a basis for the new environment arrangement. The decisive harmful impact on the artistic exhibits consisted in unfavourable combinations of both indoor temperature and air humidity values. Particularly at the time when the ambient dew point temperature exceeded the temperature of the interior surfaces the leakages through the windows, doors etc. caused the dew condensation on the walls with their harmful consequences on the exhibits.

A specific issue of the indoor environment is the attendance of the visitors in the Chapel. In the analysis the visitors are to be considered as an intake of heat and moisture which may contribute considerably to the overall harmful impact. This aspect is to be preferred to the viewpoint of the visitors' comfort. Anyway the key aspect of the environment analysis is the indoor air circulation in the Chapel. The Chapel interior is composed of two separately vaulted parts divided by a gilded screen. To improve the air circulation conditions was one of the crucial tasks in preventing the Chapel interior from the moisture originated harmful effects and from opening the possibility of microorganism growth.

2. MOISTURE CONTENT AS A KEY PARAMETER FOR PRESERVATION

Twelve years ago the analysis of the heat and moisture exchange between the Holy Cross Chapel indoor environment and the outdoor conditions resulted in a novel approach to assess and to improve the preventive conservation state. The key idea consists in the fact that it is not the state of air, i.e. its temperature and humidity, but the amount of moisture absorbed in the moisture sensitive materials that decides whether or not a damage of these materials is to arise. For example wood and paper are typical moisture sensitive materials and as regards wood its different mechanical properties and extensibility in each of three primary axes cause stresses leading to deformations or even to cracks when the moisture content changes substantially. More precisely the steady state value of this moisture is not as critical as its changes in time. The absorbed moisture content in the materials of sculpture works, paintings, plasters, stuccos, etc. tends to settle at an equilibrium level corresponding to the relative humidity and temperature of the surrounding air (Camuffo, 1998). Material extensions resulting from common moisture content changes are relatively high and it is important to notice that these extensions are largely higher than only thermal extensions for most materials. The internal environment regulations in prominent galleries and museums prescribe to keep constant both the interior temperature and the air humidity in the exhibition rooms.

However, due to impracticable costs and technical demands, standard air-conditioning cannot be implemented as far as remote historical interiors like the Holy Cross Chapel are concerned (Cassar, 1993).

To some extent, most of the castles and mansions serve as exhibition rooms for historical or artistic collections, as archives, historical libraries, as concert rooms etc. and the microclimate regulations for these interiors are still a subject of controversial discussions (Kotterer, 2002). Particularly due to the *impact of air humidity* it is a hard task to achieve a stable and non-aggressive internal environment in historical buildings, and owing to this an invaluable part of cultural heritage is exposed to a more or less damaging impact of an unsuitable microclimate. Internal air humidity is the most significant harmful exposure for the exhibits made of porous organic materials, such as wood, paper, parchment, canvas, etc.

From the conservation point of view, the aim of keeping both air temperature and humidity in exhibition interiors within certain tight limits is not as important as it is commonly assumed. The decisive condition to prevent the preserved exhibits from moisture originated damage it is to keep constant an acceptable level of moisture content in these exhibits, i.e. to maintain an admissible moisture sorption in *equilibrium*. From this fact the following principle of controlling the interior environment has resulted. For the sake of untouched state of the preserved exhibits the interior temperature may vary in relatively wide range if simultaneously the air humidity is adjusted simultaneously on the level excluding harmful change in the *equilibrium moisture content* (EMC) in the materials the preserved exhibits are made of. Unlike the human visitors the exhibits are widely insensitive to slow temperature changes as such if they are not followed with moisture sorption variations.

The equilibrium moisture content has been investigated in most of the materials typical for the cultural heritage and the results are presented in the form of the so-called *sorption isotherms*. The models of these isotherms are discussed in Section 3. From their shape it results that, e.g. lower temperature of surrounding air necessitates specifically reduced air humidity if the EMC of the exposed material is to be kept unchanged. In this way for the sake of preventive conservation it is not important to maintain constant a desired temperature but to maintain the air humidity at a level corresponding to the spontaneously and slowly varying interior temperature. In such thick wall constructions like the Great Tower there is no need to worry about rapid temperature changes because of its enormous thermal capacity. Therefore the air temperature in the Chapel may be left near its natural annual cycle through the year seasons while a special air handling device provides both temperature and air humidity adjustments to keep the level of the EMC almost constant.

In this way it became possible to protect the exhibits against the moisture variations impact without the need of expensive air-conditioning, however, only if both the temperature and the compensating air humidity changes are smooth and slow enough so that the absorbed moisture in the exhibit materials may be kept within safe range. Apparently, the visitor's comfort is not the priority of this approach, the viewpoint of the beneficial environment for the exhibits is preferred. Now after the twelve year operation of the air handling device we can evaluate the long term effect of the microenvironment and also to modify a bit the control according to the recent research results presented in (Zítek and Vyhlídal, 2009).

2.1. Current installation of the air handling system in the Holy Cross chapel

The tailor-made air handling system fulfilling the preservation requirements in the Holy Cross Chapel was designed and manufactured by PZP Complet, Dobruška, Ltd. (L. Klazar) and the control system has been designed by Proteco Pardubice, Ltd. (O. Sládek). The complete system was put into operation in the end of 1999 and since that time the interior microclimate is controlled. In Fig. 3, the scheme of the installation is shown in the control panel of the SCADA system. The system controls temperature in the chapel according to the pre-calculated set-point that takes into consideration the thermal inertia of the chapel in response to the outdoor climate. Next, the relative humidity is being adjusted as well. Due to minimization of the energy consumption, the rule based control of relative humidity is implemented that utilize mixing outdoor and indoor air if possible. The system also enables to perform humidification by humidifiers and dehumidification by condensation on the coolers, if needed. The air handling device is installed in a small neighbouring room separated by a window from the chapel. The conditioned air is being continuously blown into the chapel through the window and slightly less air-flow is being continuously exhausted from the chapel. In this way, the chapel interior is slightly pressurised, which prevents the outdoor air infiltration from undesirable affecting the microclimate in the chapel.

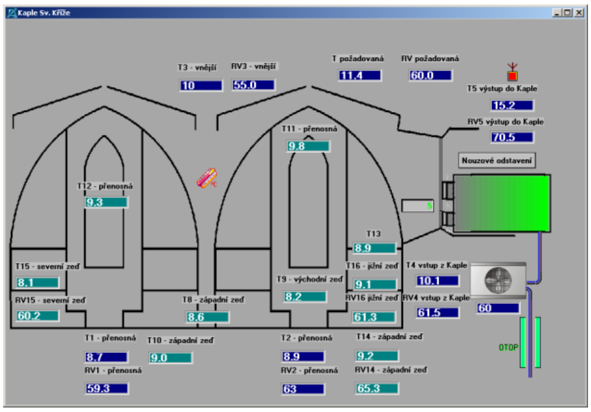


Figure 3 Control panel of the SCADA system of microclimate control in the Holy Cross Chapel.

3. EQUILIBRIUM MOISTURE CONTENT – ITS DEPENDENCE ON INTERIOR AIR PROPERTIES

The air humidity and temperature in exhibition interior are considered as the primary and the most important attributes of the microclimate (Cassar, 1993). Particularly in the remote sites of deposits, where neither heating nor air handling device is in operation, the humidity impact represents the most dangerous exposure from the preservation point of view. The decisive role of moisture sorption impact is typical for most of the materials the artistic works are made of, i.e. for wood, paper, parchment, leather, ivory, bone, paintings, plaster, stucco or stones containing abundant clay minerals etc. The steady state amount of water absorbed in them, corresponding to the surrounding air humidity and temperature, *equilibrium moisture content* (EMC), is usually expressed as the ratio of the mass of water per unit mass of anhydrous material. After the ambient temperature or humidity change their values, the absorbed moisture content changes accordingly (Massari, 1993, Jakiela, et al., 2008) but its change is a very long-run process. The EMC increase is then followed by swelling of the material and, contrarily, its decrease results in contraction. Due to the non-isotropic character of these size changes the harmful deformations or destructive cracks appear as the result. The material extensions resulting from growing EMC are relatively high and it is important to notice that this extension is largely higher than the only thermal extension of the dry wood.

In fact the expansion phenomenon is a bit more complex. For example, a rise of temperature induces primarily a thermal expansion but consequently a drop in relative humidity and therefore also the adequate drop in the EMC which brings about a material contraction and vice-versa (Camuffo, 1998). In this way the thermal expansion and EMC contraction are of opposite character and the shrinkage is partially mitigated by the expansion. However, the dimension change due to relative humidity is largely dominant, since the only temperature expansion itself is by more than ten times weaker than that of relative humidity (Kowalski, 2003).

For each of the considered materials the equilibrium moisture content settles on a level appropriate to the ambient air humidity and temperature. Although the EMC levels are different for various materials, the following properties are common for all of them

- the EMC always increases with growing φ and decreases with growing *T*,
- the EMC value is much more sensitive to the air humidity change than to varying temperature.

The relationship between the EMC as *u*, and the pair of air temperature *T* and relative humidity φ, $u = \Psi(\varphi, T)$ has been fitted by several formulae developed for various areas of application. Usually this relationship is used to be plotted in the coordinates φ and *u*, as the so-called *sorption isotherms*, with temperature considered as a parameter. In particular the mathematical models by Day and Nelson and Simpson (Ball et al., 2001) were found as well fitting the experimental data for professional evaluating the EMC. But for the microclimate control idea proposed in (Zítek, at al. 2007, 2009) and outlined below, these models are less suitable because their derivatives result in fairly complicated forms. For the purposes of moisture sorption stabilization method, the logarithmic Henderson model was chosen as the most suitable available model for the equal-sorption compensation, namely its three-parameter version (Avramidis, 1989)

$$u = \left[\frac{-\ln(1-\varphi)}{A(T-B)}\right]^C = \Psi(\varphi, T) \tag{1}$$

where $\varphi \in \langle 0, 1 \rangle$ is the relative air humidity expressed as dimensionless ratio, *T* (K) is the absolute temperature of air and *u* is EMC expressed as the mass ratio of moisture mass content to the mass of anhydrous material. The parameters of the model are specific for each material: the additive temperature parameter *B*, ($B < 273.16\ \mathrm{K}$) is in K, *C* is a positive dimensionless exponent less than one, the sensitivity coefficient *A* is in K^{-1}. Apparently the model is not applicable for humidity approaching the state of saturation, i.e. for $\varphi \to 1$, where the logarithm of $(1-\varphi)$ is not defined. The function $\Psi(.)$ can be used to derive an equal–sorption condition, however, attributed to a specific material.

Consider two moderately different equilibrium states of the ambient air φ_1, T_1 and φ_2, T_2. Suppose a selected moisture sensitive material with adsorption properties described by the Henderson formula (1) where parameter *B* is known. If for these states φ_1, T_1 and φ_2, T_2 the following equality holds

$$\frac{\varphi_2 - \varphi_1}{T_2 - T_1} = \frac{(1-\varphi_0)[-\ln(1-\varphi_0)]}{T_0 - B} = K_S(\varphi_0, T_0) > 0 \tag{2}$$

for an intermediate state φ_0, T_0, $\varphi_0 \in \langle \varphi_1, \varphi_2 \rangle$, $T_0 \in \langle T_1, T_2 \rangle$ then the equilibrium moisture contents in the selected material are equal to each other in both the states. The parameter $K_S(\varphi_0, T_0)$ is positive and will be referred to as *equal-sorption humidity rate.*

Equation (2) results from considering a small increment of *u* expressed by means of the differential $d\Psi$ and from the requirement of its zero value

$$\Delta u \cong \frac{\partial \Psi}{\partial T}\Delta T + \frac{\partial \Psi}{\partial \varphi}\Delta\varphi = 0 \tag{3}$$

where ΔT and $\Delta\varphi$ are small temperature and humidity differences between two equilibrium states respectively. Using the Henderson model (1), the derivatives can be obtained in the following form. As to the air temperature the derivative is always negative

$$\frac{\partial u}{\partial T} = \left[\frac{-\ln(1-\varphi)}{A(T-B)}\right]^C \frac{(-C)}{(T-B)} < 0 \tag{4}$$

where $0 < \varphi < 1$, and on the contrary, the humidity derivative is always positive

$$\frac{\partial u}{\partial \varphi} = \frac{C}{\left[A(T-B)\right]^{C}} \frac{\left[-\ln(1-\varphi)\right]^{C-1}}{(1-\varphi)} > 0 \tag{5}$$

and with respect to continuity of (1) the ratio of the derivatives

$$-\frac{\partial u/\partial T}{\partial u/\partial \varphi} = \frac{\left[-\ln(1-\varphi)\right](1-\varphi)}{T-B} = K_S \tag{6}$$

in a point φ_0, T_0, $\varphi_0 \in \langle \varphi_1, \varphi_2 \rangle$, $T_0 \in \langle T_1, T_2 \rangle$ is equal to the difference ratio in (2). Notice that the ratio K_S is dependent only on *B* and independent of *A* and *C*.

The potential of a new air treatment emerging from the relationship (2) is apparent. If the temperature *T* of air surrounding an exhibit with an equilibrium moisture content *u* is slowly and continually changing by ΔT and if simultaneously the relative air humidity is changed by $\Delta\varphi$ so that $\Delta\varphi = K_S \Delta T$ then in spite of the changing air state the absorbed moisture does not change its equilibrium level. Such adjustment of air humidity is feasible by means of implementing a dehumidifying or humidifying device with a control providing that the relationship holds (Zítek, et al., 2006).

In general, various materials are distinguished by different parameters *A*, *B*, *C* of model (1) and therefore also by different K_S so that different humidity corrections $\Delta\varphi$ are to be expected for them. Nevertheless the investigations of moisture sorption isotherms have shown that the differences between K_S values for various kinds of wood, paper and other materials typical in cultural heritage are relatively small. Besides it is to notice that K_S value is rather small itself, typically $K_S(\varphi_0, T_0) \cong 0.005\,\mathrm{K}^{-1}$. This value means that, e.g., 10 K temperature change would require only a humidity readjustment by about 5 per cent. With regard to the really attainable accuracy in humidity measurement it is apparent that the differences of K_S for various materials may be neglected in most cases and the value $K_S = 0.005\,\mathrm{K}^{-1}$ may be used as common. The only exception to this rule are the paintings on interior walls where the humidity readjustments preventing the surface moisture content from varying need be substantially higher than for the other sorts of protected exhibits. In the Holy Cross Chapel the main aim of preventive conservation is the medieval painting collection and therefore the mentioned K_S is to be applied.

The low value of K_S may create an impression that the considered humidity correction represents only a weak intervention into the natural indoor environment conditions, but on the contrary, its impact is substantial in fact. Air temperature and relative humidity are not independent variables as they look in model (1). Comparing the empirical formula for the saturated vapour tension pressure at the given temperature, attributed to Magnus, and the Clapeyron equation with the original definitions of both relative humidity and the *mixing ratio x*, i.e. the mass ratio of water vapour to dry air (kg/kg), the following practical formula can be derived for estimating the mixing ratio *x* from the measured relative humidity φ and air temperature *T* under the usual air conditions in buildings

$$x = 3.795 \cdot 10^{-3} \cdot \varphi \, 10^{aT/(b+T)} \tag{7}$$

where $a = 7.5$, $b = 237.3^{\circ}C$ (Camuffo, 1998). It is evident that *x* of an air parcel is independent of atmospheric pressure changes if it is unaffected by condensation, evaporation or mixing with other masses. Hence, by differentiating relationship (5) the following inverse proportionality is obtained between small increments of air temperature and relative humidity, ΔT and $\Delta\varphi$ respectively, when the *mixing ratio x* is maintained constant

$$\Delta\varphi = -\frac{ab\ln 10}{(b+T)^2} \cdot \Delta T = -K_H \Delta T \tag{8}$$

where K_H varies from 0.067 to 0.062 for temperatures ranging from 10 to 20 $^{\circ}C$. Therefore the equal – sorption correction (2), providing a direct proportionality $\Delta\varphi = K_S \Delta T,\ K_S > 0$, stands out in a sharp contrast to the usual inverse proportionality (8) between temperature and relative humidity. In other words, if the temperature of humid air is changing without changing the mass ratio x the relative air humidity moves in the *opposite way* according to (8). That is why the humidity adjustment (2) represents a substantial intervention into the usual temperature – relative humidity relation. Note that the phenomenon (8) can be observed in the usual records of φ and *T* where it can be seen that most of the relative humidity fluctuations are due to temperature changes while only a minor part is due to the actual change of water vapour content.

4. REVISION OF EQUAL-SORPTION AIR HUMIDITY CONTROL IN THE CHAPEL

One of the main tasks of preventive conservation is to prevent the moisture sensitive materials the artworks are made of from anisotropic *swelling* or *shrinking* caused by the changes of the absorbed moisture content. As shown above to meet this demand there is no need to maintain air temperature and humidity constant since even their slow and smooth changes satisfying (2) leave the level of moisture sorption also unchanged. If simultaneously the environment is maintained in quasi-steady state all the time the cause of deterioration due to the moisture impact is eliminated and the well-being of the preserved exhibits can be provided despite the temperature slowly and smoothly changes.

The problem of guaranteeing such condition does not lie in the technological feasibility to provide air humidity adjustments maintaining equation (2) satisfied but rather in keeping the quasi-steady state in the environment. Since the process of any moisture sorption change is extremely slow the admissible temperature variations are to be kept as only very slight and slow. But the visitors' traffic density usual in the Holy Cross Chapel does not allow us to assume that the temperature variations are as slow and smooth as required. In order to satisfy the assumption of almost steady state the long-term records of the spontaneous temperature course in the Chapel were used to prescribing an averaged temperature T_A course expressed as the following sinusoidal function

$$T_A(t) = \Theta \sin\left[\frac{360^\circ}{365}(k-d)\right] + T_0 \tag{9}$$

where $\Theta = 4.5\ ^\circ C$ is the temperature amplitude, k is the serial day number in the current year, $T_0 = 15.5\ ^\circ C$ is the long-term mean temperature in the Chapel and $d = 106.5$ is the serial number of the day when at first the mean temperature T_0 is achieved in the average (the middle of April). The temperature T_A is considered as the *desired temperature* in the Chapel and the air handling unit is controlled to adjust the interior temperature towards this value. At the time of setting up the air handling unit the research of sorption phenomena was only at its start and therefore the humidity adjustments were assessed according to the psychrometric chart evaluation of the humid air.

Using the results presented in Section 3 and a reliable knowledge of the equal sorption rate K_S we now propose a revised version of the proper humidity adjustment preventing the change of EMC in moisture sensitive materials. The *desired relative humidity* φ_D of the airflow from the air handling unit results from the measured T or desired temperature T_A and the equal sorption humidity rate K_S from (2) as follows

$$\varphi_D = K_S(T - T_0) + \varphi_0 \tag{10}$$

where φ_0 is the desired relative air humidity at the mean temperature T_0. The adjustment of indoor air humidity is provided by means of dehumidifying or humidifying devices. As soon as both the temperature and humidity of air supplied to the Chapel are effectively controlled at the values T_A and φ_D varying according (9) and (10) respectively, then there is no reason any more for a change in moisture content in material for which K_S has been applied in (10). In this indirect way the moisture sorption can be maintained constant although a real-time measurement of moisture content is not available.

The described principle of the air handling unit operation is favourable from the point of view of power demand. Only a slight power of air warming is sufficient to compensate the temperature differences between T_A and the actual temperature in the Chapel and also the power needed for humidity adjustment is rather modest. The enormous thermal capacity of the Great Tower is favourable in this respect since the temperature deviations from T_A caused by temporary swings of the weather are only minute. Also the changes required for humidity compensation are moderate, around ten per cent of RH value corresponds to temperature fluctuations from 5 °C to 25 °C (Camuffo, 1998), and therefore the demand on power supply remains modest.

The desired relative humidity φ_D can also be easily assessed using the Henderson model (1). If T_0 and φ_0 denote the mean indoor temperature and the reference desired RH respectively then apparently any other relative humidity φ_D appropriate to measured temperature T adjusting the same EMC as in T_0, φ_0 has to satisfy the following equality resulting from (1)

$$\frac{\ln(1-\varphi_0)}{A(T_0 - B)} = \frac{\ln(1-\varphi_D)}{A(T-B)} \tag{11}$$

From this condition the formula corresponding to (10) for the desired humidity keeping EMC constant is as follows

$$\varphi_D = 1 - \exp\left(\frac{\ln(1-\varphi_0)}{T_0 - B}(T-B)\right) \tag{12}$$

where only parameter B stands for again and T is measured temperature. Alternatively, T in (12) can be substituted by the temperature setpoint T_A given by (9).

4.1. Allowable variation of moisture content

For the practical purposes of implementation of the humidity control according to (10) or (12), the allowable variation of the relative humidity from the prescribed set-point needs to be determined. Considering the temperature constant (or neglecting the slight dependence of the moisture content variations on the variations of temperature), it results from (3) that

$$\Delta u = \frac{C}{[A(T-B)]^C}\frac{[-\ln(1-\varphi)]^{C-1}}{(1-\varphi)}\Delta\varphi = K_\varphi(T,\varphi)\Delta\varphi \tag{13}$$

In order to determine the allowable variations of the moisture content, the relation between the moisture content and the material strain can be utilized. As it has been shown in (Jakiela, et al., 2008), (Bratasz, 2010), (Camuffo, 1998), see also references therein, the generally nonlinear dependence between the EMC and the material strain can be approximated, within limited ranges of these quantities, by the linear equation

$$\Delta d = \alpha \Delta u \,, \tag{14}$$

where Δd and Δu are the changes of the strain and EMC from the given equilibrium point, and α is the dimensional change coefficient. Taking into consideration that the generally reported yield point for wood is close to $\Delta d_y \approx 0.004$ (Mecklenburg, et al., 1998), see also discussion in (Bratasz, 2010), it is possible to use (14) to determine the maximum changes in moisture content that do not result in irreversible responses in the wooden structures. Thus, the final control law for adjusting the relative humidity should be considered as keeping the relative humidity within the range

$$\varphi \in [\varphi_D - \Delta\varphi_S, \varphi_D - \Delta\varphi_S] \,, \tag{15}$$

where φ_D is given by (13) and

$$\Delta\varphi_S = \frac{0.004}{\alpha K_\varphi(T,\varphi)} \,. \tag{16}$$

For practical purposes, the dependence of the coefficient $K_\varphi(T,\varphi)$ on temperature and humidity can be neglected and their yearly average values can be substituted instead.

5. EVALUATION OF THE RECENT MICROCLIMATE RECORDS FROM THE CHAPEL

In this section, the measurements of air temperature and relative humidity collected in the year 2010 are to be investigated from the preventive conservation point of view. In Fig. 4, the measurements of the temperature and relative humidity of the air that is being taken away from the chapel by the air conditioning unit are shown. Considering that the air in the chapel is properly mixed up, these measured values can be considered as fairly good representation of the air condition in the chapel. As regards the air temperature shown in upper part of Fig. 4, it is kept close to the periodic function (10) utilizing the thermal capacity of the chapel. In winter season, the air temperature is kept above 10 °C. Starting from mid of March, the temperature set-point is being gradually increased until the end of June, when the heating is switched off. During the summer season, air-temperature can be temporarily decreased by the cooling system if needed. Consequently, heating period starts in November and the temperature slowly reaches the minimum of the yearly cycle above 10 °C. As regards the relative humidity measurements shown in lower part of Fig. 4, unlike the temperature, it seemingly does not follow any generated set-point. In fact, the rule based control of relative humidity is used. In order to achieve desired range of relative humidity, outdoor and indoor air is being mixed if possible. Besides, the system performs humidification by humidifiers and dehumidification (via air cooling induced water condensation), if needed.

5.1. Evaluation of the microclimate according to ASHRAE standards

For the evaluation of the microclimate in the chapel, we first use the classification by ASHRAE (2003) - regulations for Museums, Galleries, Archives and Libraries. The year average temperature and relative humidity are $\overline{T} = 16.5\ ^\circ C$ and $\overline{\varphi} = 52\,\%\,\mathrm{RH}$, which in agreement with the ASHRAE recommendations $\overline{T} = 15 - 25\ ^\circ C$ and $\overline{\varphi} = 50\,\%\,\mathrm{RH}$. Regarding the fluctuation of the temperature and relative humidity, ASHRAE standards distinguish between short fluctuations and seasonal adjustment of the set-points or the mean values. Regarding the temperature, the seasonal adjustment of the set-point stays between $\overline{T}_{SET,\min} = 10\ ^\circ C$ and $\overline{T}_{SET,\max} = 25\ ^\circ C$. Short time fluctuation amplitudes stay within the range $\Delta T_{short} = \pm\, 2\ ^\circ C$ most of the time. The seasonal mean values of relative humidity range between $\overline{\varphi}_{S,\min} = 40\,\%\,\mathrm{RH}$ in winter and $\overline{\varphi}_{S,\max} = 60\,\%\,\mathrm{RH}$ in summer. The short time fluctuations most of time stay within the range $\Delta\varphi_{short} = \pm 10\,\%\,\mathrm{RH}$. According to Class of Control scale defined in ASHRAE (2003) (AA, A, B, C, D), the microclimate in the chapel can be classified as B – precision control. In such microclimate, a moderate risk of mechanical damage applies only for high vulnerable artefacts. For the painting of any kind, only tiny risk is assessed for most of the cases.

5.2. Evaluation of the microclimate using equal-sorption principle

As analysed above, the interior microclimate can be considered as satisfactory with respect to ASHRAE standards. In what follows, we analyse the microclimate using equal-sorption theory described above. Besides, the recent results and recommendation by (Bratasz, 2010), see also (Jakiela, 2008), on the acceptable microclimate variability will be considered. As the constants *A*, *B*, *C* in (1) of the wooden material of the panel paintings are not known, we consider A=0.431 K^{-1}, B = 204 K and C = 0.605 that have been assessed for aged wood in Zítek, et al., (2007, 2009). Applying the model (1), the equilibrium moisture content for actual values of relative humidity φ and temperature T is shown in Fig. 5. As can be seen, the value of EMC varies considerably within the yearly cycle. As the dynamics of the sorption phenomenon is not considered in the model (1), it should be emphasized that the short time variations of computed EMC do not represent the true evolution of moisture content in the material, except possibly very thin layer on the material surface (Jakiela, et al., 2008).

In order to evaluate the variations in the moisture content, let us determine first its allowable variations with respect to the allowable variations in the strain using equation (14). As reported in literature, for EMC values $u \in [0,15]\,\%$, the dimensional change coefficient

$\alpha \approx [0.13, 0.28]$ for lime wood (Jakiela, et al. 2008), $\alpha \approx [0.13, 0.23]$ for pine wood and $\alpha \approx [0.17, 0.32]$ for oak wood (Camuffo, 1998). The first value in the coefficient ranges is for the radial and the second number is for tangential direction. Taking into account the maximum strain for wood as its yield point $\Delta d_y \approx 0.4\,\%$ (Mecklenburg, et al., 1998), see also discussion in (Bratasz, 2010), the maximum value of the dimensional change coefficients reported above $\alpha_{\max} = 0.32$, the safe change in the moisture content is $\Delta u_R = \Delta d_y / \alpha_{\max} = 1.25\,\%$. In Fig. 5, the safe range of the EMC is shown centred in the yearly average value of EMC, $\bar{u} = 9.4\,\%$. If the moisture content in wood stays within this range, only elastic, i.e. recoverable deformation should take place. As can be seen, it is not the case for the EMC evaluated in the chapel, especially in winter and partly in summer seasons. Thus, according to the performed analysis, the microclimate in the chapel cannot be considered as entirely safe.

From (1), the desired relative humidity that keeps the moisture content in the material constant considering the actual value of the measured temperature can be determined as follows

$$\varphi_D = 1 - \exp(-A(T - B)u^{\frac{1}{C}}) \tag{17}$$

How does this relate to the Euroepan standard proposed by Camuffo et al

Considering this relationship, the derived safe range of moisture content $u = 9.4 \pm 1.25\,\%$ can be projected into the safe range of relative humidity, which is temperature dependent, as shown in Fig. 4. As can be seen, in the winter season (months 1, 2, 12) and in months 5, 6, the measured relative humidity is mainly outside the safe region. Thus, the relative humidity should be adjusted in these seasons, performing slightly stronger humidification in winter and dehumidification in summer. On the other hand, it is to be emphasised that the determined range of safe relative humidity might be rather conservative, as it was determined based on the maximum value of the available dimensional change coefficient. It is likely that the dimensional change coefficient of the thoroughly aged wooden material of the artefacts in the chapel may be lower. Besides, no dynamics of the moisture sorption phenomenon has been considered. As has been shown in (Jakiela, et al. 2008), the strain and accompanying stress development in the material layers is rather complicated phenomenon the dynamics of which also considerably depends on the material shape. As it has been concluded in (Bratasz, 2010), the safe changes of relative humidity also depend on the starting value of the relative humidity as well as on the speed of the changes. The safest starting value of relative humidity reported was 50%, which is in agreement with the general recommendations for museums and other exhibition interiors. Next, it was shown in (Bratasz, 2010) that the safe change of relative humidity in diurnal cycles is almost twice as high as the safe instantaneous change of relative humidity. Also, the fact that the artefacts are composed of several materials with nonhomogeneous structure and sorption properties as a rule need to be considered. The surface layers are often painted for the decoration purposes or for enhancing the durability of the material, which also affects the sorption phenomenon. To conclude, as has been discussed, the moisture sorption in the historical artefacts is very complex phenomenon. Even though the performed analyses based on sorption theory showed that the microclimate in the chapel needs certain adjustments, further and more detailed analysis is to be performed in order to fully justify this conclusion.

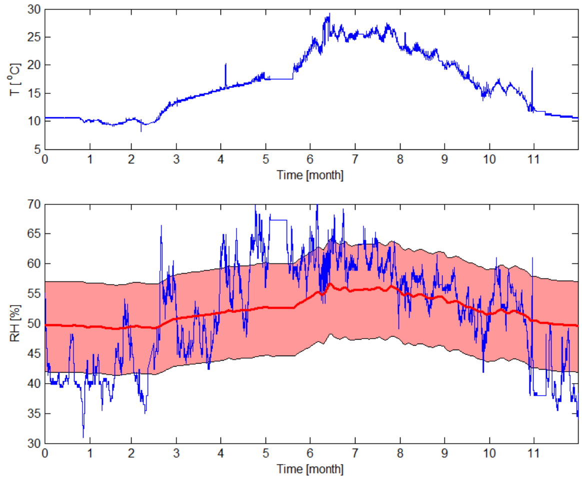


Figure 4 2010 yearly records of temperature and relative humidity of the air being exhausted from the chapel (blue lines). Red line – the set-point of the relative humidity determinned by (12) with the objective to keep the moisture content in the yerly mean value $\bar{u} = 9.4\,\%$. Red region – the range of relative humidity determined using (17) in order to keep the moisture content within the range $u = 9.4 \pm 1.25\,\%$.

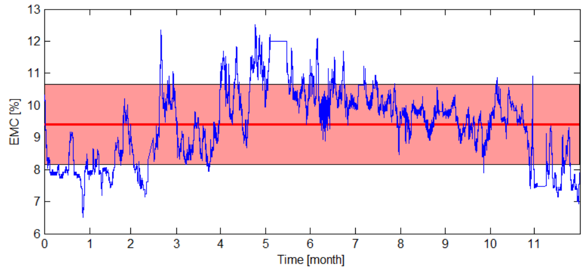


Figure 5 Moisture content in wood determined using (1) for the measured records of temperature and relative humidity measured in the chapel (blue line). Red line – the mean value of the moisture content. Red region – the safe region for moisture content changes that would not result in irreversible deformation.

5.3. Parameterization of the control algorithms for the Holy Cross Chapel

Consider the material parameters $A = 0.431\ \mathrm{K}^{-1}$, $B = 204\ \mathrm{K}$ and $C = 0.605$, nominal moisture content $\bar{u} = 0.094$ (that is achieved for example for the values $T_0 = 284.4\,K$ and $\varphi_0 = 0.5$). For computation of coefficient $K_\varphi(T,\varphi)$, consider the yearly mean values temperature $\overline{T} = 289.7$ K and $\overline{\varphi} = 0.52$, then $K_{\varphi}(\overline{T},\overline{\varphi}) = 0.161$. Consequently, from (16), the allowable variation of relative humidity from the nominal value of desired φ_D given by (12), results as $\Delta\varphi_S = \pm 0.077$. As (12) is identical with (17) for $u = \Psi(\varphi_0, T_0)$, the desired value of relative humidity is the thick red line in Fig. 4. Instead (12), simplified rule (10) can be used, where $K_S(\varphi_0, T_0) = 0.0041\text{K}^{-1}$.

6. CONCLUDING REMARKS

The microclimate control in the Holy Cross Chapel had to be implemented just in time of 1999 when the collection of Theodoric's pictures was transferred back to the Chapel. At that time our research of sorption isotherms was only at its beginning and therefore the control of air handling unit was preferably oriented on the temperature control tracking the average temperature $T_A(t)$ and on an approximately adequate humidity adjustment. Unlike that, application of the equal-sorption humidity control has been tested for more than seven years in the State Archives in Třeboň with results published in (Zítek, et al., 2007, 2009). Recent measurements in the Holy Cross Chapel have shown certain humidity variations slightly beyond the safely allowable limits and on the basis of the recent investigations it is now possible better to compensate for by means of the control strategy described in Section 3. The equal-sorption microclimate control represents a novel approach to preventing the preserved exhibits from changing the equilibrium moisture content in the materials these exhibits are made of. Although the EMC as an alternative controlled variable is unavailable for continual measurement, its change can be estimated by non-linear model (1) according to the humidity and temperature measurements. Compensating the natural interior temperature variations simultaneously by appropriate adjustment of air humidity according to (2) proved efficient in maintaining a reference EMC constant during the entire weather year cycle. Basically, the non-linear model-based microclimate control is marked out with a *model-predictive control* character since the changes of the thermodynamic air state variables are much faster than the sorption phenomena and therefore they inhibit the possible sorption process.

7. REFERENCES

[1] ASHRAE, 2003, ASHRAE Handbook - HVAC Applications, Chapter 21, Museums, libraries, and archives, pp. 21.1-21.16.

[2] Ball, R.D., Simpson, I.G. and Pang, S.: Measurement, Modelling and Prediction of E.M.C. in Pinus Radiata Heartwood and Sapwood. Holz als Roh- und Werkstoff 59 (2001), Springer-Verlag 2001, pp. 457 – 462

[3] Camuffo, D.: Microclimate for Cultural Heritage. Elsevier Science Ltd., Amsterdam, London, 1998

[4] Camuffo, D., Bernardi, A,, Sturaro, G., Valentino, A.: The Microclimate inside the Pollaiolo and Botticelli Rooms in the Uffizi Gallery, Florence. Journal for Cultural Heritage, Vol. 3, 2002, pp. 155 – 161

[5] Cassar, M.: Environmental Management. Guidelines for Museums and Galleries. Routledge, London 1995

[6] Cassar, M.: A Pragmatic Approach to Environmental Improvements in the Courtauld Institute Galleries in Somerset House. ICOM Committee for Conservation, Vol. 2, 1993, pp. 595 – 600.

[7] Jakieła S., Bratasz Ł., Kozłowski R.: Numerical modelling of moisture movement and related stress field in lime wood subjected to changing climate conditions. Wood Science and Technology, Vol. 42, 2008, pp. 21–37

[8] Bratasz Ł, Acceptable and non-acceptable microclimate variability: the case of wood, Capter 4 in Basic environmental machanisms affecting cultural heritage, Nardini Editore, Firenze, editted by D. Camuffo, V, Fassina, J. Havermans, 2010.

[9] Kotterer, M.: Research Report of the Project EU 1383 PREVENT, Museum Ostdeutsche Galerie Regensburg, 2002

[10] Kowalski, S. J.: Thermomechanics of Drying Processes. Springer, Berlin, 2003

[11] Massari, G. and Massari I.: Damp Buildings. Old and New. ICCROM, Rome, 1993

[12] Zítek, P. - Němeček, M.: Stabilizing Microklimate in Historical Interior by Moisture Sorption Control. In Proceedings of 10th IEEE Conference on Methods and Models in Automation and Robotics 2004. Szczecin: Wydawnictwo Uczelniane Politechniki Szczecinskiej, 2004, p. 407-412.

[13] Zítek, P. - Vyhlídal, T. - Chyský, J.: Experience of Implementing Moisture Sorption Control in Historical Archives. Acta Polytechnica. 2006, vol. 46, no. 5, pp. 55-61.

[14] Zítek, P. - Vyhlídal, T.: Model-based moisture sorption stabilization in historical buildings. Building and Environment. 2009, vol. 44, no. 6, pp. 1181-1187.

CALCULATIVE INVESTIGATIONS ON THE "TEMPERIERUNG" WALL HEATING SYSTEM – HYGRIC AND THERMAL ASPECTS

Martin Krus, Ralf Kilian
Fraunhofer Insitute for Building Physics, Holzkirchen, Germany

Abstract: The aspects of reducing rising damp and energy use of the Temperierung wall heating system are examinated with hygrothermal 2D building simulation. In comparison to the non-heated walls the change of moisture profiles, the heat losses by heat transmission and the moisture flux from the outer wall to the room are shown.

Keywords: Wall heating, rising damp reduction, energy efficiency, building simulation

1. INTRODUCTION

The "Temperierung" method is often used in historic buildings. It is based on providing continuous heating to the building envelope. Normally this is done with heating tubes installed in the plaster on the inside of outer walls or painted pipes on the surface of the walls. This creates in general a homogenous distribution of heat on the surfaces of the room except near the pipes and can help to reduce draughts.

The system will heat the most critical points in the construction (corners) where otherwise often condensation happens. Thereby it helps to prevent mould or algae growth in massive buildings.

Two much discussed aspects of the system are an assumed reduction of rising damp and a supposed general low energy demand due to the drying out of the walls. To give answers to these questions hygrothermal 2D building simulations are applied on a case study – the St. Renatus Chapel in Lustheim from 1686, built by Henrico Zuccalli. In comparison to the non-heated walls the change of moisture profiles, the heat losses by heat transmission and the moisture flux from the outer wall to the room are shown.

The Chapel is situated in the park of Schleißheim Castle near Munich and showed severe moisture damages in the second half of the 20th century. Therefore a horizontal moisture barrier was carried out in the early 1970ies that showed no effect at all. Most of the moisture in the Chapel came from condensation of moisture during summer. In the course of major restoration works a "Temperierung" wall heating system was introduced in 2003. The effect on the indoor environment was recorded and documented (Kilian 2004, Kilian 2007). By raising the temperature level of the church, the level of relative humidity was lowered from a mean of 70 % RH to 50 % RH. Also a slightly raised absolute humidity in comparison to outdoors was recorded after installing the "Temperierung" system that meant an additional source for moisture in the building. By making the windows more airtight also the short term fluctuations could be lowered. In 2010 the building is still in very good state, except for salt crystallisation on some parts of the exterior walls.

Since restoration the building is used only for weddings in the summer and is heated continually for conservation reasons during the colder seasons of the year.

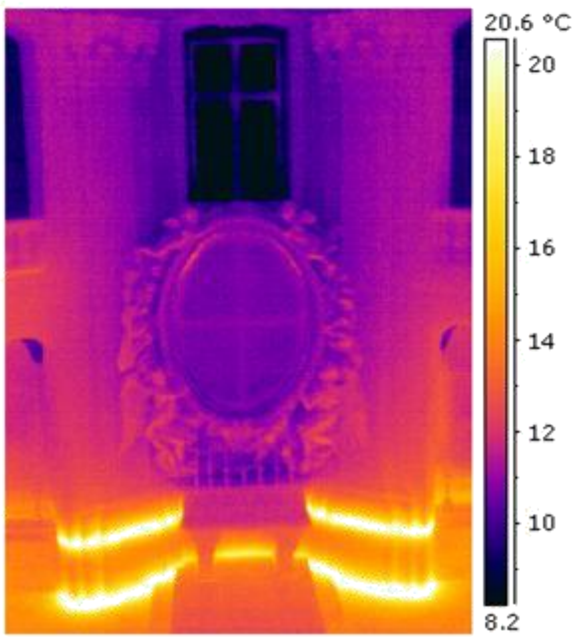


Figure 1 The thermography of the Renatus Chapel shows clearly the wall heating of building components. Above the heated zone, the temperature distribution is homogenous.

2. BACKGROUND AND OBJECTIVE OF CALCULATIVE INVESTIGATIONS

In case of locally high moisture contents in materials on internal surfaces caused by rising damp, condensation in summer or other effects, the advantages concerning the wall heating (Temperierung) of building components are controversial. This technology allows the reduction of moisture in certain problematic areas and can avoid for example microbial growth. But it is consistently argued that the wall heating of building components is also an energy-saving way of heating a room. The reasons given for this fact are that due to the drying of a wall the thermal conductivity of the material decreases, and thus heat transmission losses are clearly reduced in comparison to a conventional heating, resulting in a considerable energy-saving effect. With regard to the application in the Renatus Chapel additional problems arise concerning the effect of such wall heating. With this example of rising damp in the foundation it is especially important to know whereto the released moisture is transported. Is the wall section drying mainly towards the outside or towards the inside? Is the capillary transport, which is caused by rising damp, significantly reduced by wall heating or even permanently intensified?

These questions cannot be answered by measurements, since it is impossible to determine in situ moisture mass flows in the wall construction caused by diffusion or capillary transport processes. Therefore, calculative investigations are carried out to solve these problems. They allow to analyse the processes in the brickwork as well as to compare conventional heating and wall heating of building components under the same boundary conditions.

2.1. Calculative investigations

A tested and validated one-dimensional and two-dimensional EDV program WUFI®-Pro and WUFI®-2D (Künzel 1994) is available at Fraunhofer IBP for the calculative investigation of coupled heat and moisture transfer processes. Previous statements on the moisture transfer behaviour of building materials by means of this method showed good compliance of calculations and experimental investigations at the object (Künzel & Krus1995; Künzel 1999).

To carry out calculations, a wall construction is implemented which is as similar as possible to that of the Renatus Chapel. Material parameters were derived from the WUFI® materials database and modified for better compliance, where necessary.

The Munich test reference year is applied as outdoor climate. The indoor climate is based on measurements and is similar to the course of a year with an indoor temperature between 8 °C and 20 °C and a relative humidity from 40 % to 65 %. The orientation of the wall is towards the north so that the impact of driving rain and solar radiation can be neglected to a large extent.

Fig. 2 shows the implemented construction. The wall consists of solid bricks and has a lime plaster on both sides. A horizontal barrier is installed approx. 10 cm above ground as in the real Renatus Chapel. The flow pipe for wall heating building components is directly behind the internal plaster with a thickness of 1.5 cm in the middle of ground and horizontal barrier. The return pipe is 1 m above ground, i.e. clearly above the horizontal barrier. The flow temperature amounts to 60 °C, return temperature is 55 °C. The foundation is permanently in ground water so that rising damp occurs. In Fig. 2 the entire construction implemented for calculations is represented. The same construction is applied for calculations without wall heating of the building components but without heating pipes.

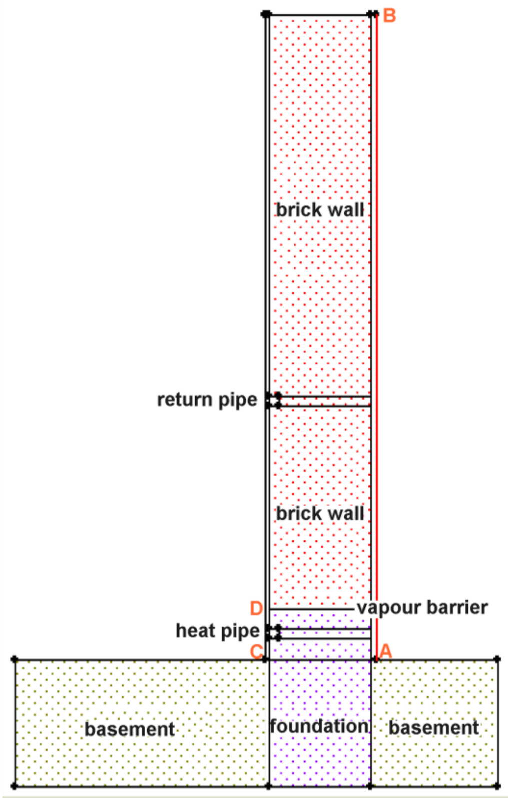


Figure 2 Implemented construction to calculate hygrothermal processes in case of wall heating of building components as in the example of the Renatus Chapel.

2.2. Results

Drying by the wall heating

Fig. 3 shows the course of the water content in the foundation beneath the horizontal barrier. It can be clearly seen that even without wall heating of the building components drying takes place by simply heating the room. Because the calculations starts with saturated material in this section a drying can be observed also without wall heating. However the heating of the wet building components results in intensified drying.

The faster drying with heating of the building components is caused by the intensive local heating of the brickwork. This is obvious from the temperature distribution as represented in Fig. 4 for a selected time in winter. Fig. 5 (bottom) represents the distribution of water content for the situation without wall heating after 1.5 years. Certain drying towards the inside and outside is evident. Compared to the result of the situation with wall heating (Fig. 5 top), the strong drying around the heating pipe is apparent. Stronger drying can also be found in the outside section. The reason for this is that the temperature level of the whole wall is higher in comparison to the situation without wall heating.

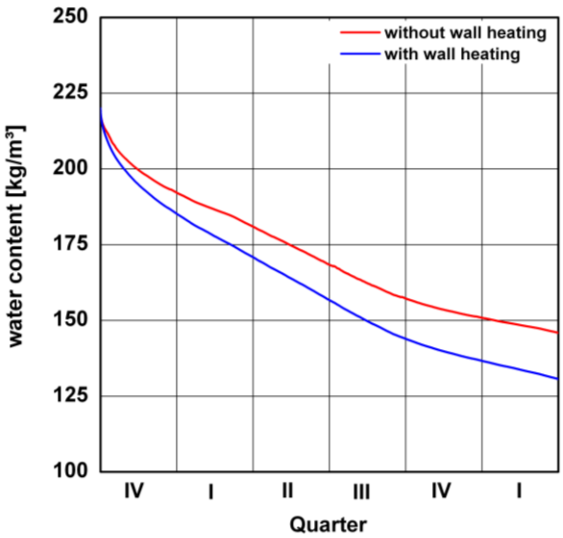


Figure 3: Course of water content in the area beneath the horizontal barrier without (red line) and with (blue line) wall heating.

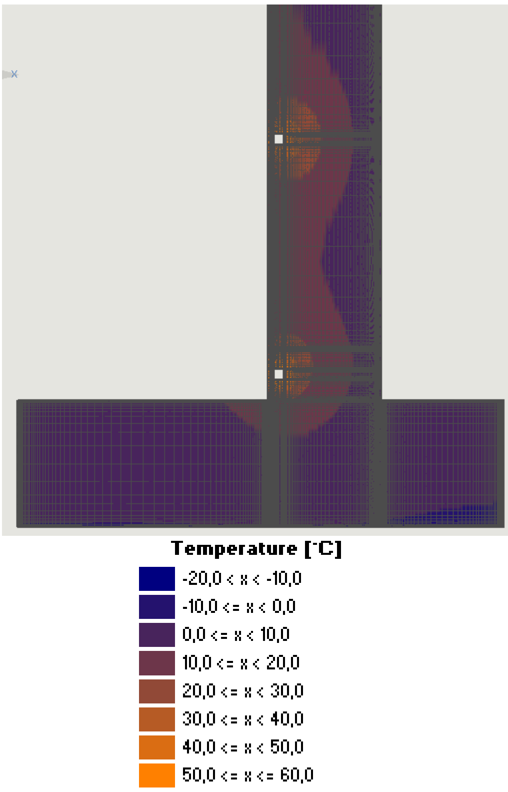


Figure 4 Calculated temperature distribution in winter (Feb. 15th).

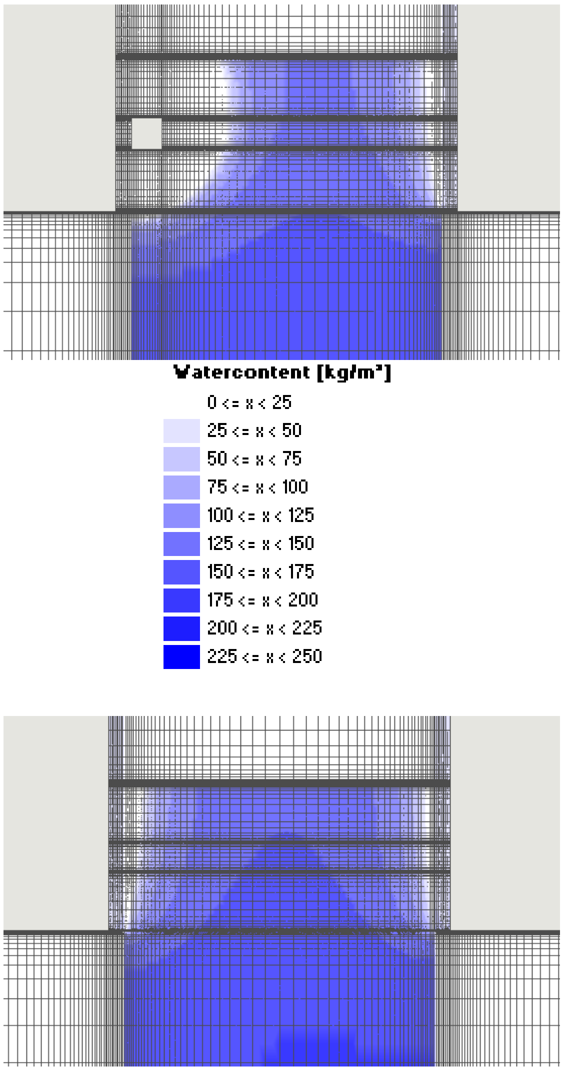


Figure 5 Calculated moisture distribution after 1.5 years without (bottom) and with wall heating (top).

Energy consumption

To test whether wall heating represents an energy-saving way of heating due to the drying of the walls, the evolution of the energy flow on the external wall above floor level (between point A and B in Fig. 2) with and without wall heating is compared. Since investigations are based on the same indoor climate in both cases, potential energy savings should be identified. It is, however, obvious that remarkably higher heat flows occur with wall heating (see Fig. 6). Moreover, wall heating of the building components is also operated beyond the usual heating periods.

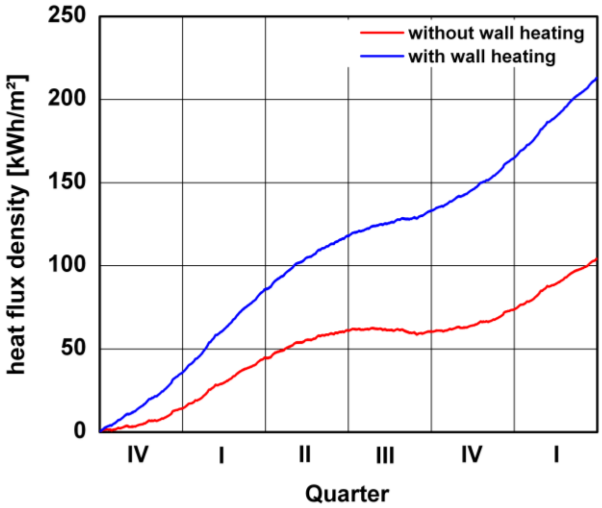


Figure 6 Integral courses of the heat flux densities with (blue line) and without wall heating (red line).

Considering the thermal resistance or thermal transmittance of the wall explains this fact. At the end of the calculation the mean water content amounts to 113 kg/m³ without wall heating, and to only 75 kg/m³ with wall heating. Thus, the thermal resistance of the brick wall increases from 0.34 m²K/W to 0.42 m²K/W. Heat transfer, however, takes place directly in the wall in case of wall heating so that the thermal resistance from indoor air to the wall is negligible. Therefore the thermal transmittance increases from 1.9 to 2.2 W/m²K.

Rising damp

Fig. 7 represents the capillary flow over C-A (see Fig. 2). A higher capillary flow results from wall heating in comparison to the situation without wall heating. The reason is that due to the drying in the section around the heating pipe the water content gradient is higher and thus the driving force for capillary transport as well.

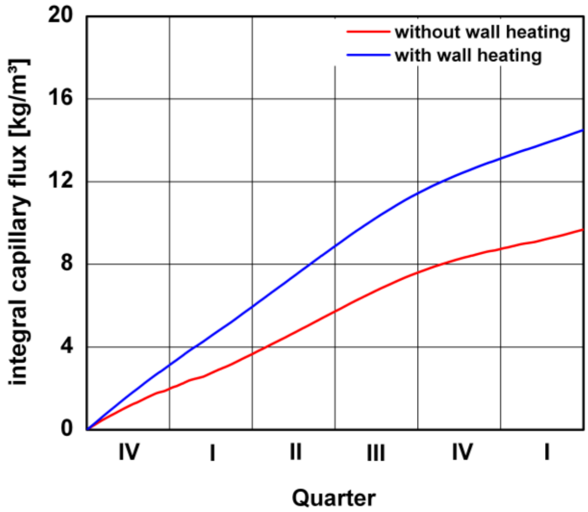


Figure 7 Integral courses of capillary flow densities over C-A (see Fig. 1) for the construction with (blue line) and without wall heating of the wall (red line).

Diffusion towards the inside

Fig. 7 shows the integral course of the diffusion flux over C-D (see Fig. 2), i.e. towards the interior. Wall heating results in a significantly higher diffusion flow than without. The fact is that a large part of the moisture is emitted to the interior. The representation of the diffusion flux density in Fig. 8 (bottom) shows that the difference to the non heated case is extremely high in the beginning. The high water content at the beginning is evapurating very rapidly causing extremely high diffusion flows towards the interior. An almost steady state, however, is reached after approximately 10 months resulting in an almost parallel course from this time. With wall heating, however, the diffusion flow towards the interior is still significantly higher, approximately double as high.

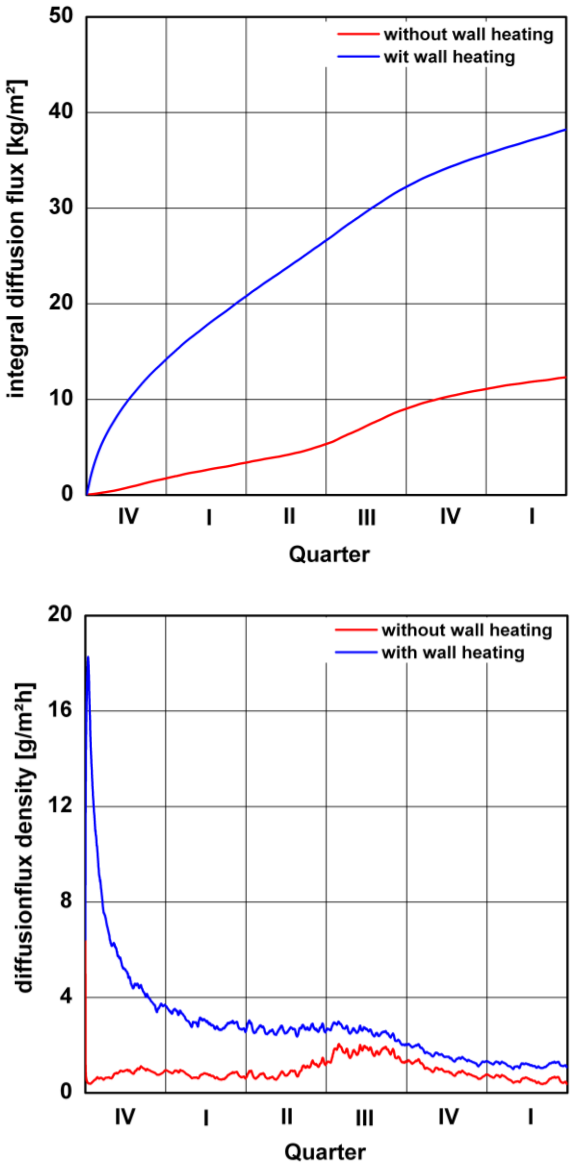


Figure 8 Integral courses of diffusion flux (left) and diffusion flux densities (right) over C-D (see Fig. 1) with (blue line) and without wall heating (red line).

3. SUMMARY

Two-dimensional transient calculations were carried out to assess the hygrothermal processes with the Renatus Chapel as an example. The purpose of the investigations was to answer the questions occurring with the wall heating systems.

Calculations confirm that the wall heating comes up to the real task, i.e. to dry vulnerable building components rapidly, and to avoid damage caused by microbial growth or frost. But it does not represent an energy-saving way of heating. Even if the drying of the brickwork results in a reduction of the thermal conductivity, the lack of the internal heat transmission resistance, which is of significant importance due to the typically inadequate insulation standard of the brickwork, will cause higher heat flows towards the outside all in all.

As calculations show it is necessary to take into consideration that due to the increased water gradient the wall heating may cause the intensification of rising damp. This does not mean that the water keeps on ascending, since clearly increased evaporation takes place due to the locally elevated temperature. The capillary flow, however, beneath the wall heating will be increased. As a worst-case scenario this means the enhanced accumulation of salt in the brickwork, and therefore this fact should be taken into consideration in each individual case of assessing the measures.

The computation also shows that the wall heating may cause an enhanced diffusion flow to the interior. This is most obvious in the beginning of wall heating, since a large amount of water is released from the brickwork at this time. But even under long-term operation an increased diffusion mass flow towards the interior can occur. This can result in an increase of indoor humidity. In general an enhanced removal of moisture must be cared for at least during the first months after the start of operation.

If correctly applied, the wall heating is a reasonable and appropriate measure in many cases to preserve precious cultural heritage. Against this background, other topics, e.g. energy saving, may be of secondary importance in these cases.

4. REFERENCES

[1] Kilian, R. 2004 Die Wandtemperierung in der Renatuskapelle in Lustheim – Auswirkungen auf das Raumklima, Siegl Verlag, München.

[2] Kilian, R. 2007 Statistische Untersuchungen der Klimaschwankungsbreite in unterschiedlich genutzten Kirchenbauten, in: WTA Almanach 2007, WTA-Publications, München.

[3] Künzel, H.M. 1994. Verfahren zur ein- und zweidimensionalen Berechnung des gekoppelten Wärme- und Feuchtetransports in Bauteilen mit einfachen Kennwerten. Dissertation Universität Stuttgart.

[4] Künzel, H.M. 1999. Praktische Beurteilung des Feuchteverhaltens von Bauteilen durch moderne Rechenverfahren. WTA-Schriftenreihe, Heft 18, Aedificatio Verlag.

[5] Künzel, H.M. & Krus, M. 1995. Beurteilung des Feuchteverhaltens von Natursteinfassaden durch Kombination von rechnerischen und experimentellen Untersuchungsmethoden. Internationale Zeitschrift für Bauinstandsetzen 1, H. 1, S. 5-19.

DAMAGE ASSESSMENT OF OBJECTS OF ART CORRELATED TO LOCAL OUTDOOR CLIMATE DURING 300 YEARS

Jan Holmberg*, Bengt Kylsberg, Karin Skeri
jan.holmberg@haftcourt.se
Skokloster castle
bengt.kylsberg@lsh.se
**Haftcourt Ltd., Dalagatan 78, 11324 Stockholm, Sweden,*

Abstract: Skokloster castle, located north of Stockholm, has a rich collection of furnishing and decorative objects of various kinds dating back to the 17th century. The castle has no active climate control. The objective of this paper is to investigate the deterioration of selected objects correlated to outdoor climate over a 300 year period and to analyse the preservation strategy chosen at Skokloster. The results show that the selected object overall were in good condition, as the were selected to represent the whole collection this would indicate a major part of the collection has been relatively well preserved and that the strategy of "doing nothing" has been favourable.

Keywords: Damage assessment, outdoor climate impact, housekeeping strategy

1. INTRODUCTION

At Skokloster Castle, located waterfront at Lake Mälaren, between Stockholm and Uppsala, generations of noble families have collected utility, furnishing and decorative objects of various kinds since the end of the 17th century. Together, the objects of art give us valuable knowledge of the functioning of an upper-class residence, both on festive occasions and on an everyday basis. The building and its collections have been an entailed estate since 1701. Thanks to this arrangement the objects have not been allowed to be sold or moved away. The Swedish state bought the castle together with the collections in 1967.

The buildings first proprietor was fieldmarchal Count Carl Gustaf Wrangel (1613-1676). The construction took place from 1654 to 1676. After Wrangel´s death, the property passed on to the Brahe family through the marriage by Wrangel´s eldest daughter Margareta Juliana. In 1930 Skokloster was inherited by the family von Essen.

Objects have been added to the collections over time by inheritance, but also taken especially from two castles belonging to the family Brahe, Rydboholm and Salsta, situated north of Stockholm.

Besides inventories, drawn up for each room on various occasions between 1710 and 1910, there is a list of personal property at Skokloster dating from 1672, the only extant one from Wrangel´s time. The inventory lists are the original sources to identify the conditions of the objects of art over time in the building.

Until 1947, the owners spent only very brief periods at Skokloster, mainly during the summer period. The fact that the castle has been used only on a limited scale and not been heated has helped to preserve the objects and the interior design in good condition. Drawn curtains and window shutters have provided protection against light and heat/cold from outside. Only the ground floor has been partly heated since 1947.

The aim for this paper is to investigate the deterioration of some different objects of art at Skokloster correlated to registered outdoor climate over a time period of 300 years. The paper analyses the strategy chosen to minimize physical and chemical deteoration of objects of art and interior design at Skokloster castle.

Figure 1 The west facade of Skokloster

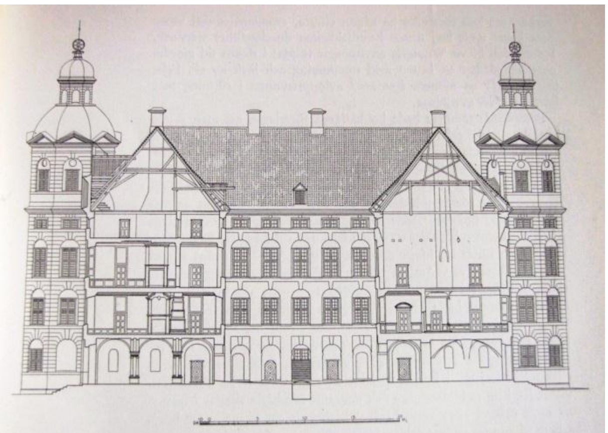


Figure 2 Cross section of Skokloster

2. SIX OBJECTS IN THE SKOKLOSTER COLLECTION

As part of the project Climate for Culture (EC No 226973) we have studied how some objects of art at Skokloster have responded to the climate change impact over the last 300 years. Outdoor climate observations are available since 1722. They were from the beginning carried out by Anders Celsius and his students at Uppsala University. The observations done included even night temperatures. The temperature series used in this study are compiled by Bergström & Moberg (2002).

Since the middle of the 17th century objects have been located in different rooms in the castle.

Six objects out of among 50 000 have been chosen to show their different treatment through the centuries. They have been moved inside and outside the castle, been on international loans, suffered from conservation and documentation (photographing) as well as from cleaning and airing. They were all made in the 17th century of exquisite craftsmanship, in Germany, Holland and Sweden. It is remarkable how all the different materials used have managed to survive. One of the most important reasons is that the castle has not been heated. In 1940s central heating was installed at part of the ground floor. Before that the owners very seldom visited Skokloster in winter time. Window shutters were closed, curtains drawn and many of the furniture were covered up.

Already in the 17th century an armourer (staff sergeant) was employed. The last gentleman with that title left Skokloster in 1980. The armourers were not only working in the armouries, but were also watching the other collections. In 1916 the then armourer wrote to the owner count Brahe in Stockholm: “Sir, will you please ask the butler to collect all the long corks from the white and red wine bottles, it would be preferable to put them in every corner on the back side of the paintings to get air between the cold wall and the painting”.

During the 20th century the care of the collections was taking over by trained conservatories, experts on for instance paintings, weapons, textiles and so on. In 1991 a special exhibition was arranged, called “The secret of preservation”.

To be able to describe where – in which room – in the castle the objects have been located over time, the most important source is the inventory lists from 1672 onwards. In 1930 a special catalogue was made.

When the Swedish state took over Skokloster, it was the first museum in Sweden to use computerization, when making a new catalogue with special inventory numbers for each object. The elder Library with 30 000 books was excluded.

From the 17th century and onwards the rooms are named after their function and on the 2nd and 3rd floor they are named after European cities. In 1942 numbers and letters became a new way to name the rooms, which we still use combined with the city names. 1 = ground floor; 2 = first floor; 3 = second floor; 4 = third floor. There is also a basement and an attic.

3. LAY OUT OF SKOKLOSTER CASTLE

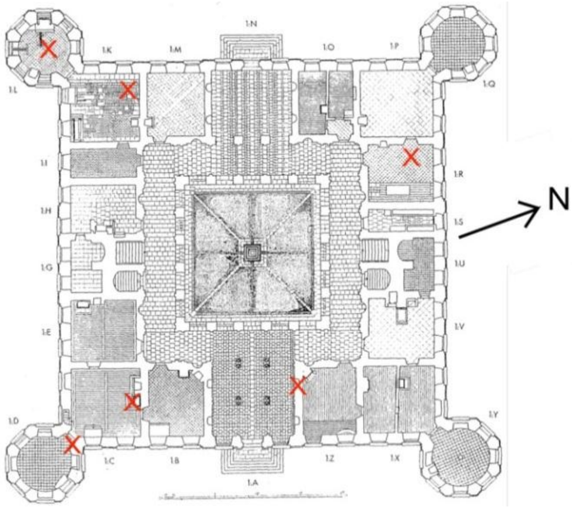


Figure 11 Ground floor

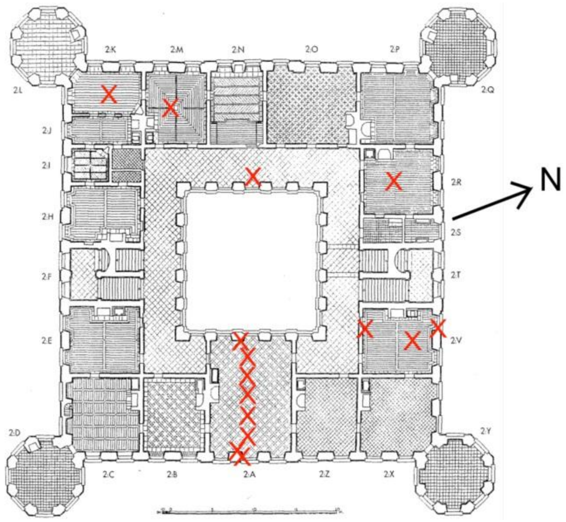


Figure12 First floor

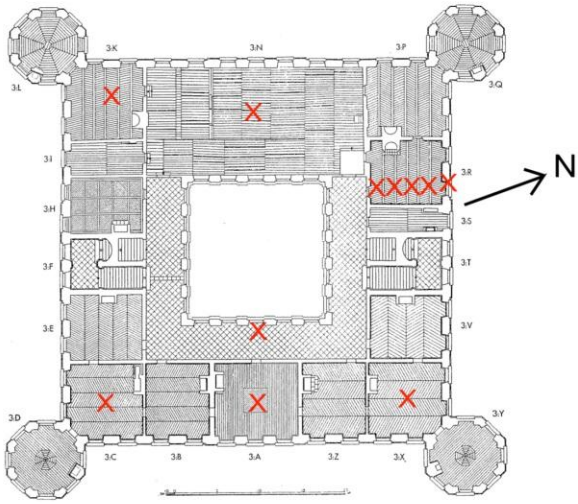


Figure 13 Second floor

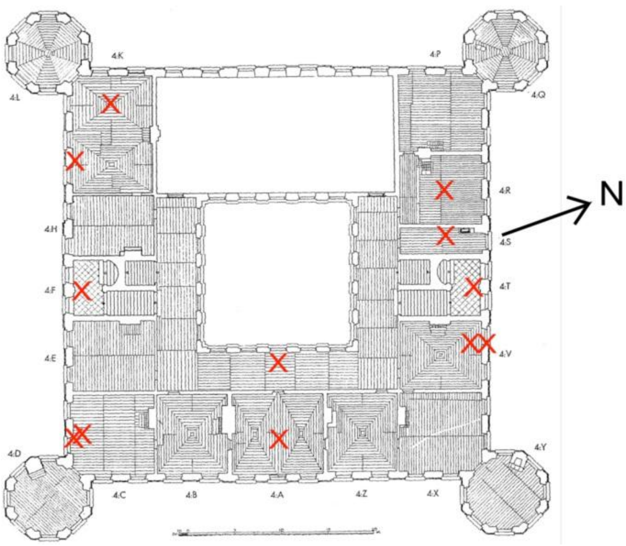


Figure 14 Third floor

(A red cross mark position of measuring point for the project Climate for Culture)

4. CLIMATE MEASUREMENTS 1722-2009

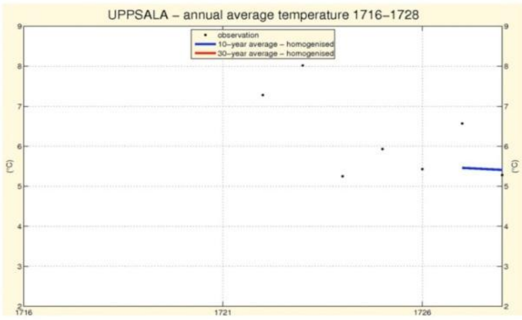
Climate measurement has been carried out at Uppsala University. The temperature series available are here divided according to the periods between inventory reports. Thus we have the following list:

The climate information gives yearly average temperature as well as 10 year average, blue graph, and 30 year average, red graph. The information is valid for Skokloster, situated not far from Uppsala. The yearly average temperatures illustrate the hash climate during the 18th century and even onwards.

The blue graphs are of interest for us and the red graphs give a clear picture of the tendency. The red graph is a god argument in favour of the project Climate for Culture.

Table 1

Invertory period	Years	Climate graph
A	1710 – 1716	–
B	1716 – 1728	Figure 15
C	1728 – 1756	Figure 16
D	1756 – 1793	Figure 17
E	1793 – 1823	Figure 18
F	1823 – 1845	Figure 19
G	1845 – 1910	Figure 20
H	1910 – 1930	Figure 21
I	1930 – 1967	Figure 22
J	1967 – 2009	Figure 23



Figuere 15 Climate graph B

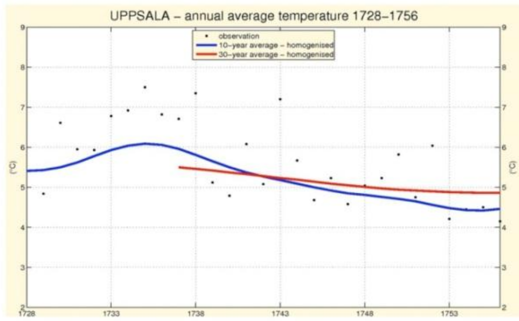


Figure 16 Climate graph C

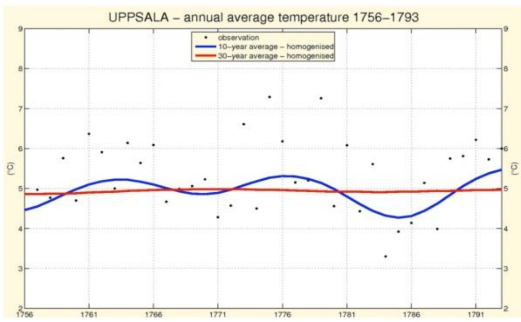


Figure 17 Climate graph D

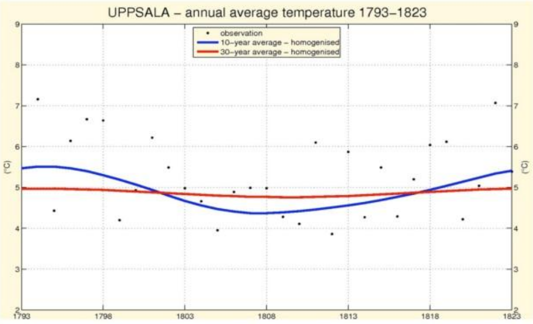


Figure 18 Climate graph E

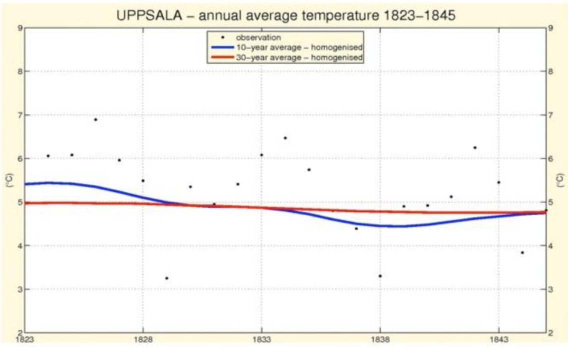


Figure 19 Climate graph F

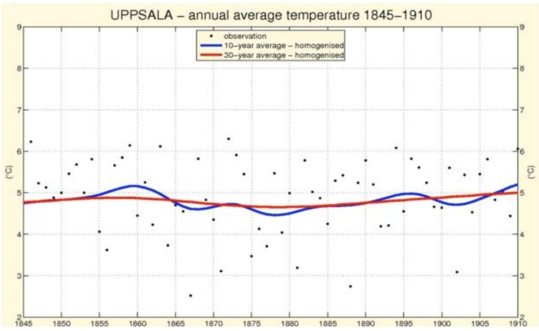


Figure 20 Climate graph G

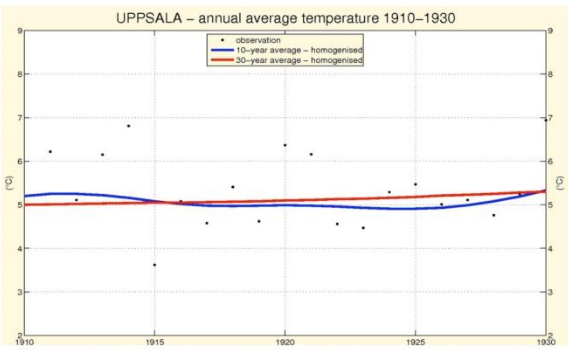


Figure 21 Climate graph H

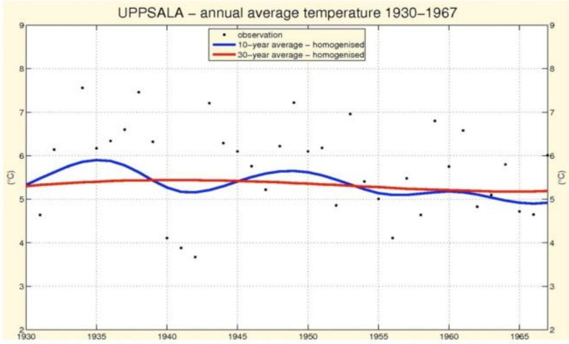


Figure 22 Climate graph I

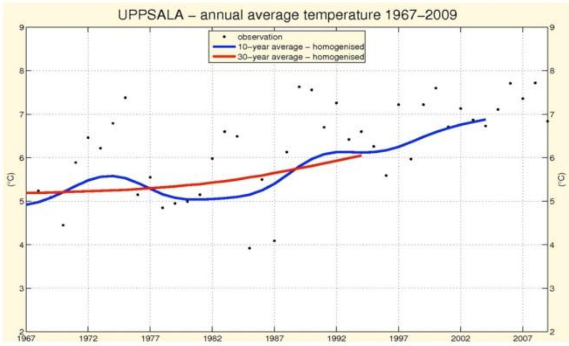


Figure 23 Climate graph J

4.1. Object No 1, LANDSCAPE PAINTING

Inventory number 10032

Winter landscape, painted by the Dutch painter Jan Steen around 1650.

Material: oil on panel. Frame original.

Carl Gustaf Wrangel bought the painting 3rd of July in 1651, via his agent Harald Appelbom in Amsterdam. Before it came to Skokloster it was probably in Wrangels´s residence in Wolgast.

This painting is the object, out of the six, that has been moved most times. Both inside and outside Skokloster. Nine times inside (incl. an exhibition at the ground floor in the castle). Seven times on loan to other countries.

On the inventory occasion in 1728 it was on the ground floor in the room 1C.

In 1756, 1793 and 1823, on all these occasions the painting was in the same room on the 1st floor in room 2J. In 1845, 1910 and 1930 it is still on the same floor, in 1845 in room 2R facing north and in 1910 and 1930 in room 2Z, facing east.

Some time between 1930-1947 the painting was moved to the ground floor, in room 1B, when the last private family owned Skokloster. This room was heated (central heating) in the winter. In 1967, when a new catalogue was made it was on the 2nd floor in room 3C, quite close to a window, facing east. In 1994, when nine rooms were rearranged the painting was moved to another room 3K on the same floor. After having been on loan to USA it was rehanged in a room 2B on the first floor, and it is still there, except for loan to The Hague. Hanging on an inner wall, not far from a window.

Minor conservation work has been made on the painting and the frame in connection with the loans to the USA and Holland, but it is remarkable that its condition is so good having been moved so many times.

Condition of object no 1 today according to the Skokloster staff: acceptable *Figure 3*.

Figure 3

4.2. Object No 2, WOVEN TAPESTRY

Inventory number 389

A series of 8 pieces representing parts of the Biblical history.

This piece is about the creation of Eve. The tapestries were made by Tobias Schaep in Gouda, Holland, 1634-47. They were taken as war booty from Denmark by Carl Gustaf Wrangel, in 1658.

Materials: wool and silk.

The suite was mentioned already 1672 in the inheritance document after Wrangel.

It has been in the same room, 2C on the first floor, except on three occasions.

1716 in room 1X, i.e. ground floor, 1728 in room 2C, 1845 in room 1P, in 1910 back to room 2C, where it still hangs on a wall facing west. Behind the tapestry is a window, which was walled up in the 18^{th} century.

The colours are extremely well preserved. The green colours are very good examples.

The tapestry was on loan to Fredriksborg castle in Denmark, 2006-2007. Before that, in May 2006, it was sent to Mechelen, Belgium, to be washed.

Condition of object No 2 today according to the Skokloster staff: very good staff.

4.3. Object No 3, CABINET

Inventory number 569

Made in Augsburg, Germany, circa 1640-45. It is marked EBEN and a pine cone, the Augsburger town stamp.

Materials: pine, oak, inlay of ebony, ivory and pewter, gilded brass or copper.

The drawers are covered inside with silk and paper. The table underneath is dated circa 1700 and was specially made for the cabinet.

The cabinet has been moved three times inside the castle. From 1728 in room 2N, in 1756 it was in room 2Y, and in 1793 in room 2X. Before 1823 it was moved to the present room 2A.

Condition of object no 3 today according to the Skokloster staff: very good, the cabinet has remarkably few cracks. The drawers are easy to move.

4.4. Object No 4, TWO RIFLES, A PAIR

Inventory numbers 5413, 5874

Made by gun maker Hans Stifter in Prague, circa 1645.

Materials: pear wood, inlay of stag’s horn, brass, steel.

They were mentioned in Carl Gustaf Wrangel´s German inventory list in 1651. He then resided at the castle in Wolgast. It was a gift by colonel Copij.

They were transported to Sweden in 1653. These rifles were kept in the Wrangel armoury at Skokloster on the 3^{rd} floor, which was filled with weapons and other treasures.

The oldest inventory, known today, is from 1710, when both rifles were in room number III, a tower room. In 1793 they were still in the same room. At two inventory occasions, 1930 and 1967, they were in room number II, next to the tower room. Today are the rifles again in the tower room, above the entrance door.

In 1911 the armourer wrote to count Brahe in Stockholm: “Sir, I can not polish the hilts because a number of the weapons we varnished last year are now red as foxes. It was a great mistake and I am happy that I did not varnish them all”. Kylsberg (1988).

The two rifles were taken down to be cleaned and oiled at the Royal Armoury in Stockholm, 1970-73.

Condition of object No 4 today according to the Skokloster staff: mint condition.

Figure 4

Figure 5

4.5. Object No 5, ATLAS MAJOR

"Le grand Atlas" (the books have no inventory numbers)

The publication of Atlas Major started in Amsterdam in 1662, by Willem Bleau. It consists of 11 volumes in folio. Materials: parchment and paper of linen rags.

They were originally owned by count Per Brahe the younger (1602-1680), living on the island of Visingsö, in the castle Wisingsborg.

The noble family Brahe was related to the family Wrangel, as Per Brahe´s nephew Nils married Carl Gustaf Wrangel´s eldest daughter Margareta Juliana, who inherited Skokloster in 1676, after her father's death.

Atlas Major was sent to Skokloster in the 1680´s, and probably kept on the 3rd floor. Count Wrangel´s books were registrated in 1665, and kept on the 3rd floor, facing east, where he had decided to arrange his library. A catalogue on books belonging to the families Brahe and Wrangel was made in 1689.

Between 1830 and 1840 the books, which now had increased to circa 30 000, were taken downstairs, because the rooms were to be repainted, and new bookcases were to be installed.

Figure 6

When Skokloster was bought by the Swedish state in 1967, all the books once again, in 1970, were taken downstairs. A new modern catalogue was to be made.

This time some of them were put in room 2V on the 1st floor, and some to one of the corridors on the 2nd floor, where there were windows facing the court yard, and the walls were facing rooms 3B, 3A, and 3Z. They were taken back a few years later.

Atlas major has been taken down to the ground floor, to be a part of a special exhibition in 2001 when showcases were used.

Condition of object No 5 today according to the librarian at Skokloster : remarkably good, almost mint condition, blue colour intact.

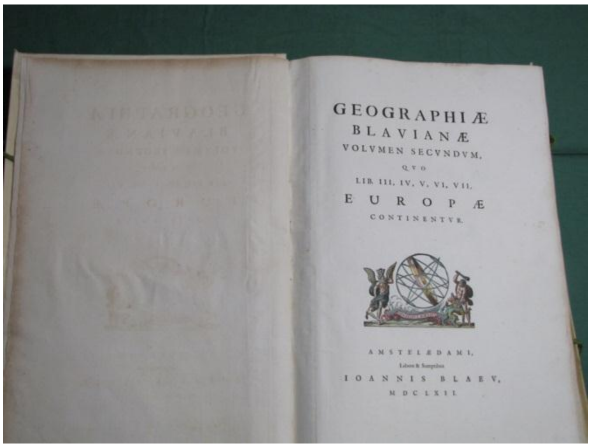


Figure 7

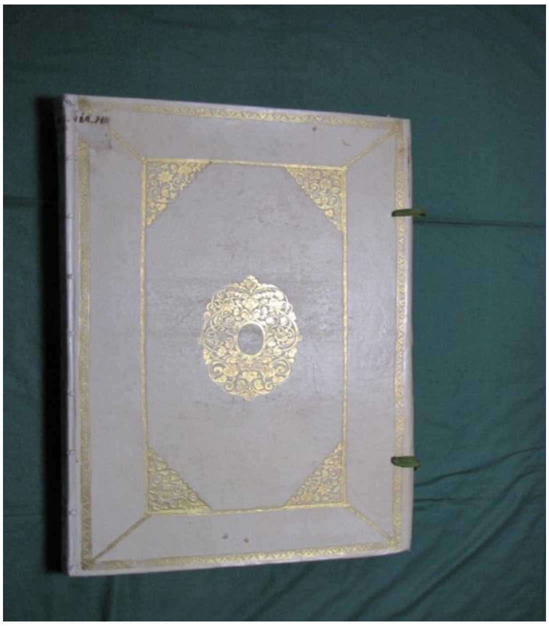


Figure 8

4.6. Object No 6, BED FURNITURE

Inventory number 393

Count Wrangel´s bed furniture, listed for the first time in the year 1676.

Material: oak and pine, not painted. Textiles of linen and silk. The red silk bedhangins are embroided with sequins.

The bed is registered in room 2X in the 1728 inventory, in room 2C year 1756 and 1793, then moved to 2X in inventories years 1823 and 1910, again in room 2C years 1930 and 1967 and today back in its original position in room 2X.

The Wrangel inventory is written in old Swedish with a strong German influence. The bed has a canopy, described as “der Himmel” of “Roten Tafft” and “mit polletten gestickt”. 1716 the inventory talks about a bed “Röd Damasck Säng (bed) med Silf:r flitter”. 1728 the staff sergeant writes about a large French Bed with a canopy of red damask with silver “polletter”, and 1756 the same bed was still in good condition.

But 1823 the staff sergeant writes that the “Silf:r flitter”, the textile with silver sprangle is in a bad condition after 147 years at Skokloster. The 1845 inventory confirms the bad condition of the canopy.

1910 and 1930 catalogues do not mention any deterioration of the canopy. Perhaps some skilled female family members have been active?

From 1968 we have detailed reports of the condition of the bed. The bed furniture was cleaned and hovered according to modern conservation reports. The bed furniture is still, after 334 years, on display at Skokloster.

Condition of object No 6 today according to the Skokloster staff: almost in original condition but the canopy has been repaired and conserved (partly replaced).

Figure 9

5. HOUSEKEEPING STRATEGY

The first proprietor to Skokloster castle, count Gustaf Wrangel (1613-1676), had several other grand houses to stay at. Even if he was born in the minor stone house close to the present castle, it is doubtful if he ever planned to reside at Skokloster. The building of the castle (should better be named palace) was a typical demonstration of power and wealth at the time. The huge collection at Skokloster indicates Wrangel´s manners and refinement. At the same time he was a warlord and took war booty all over Europe.

The building has been uninhabited since it was completed in 1676. It was a museum without visitors for many years. Closed windows, shutters closed, curtains drawn, closed doors, no heating, no light but daylight when needed and foremost no leaks from the roof. The original lead windows with green colour glass were replaced by wooden windows with bars and clear glass around 1750. Not until 1947 was the building used for permanent living and then only in a very small part at ground level.

During all the years until today the building was inspected by armourers or staff sergeants and their wives. Permanent housekeeping has been in force for the last 360 years, but having in mind the very limited workforce employed, the practical work must have been very basic.

The inventories confirm the condition of all objects of art in the building, not only the six objects discussed in this paper. We know for example that a number of the large cut-glass chandeliers were sick already when they were brought to Skokloster in the 17th century.

Oddly enough it looks as doing nothing has been to benefit for the castle and the collection.

The strategy to leave the collection in peace has been successful.

6. DISCUSSION

During the 18th century we had a small ice age in Europe. Relatively accurate temperature records from not only Uppsala University document how cold it was. The Baltic was frozen from time to time, rivers in north Germany were frozen already in November and all navigation on the River Thames ceased between December and the end of February. Fagan, (2000).

Considering only the monthly averages of each January during the years of the 18th century , the today available temperature series for Uppsala give an even more disturbing picture. It was very cold outdoors and consequently even indoors at Skokloster.

Regarding problems with mould we can confirm, that mould on books standing on the lower shelves in room Bremen in the library has been observed and measures have been taken. Holmberg, (2001).

Objects of organic materials have suffered very little from physical stress. The heavy construction of the castle is buffering changes of the outdoor temperature. In summertime the indoor temperature can be more than 25 °C and in wintertime the temperature can be well under 5 °C, but the change rate is low. Holmberg (2001).

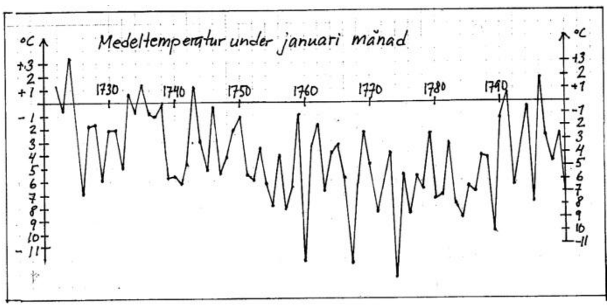


Figure 10

The indoor RH follows of course the indoor temperature, but during strong winds we have an increased air change rate, which causes rapid fluctuations in RH. Pikes of ± 15 % RH have been observed. The change of RH causes change in moisture content (MC) in organic materials and risk for deformation (swelling or shrinking). Change in MC has been observed but the response in MC takes several days, almost weeks at room temperatures below 10 °C (i.e. in a 1 inch thick wood panel). And the over a season change in MC in wood panels gives not elongations over 0.4 % . It is obvious that low indoor air temperature has an influence on the diffusion coefficient and thus the response time for i.e. wood increases. Mecklenburg (1998), Erhardt (1994). Jakiela (2006). Brostrom and Leijonhufvud (2010).

Chemical deterioration is decreasing at lower temperatures, thus Skokloster benefits from the lack of heating.

Daylight has never been a problem at Skokloster because the staff sergeants always have kept the windows closed and covered up by shutters and dark curtains.

Insects and pests have been a problem from time to time. Moths have gone into some saddles in modern time. We can take for granted, that the armourers, the staff sergeants, always kept cats around the castle, why four legs guests have been infrequent visitors. Birds have nested in the chimneys, they were cleaned some years ago and debris was removed. All chimneys are today open and controlled by dampers.

Air infiltration is a problem. Strong winds penetrate the leaky windows. As already mentioned strong winds can change the RH quite fast in rooms exposed to winds. On the other hand strong winds are normally of short duration, less than a day. Holmberg (2001).

Air pollution is not a well investigated problem at Skokloster. The location on the countryside is probably an advantage. Corrosion coupons have been used in modern time to check if the armouries are affected by air pollution. Acetic acid and Formic acid is measured to be less than 40 $\mu g/m^3$ and the ISO 11844 class of the indoor air is between 1 and 2, very close to1. Fjaestad (2010). Kylsberg (2010).

Condensation has been observed on windows but the water evaporates direct to the room air.

7. CONCLUSION

We have studied six out of about 20 000 objects of art. They are selected to represent the different types of objects at Skokloster. In the inventory reports one of the objects is mentioned in special: the bed furniture. As we can see in the inventory the bed was still in good condition in 1756. After 1793 the bed was moved from room 2C to room 2X. Room 2C is facing south and room 2X is facing north. After 1793 we had very cold period but a number of summers were very warm according to climate graph E. That can be the reason for the increased deterioration of the bed´s textiles. And of course that silk is a vulnerable material that will degenerate over time.

For several reasons the described selection of different objects of art at Skokloster castle is representative for the whole collection. That means that the major part of the collection,has survived the last 300 years relatively well under the climate conditions registered.

The strategy of "doing nothing" seems to be a conscious decision rather than one that has slipped in through inaction. Temperature and RH levels are nowadays monitored and the collection has been regularly surveyed. In the Skokloster library there is a handbook about psychrometrics with recommendations. On the titlepage of the book count Abraham Bielke has written "belongs to my writing desk at Skokloster", dated 7th of June 1716. Inventory no 10635 at Skokloster is a hygrometer of wood. Holmberg (2010)

What about the future? Today we can measure that the indoor climate is different in rooms facing south and north. The conservators at Skokloster use the sunshine on windows to air rooms, they open up the curtains halfway to let in the radiation on the floor close to the window to increase the floor temperature. That increase the room air temperature slightly as well as the air movement in the room. The sunshine is important for the preventive conservation at Skokloster.

We do not know to what extent the climate change is natural or has to do with the sun. The sun has always been a dynamic player in local and global climate change, but it still looks as the extent of its influence is a mystery. Fagan (2000). For the collection at Skokloster castle, the sun is important.

8. REFERENCES

[1] Bergström, H., Moberg, A., 2002, Daily air temperature and pressure series for Uppsala. Climate change 53.

[2] Brostrom, T., and Leijonhufvud, G., 2010,The indoor climate in Skokloster castle, Historical buildings as museums, Milan 2010.

[3] Erhardt, D. and Mecklenburg, M., 1994, Relative Humidity Reconsidered, Preventive Conservation: Practice Theory and research, preprints IIC Congress, Ottawa.

[4] Fagan, B., 2000, The little ice age, How climate made history 1300-1850, Basic Books, New York.

[5] Fjaestad, M., et.al. 2010, Bevarande inomhusmiljö? Neutrala material i museimiljö. The Swedeish National Heritage Board.

[6] Holmberg, J., 2001, Environment control in historical buildings, Bulletin no. 53, Royal Institute of Technology, Stockholm.

[7] Holmberg, J., et.al. 2010, Climate for care and conservation of Ottoman artefacts in northern Europe, CLIMA 2010, Antalya.

[8] Jakiela, S., et.al. 2007, Numerical modelling of moisture movement and related stress field in lime wood subjected to changing climate conditions, Wood Sci Technol, Springer-Verlag.

[9] Kylsberg, B., 1988, Skokloster, ett fönster mot stormaktstiden, Byggförlaget, Stockholm.

[10] Kylsberg, B., 2010, Corrosion measurements at Skokloster armoury. Not published yet.

[11] Mecklenburg, M., et.al. 1998, Structural response of wood panel paintings to changes in ambient relative humidity. In painted Wood: History and Conservation, Getty Conservation Institute, Los Angeles.

Ralf Kilian, Tomáš Vyhlídal, Tor Broström (Ed.)

DEVELOPMENTS IN CLIMATE CONTROL OF HISTORIC BUILDINGS

Proceedings from the international conference "CLIMATIZATION OF HISTORIC BUILDINGS, STATE OF THE ART"

Linderhof Palace, December 2nd, 2010

The book summarizes current developments in climate control of historic buildings taking into account the aspects of energy efficiency. Special emphasis is laid on low impact and low tec solutions and their effectiveness in preserving cultural heritage objects and buildings alike. Among the methods discussed are conservation heating, dehumidification, low impact heating in churches and the Temperierung system for wall heating. Hands on practice, innovative concepts, results from European research projects and environmental simulation are combined to show new solutions for preventive conservation and the preservation of collections in historic buildings.

SEVENTH FRAMEWORK PROGRAMME

Climate for Culture

Denkmalpflegezentrum Benediktbeuern

Fraunhofer

Gotland University Passion & Science

Bayerische Verwaltung der staatlichen Schlösser, Gärten und Seen

ISBN 978-3-8167-8637-5

9 783816 786375