# Climate Control in Historic Buildings

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# Preface

The purpose of this handbook is to provide help in choosing the best climate control strategy for historic buildings. We hope that architects and engineers, conservators and curators will benefit from our experience. We also believe that politicians, administrators and building owners will find this handbook useful. The work was financed by the Swedish Agency for Energy as a part of the project *Spara och bevara*. Some of the investigations presented here were part of the project, whilst others were initiated by other public or private institutions. We sincerely acknowledge the effort of all the people and institutions that have contributed to the results we present.

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# 1. Introduction

The indoor climate in historic buildings is a crucial factor in preserving the building and its interiors. Rising energy costs and the threat of global climate change has put more focus on indoor climate issues in recent years. This handbook is a guide to climate control in cultural heritage buildings, where the indoor climate is dictated by preservation requirements as well as by human comfort. It is based on scientific literature and extensive practical experience.

Historic houses such as churches, palaces or public buildings are the main subject, but also more recent buildings used for exhibition and storage are considered. The handbook is mainly concerned with buildings in temperate climate zones but some aspects are also relevant for buildings exposed to more extreme climatic conditions. There are other important environmental parameters for cultural heritage buildings, such as light and air pollutants, but these aspects are not considered here.

Sustainable management of these buildings demands a balance between preserving cultural heritage and energy efficiency. For most buildings there is no contradiction between these aims. Simple energy efficient solutions are often better for preservation of the objects and interiors than more elaborate and energy consuming equipment. Human use of the buildings complicates the issue. It is the need for human comfort that uses the most energy, because we need to heat in winter and cool in summer. Humans also demand ventilation to ensure health and comfort. Historic buildings with permanent human occupation for living or working therefore may need complex air conditioning systems to meet all requirements. These types of buildings have been treated by many other authors and will not be dealt with here.

Most of our historic buildings and their contents have survived for centuries without any special attention to climatic conditions. So why has this suddenly become relevant? One reason is that the ambient climatic conditions may change over time. Whether this is an effect of global warming or not, it will have an influence on the indoor climate in the future. Furthermore, the preservation requirements for the indoor climate have developed over the years. This is partly due to a better understanding of deterioration processes, and partly because natural decay is not accepted as an inevitable part of life. Another concern is that climate change will increase and geographically extend the risk of insect attacks; it may even introduce new species. The use of fungicides and pesticides in previous centuries has helped keep the mould and insects away, but most of these poisons have been abandoned in recent times, so climate control is the only option left for long time preservation of organic materials.

The handbook deals with the two basic questions of indoor climate control:

- What is an appropriate indoor climate?
- How do we achieve it in a sustainable way?

The handbook is divided into 8 chapters.

- Chapter 2 gives an introduction to the physical parameters of temperature and relative humidity, and describes how to measure it and analyse the data.
- Chapter 3 presents the microclimatic conditions and needs for various objects and materials relevant to historic buildings.
- Chapter 4 introduces building physics; heat and moisture in buildings.
- Chapter 5 describes different ways of heating a historic building.
- Chapter 6 describes dehumidification, which is relevant if a lower or more constant RH is required.
- Chapter 7 describes the effect of air exchange on the indoor climate.
- Chapter 8 introduces a procedure for decisions regarding climate control strategy.

In most chapters, examples and suggested literature for further reading are provided.

# 2. Climate measurements

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"To measure is to know"
Lord Kelvin
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## Introduction

Reliable measurements of temperature and relative humidity are essential for energy efficient climate control. The measurements are needed for proper analysis of indoor climate, for control and for documentation. The following is a description with a focus on the practical aspects of indoor climate measurements. More information can be found in the two following European Standards:

*EN 15758 Conservation of Cultural Property — Procedures and instruments for measuring temperatures of the air and the surfaces of objects.* 

*EN 16242 Conservation of Cultural Property — Procedures and instruments for measuring humidity in the air and moisture exchange between air and cultural property* 

#### **Planning your measurements**

Measurements are not an objective in themselves. Before investing time and money in measurements, a plan should be made comprising the following steps:

- Why? Define the objective of the measurements and how the data is to be used.
- What. Specify which climate parameters need to be measured.
- Where: Specify the location(s) for the measurement.
- When: Specify duration and intervals.

#### Temperature

*Traditional thermometers* use the thermal expansion of a liquid to indicate the temperature. The liquid, usually mercury or alcohol, is allowed to expand from a reservoir into a narrow glass tube. The temperature is read from a linear scale. The accuracy is not much better than  $\pm 1$  °C. A dial thermometer uses a bimetallic strip wrapped into a coil. The different thermal expansion of the two metals makes the coil twist. One end of the coil is fixed to the housing of the device and the other drives an indicating needle. A bimetallic strip is also used in a recording thermometer and a mechanical thermostat.

Electronic instruments use a *resistance thermometer* (RTD) to detect the temperature. They work by correlating the resistance of the RTD element with temperature. Most RTD elements consist of a fine coiled wire wrapped around a ceramic or glass core. The element is usually quite fragile, so it is often placed inside a sheathed probe to protect it. The RTD element is made from a metal, such as platinum, nickel or copper. A common type is the Pt100 based on a platinum wire with a resistance of 100 Ohm at 0 °C. RTD sensors can be very accurate, typically  $\pm$  0,01°C.



Fig. 2.1. A traditional thermometer used for outdoor measurement. It is only partly screened for radiation, so the reading is influenced by the direct sun hitting the façade.

A thermocouple consists of two conductors of different materials (usually metal alloys) in contact. The assembly produces a voltage dependent on the difference of temperature of the junction to other parts of those conductors. Thermocouples are inexpensive, respond quickly and can be made very small. This is an advantage for surface temperature measurements. In contrast to most other methods of electronic temperature measurement, thermocouples require no external power. The main limitation with thermocouples is accuracy which is no better than  $\pm 0.5$  °C.

*Infrared sensors* are useful for monitoring surface temperature on objects, where it is not possible to attach thermocouples. An infrared sensor lets the infrared radiation though a filter and a lens on to a temperature sensor. The shape of the lens and the distance to the object defines a circular area, in which an average temperature is measured. The advantage of this technique is that in most cases it is not influenced by radiation from sources other than the actual surface, but the radiation depends on the emissivity of the surface, which must be estimated. Infrared sensors cannot be used for reflective surfaces.

The time response for temperature sensors is typically in the interval of x - y seconds. This should be considered when moving the sensor between zones of different temperatures. Also this means that very quick variations in the indoor climate may not be recorded.



When measuring air temperature in a room where the surface temperatures are different from the air temperatures, the sensor may have to be shielded to eliminate the radiative effect from the surfaces.

*Fig. 2.2. Infrared image show the variation of the surface temperature and the influence of a heating element in the apse. Vä church, Sweden.* 

*Infrared temperature* cameras combine many infrared sensors to produce an image of the surface temperature of a building or an object. They provide a picture where each colour represents a temperature interval, see fig 2.2. It is an effective way to detect cold bridges or air leakages in building structures. Infrared cameras have become less expensive in recent years, but the cheaper ones tend to have low resolution and poor temperature sensitivity.

## **Relative humidity**

Mechanical hygrometers have been used for centuries. A fine example can be seen at the Skokloster castle (fig. 2.3). This simple hygrometer is made of two pieces of wood glued together. The two sticks are made of different species of wood, and have slightly different sensitivity to water vapour. The laminated pointer will therefore bend according to the variations in RH. When fixed at one end, the other end of the stick will give a reading of RH on the backboard. The response time is long and the accuracy is not very good.



Fig. 2.3. Historic hygrometer with a pointer made of laminated wood. Skokloster (S).

The hair hygrometer is based on the linear expansion of a tuft of hair, held in tension by a spring. The hair is connected to a needle that gives the reading. This device can be calibrated by an adjustable screw, and the response time is a few minutes. The hair hygrometer is still in use for household purposes. The accuracy is  $\pm 5$  % RH The hair hygrometer is used for the thermo-hygrograph, a mechanical recorder for temperature and relative humidity. The pointer has a pen to draw a graph on a paper sheet attached to a revolving cylinder. These devices are now museum relicts, replaced by electronic data loggers.



Fig. 2.4. A hair hygrometer is mainly used for household purposes and is not a reliable instrument for climate analysis.

The psychrometer has two thermometers, one to measure the air temperature (dry bulb) and one to measure the temperature of a wet sock (wet bulb). The wet bulb temperature is lower than the dry bulb, because the wet sock is cooled by the evaporation of water. The lower the RH is, the colder the wet bulb temperature gets. The RH is read from the psychrometric diagram (see appendix) or from a table. There should be some air ventilation to ensure free evaporation, and the thermometers should be screened from radiation. The aspiration psychrometer has a fan to supply a constant rate of air flow. The sling psychrometer has a handle to rotate the assembly of the two thermometers at a constant velocity. The accuracy of these devices is  $\pm 1$  -2 % RH. The psychrometer was much used for spot measurements until 10 years ago, but it has been replaced by electronic devices.

The dew point mirror contains a reflective metal plate. An LED light is reflected by the mirror on to a photo cell. The mirror is cooled by a peltier element, until dew forms on the surface. The formation of dew causes scattering of the light beam, and a Pt100 resistor records this event as the dew point temperature. The air temperature is measured by a separate thermometer, and the RH is read at the psychrometric diagram (see appendix). Notice that the dew point temperature and the wet bulb temperature are different. The accuracy of this apparatus is  $\pm 1$  % RH. The dew point mirror is mainly used for calibration.



*Fig. 2.5.* A sling psychrometer with two thermometers for wet and dry temperature measurements. The *RH* is read from the disc.

Electronic humidity sensors are used for the majority of devices for controlling and recording relative humidity. They measure the resistance or impedance of a hygroscopic polymer. They respond relatively fast (within minutes) to variations in relative humidity, if the sensor is exposed to the air. Some devices screen the RH-sensor with a permeable membrane to protect it against contamination. This extends the lifetime of the sensor and improves the accuracy, but the response time increases.

Most sensors also depend on the ambient temperature, so there should be a built-in temperature compensation. The accuracy is between  $\pm 2$  RH and  $\pm 5$  % RH. The sensors can be made very small, which is practical for microclimate investigations. However, the size of most data loggers and handheld instruments is dictated by the size of the battery and the display. In the same way as for temperature, the response time has to be considered when planning measurements.



Fig. 2.6. Electronic relative humidity sensors are quite small. Long term durability is ensured by a membrane in the cap to protect against pollutants and dust.

#### Instruments

There are a variety of electronic hand held devices for measuring temperature and relative humidity on the market. These instruments serve the purpose of local measurements or daily surveillance and recording. They can also be used to establish the interior climate in many different rooms in a large building on the same day, or to determine the climatic variation in many different locations within a large room. Some hand held instruments respond rather slowly to temperature changes, and may need up to half an hour to acclimatise, when moved from a cold to a warm environment.



*Fig. 2.7. Two instruments for measuring temperature and relative humidity. They both have a display and a logger function.* 



*Fig. 2.8. Datalogger for recording temperature and relative humidity. The humidity sensor is only partly protected by the black screen, and it is only suitable for indoor monitoring.* 

Data loggers are used to monitor the climatic variation over time in one location. A logging interval of one hour is suitable for buildings with simple climate control. Logging intervals as low as 5 minutes may be needed to evaluate indoor climate in buildings with more advanced control systems. The storage capacity is usually one year or more with a one hour logging interval. The measurements are downloaded to a computer with a cable or a wireless connection. Some data loggers can be connected to a network with multiple devices where the data is temporarily stored in a common unit. The data is retrieved on regular intervals with an internet or a mobile connection. This is particularly useful for long distance monitoring.

#### Sensors for control

It is essentially the same humidity sensors that are used for monitoring and for controlling purposes. During the last decade the mechanical hygrostatic controls have been replaced by electronic devices. Most dehumidifiers come with adjustable humidistats, that are either built into the device or mounted in a duct or inside the room. Electric heaters can be controlled directly by a plug-in hygrostat, but only to a certain level of output. Hygrostatic control (reference to chapter x) of individual radiator valves in hydronic heating systems is nowadays possible using wireless sensors. This system will allow a much better control of central heating systems for conservation heating.



*Fig. 2.9. Common types of mechanical and electronic hygrostatic controls for heating or dehumidification* 

#### Calibration

Instruments for measuring relative humidity need regular calibration, otherwise the results will not be credible. The calibration interval depends on the type and use of the instrument. An annual procedure is appropriate for most devices.

Calibration is often carried out by a specialist. A calibration procedure for "home" use is described in the following.

There must be at least two different RH set points, but three or more would be better. The temperature for calibration should be the same as for normal operations. If the temperature variation during

operation is more than 10 degrees, the RH calibration should be set at both the high and the low temperature. Not all instruments have the option of adjusting the RH after calibration. In this case the deviation should be noted on a label attached to the device.



Fig. 2.10. Calibration of a data logger with salt solutions in an air tight container.

The most convenient way to calibrate instruments is to use a climate chamber with automatic temperature and humidity control. Some can be programmed to run a sequence of different set points for T and RH. However, the built in RH control can be unreliable. The RH should always be monitored with an independent, precise device or at least checked regularly. Climate chambers are expensive and therefore not very available for most users.

Some companies and scientific laboratories offer calibration service to their clients. This is an easy and affordable solution for a few instruments. Saturated salt solutions are used for keeping the RH at specific set levels. A tray of sodium chloride solution in an air tight container will maintain 75 % RH at all temperatures. Magnesium chloride maintains 33 % RH. Each salt has a specific RH level. The salt must be well separated from the instruments in order to avoid contamination and subsequent corrosion and failure. It is sensible to wrap the instrument in a textile bag before leaving it in the salt solution.

A simpler approach is to compare instruments and loggers with one calibrated instrument. The comparison should be carried out at several values, covering the interval of actual measurements. This procedure is meant to detect major errors, it does not replace calibration.

#### **Data mapping**

Indoor climate mapping is a procedure where the indoor climate is surveyed in a horizontal grid. By walking around with hand held instruments, the variations within the room are recorded under the assumption that changes in time are relatively slow. The response time of the instruments must be considered. Special software can be used to convert the data to indoor climate maps of the building. An example from St. Maria church in Visby is presented in figure 2.11.



Fig. 2.11. Map of temperature based on spot measurements. Maria Church, Visby.

#### Data analysis

When proposing a climate control strategy, it should be mandatory to have at least a one year climate record for the building or room in question. The seasonal variation in temperature and humidity may call for different solutions in summer and winter.

#### Time variation of T and RH

A full year of data is read into a spreadsheet and presented in a chart showing both temperature and relative humidity over time. This will give a good overview of the levels and both the annual and short term fluctuations.

#### Statistical analysis

For further statistical analysis average values, maximum and minimum values as well as the standard deviation are useful. The standard deviation gives an indication of the variability of any parameter. The lower the value, the more stable the indoor climate

#### Short term variations in RH

A European standard, (CEN 2010) proposes a method to determine a target range for variations in RH based on the climate history of a building. Rather than specifying a fixed interval for RH, this method is based on a moving seasonal average around which variations should be limited. The seasonal cycle of RH is calculated as a moving average over a 30 day period, based on measurements for at least one year. The objective is to identify harmful fluctuations in relation to the seasonal cycle. A fluctuation from the seasonal cycle is considered outside the safe range when the magnitude is more than 1.5 standard deviations. Deviations of less than  $\pm 10\%$  RH are considered safe. An example is shown in fig. 2.13.

# Mould risk

By plotting T and RH together with the mould risk curve, one can get an overview of the mould risk during the period of measurement, se fig 2.15.

# Mixing ratio

The mixing ratio (MR) is calculated from the hourly data of temperature and RH. This is used to compare the climate inside and outside, of two separate rooms or between spaces within the same room. The outside MR changes over the day and week, whereas the inside is usually more stable. If the mixing ratios inside and outside are the same from hour to hour, this is evidence of a high air exchange rate. A difference in mixing ratio indicates a source or sink of water in the building. A sudden summer shower will raise the outside MR above that inside. The opposite situation may arise from human activity, for example a Sunday service in the church or a reception in a hall. This is sometimes confused with increased evaporation from the interior surfaces during heating events. If the average inside MR is always above that outside, there is a constant evaporation from the ground or the walls

# Example

An example of such an analysis is presented below with a climate record from a church that suffers from very high relative humidity. The RH at the pulpit 3 m above the floor is on average 75 - 90 % during the year, with frequent drops down to 60 % due to solar heating and heating episodes. These fluctuations are well outside the safe range of 10 % RH. The RH remains very high in winter despite basic heating to 6 - 8 °C. The mixing ratio is always higher inside than outside, indicating a moisture source within the building. The mixing ratio below the wooden floor is always much higher than above, indicating that the ground below the floor is the source of moisture. This is supported by the fact that the mixing ratio in the pews close to the floor is higher than at the pulpit in summer. There is no difference in winter, because the pew heating produces convective air movements. The combined T-RH diagram shows a considerable mould risk for most of the year.



Fig. 2.12. Exterior view of Ørsted church (DK). It has a very damp interior climate.



*Fig. 2.13. One year climate record from a church with intermittent heating for services and basic heating to 8°C in winter. The data logger was located in the pulpit 3 m above the floor.* 



Fig 2.14. Mixing ratio calculated as a moving average over 7 days from climate measurements in four different locations as indicated. The source of humidity is clearly evaporation from the floor.



Fig. 2.15. Diagram indicating the mould risk.

#### References

EN 15757 Conservation of Cultural Property — Specifications for temperature and RH to limit climateinduced mechanical damage in organic hygroscopic materials and table of resolved comments.

EN 15758 Conservation of Cultural Property — Procedures and instruments for measuring temperatures of the air and the surfaces of objects.

EN 16242 Conservation of Cultural Property — Procedures and instruments for measuring humidity in the air and moisture exchange between air and cultural property.

# 3. Microclimate and preservation

# Introduction

The objects and the decorations in a historic building usually have a long history of variable climatic conditions. For centuries the indoor climate was not controlled with respect to conservation. Any object holds a memory of previous climate which may have altered its appearance or reduced its lifetime. No matter how perfectly the future climate is controlled today, it will not heal the damages of failures in the past. It may therefore seem a waste of energy and money to try to change the conditions in a building where the climate has been poor for ages. But even a minor adjustment in climate control will increase the expected lifetime of most objects, or reduce the need for conservation and maintenance. Often, indoor climate control is a very cost-efficient tool for preventive conservation. Furthermore, a better understanding of the climate requirements will allow for an optimal use of energy. This section gives an overview of the different requirements for indoor climate and some guidelines for types of objects specific to historic buildings: Wall paintings, paintings on panels and canvas, furniture, books and church organs. In most buildings, human comfort dictates the indoor climate. Comfort requirements are not dealt with in this handbook as there is plenty of literature on this already.

# Wall paintings

Wall paintings are an integral part of the building structure, and may therefore experience climatic conditions that are quite different from the building or room, which they are facing. The surface temperature of a wall or a ceiling is often not the same as to the air temperature. A wall surface may be colder, if the room is heated in winter, or a ceiling may be warmer, when the attic heats up by solar gain in summer. The surface temperature is also influenced by radiation, which, in the case of direct sunlight, may raise the temperature several degrees above ambient.



Fig. 3.1. Direct sunlight on the wall paintings raises the wall surface several degrees above ambient.

#### Soiling

The combination of a temperature difference across the surface and air movements along the surface is the cause of soiling by air borne particles, also known as thermoforesis. The particles are dispersed by the molecular movements of the warmer air, but they lose buoyancy when the air is cooled, and settle at the colder wall surface. The paintings are discoloured by a veil going from grey to black, whereas cracks and fissures in the surface become more visible. Soiling may not be very harmful in itself, but the removal by different cleaning processes can cause considerable damage to the surface. Some wall paintings are too fragile and need consolidation before cleaning.



Fig. 3.2. Soiling of wall paintings by thermoforesis alters the colours and highlights the cracks.

Surely, the amount of soot is less today than in the time when stoves were installed in rural churches and coal or peat was the fuel. Today, the particles come from burning candles or come from outside traffic or air pollution in general. Regular vacuum cleaning using high quality filters is a way to reduce the concentration of particles in the air. Air cleaners, using different kinds of filters, is a way to reduce soiling.

Soiling is closely related to the heating practice and climate control strategy in general. It is accelerated by convective heating or warm air heating, which unlike radiant heating, causes the air to move. Soiling increases when the airflow becomes turbulent due to a disturbance. Permanent heating causes a long exposure of air movements and temperature differences and therefore much faster soiling than intermittent heating. Thus heating systems should be designed in order to minimise air movements.

#### Salt damage

Wall paintings are particularly sensitive to salt damage. The salts accumulate at or below the surface due to moisture migration inside the wall. The salts originate from the building materials used for construction or repair, or they may have been supplied from the natural environment or by the use of the building. The plaster or paint layers deteriorate due to repeated cycles of precipitation and deliquescence of various salt species. Each salt has a specific RH, at which precipitation will take place (table 2A). For some salts the precipitation also depends on the temperature. If the salt contamination is a mixture of more than two ions, the precipitation happens within an interval of RH. The safe RH-range for salt contaminated objects depends

on the salt species and should be defined in each individual case. The computer program ECOS /Runsalt is a useful tool for calculating the precipitation range for salt mixtures of nitrate, chloride and sulfate salts (Price et. al., 2000).



Fig. 3.3. Wall painting deteriorated by the precipitation of salts. Stroeby Church (DK).

When the surface temperature is different from the air temperature, the relative humidity at the surface is also different. An important aspect of this phenomenon is that wall paintings enjoy climatic stability during short heating events. The influence of intermittent heating is reduced significantly because of the thermal inertia of the solid walls, so the RH at the surface remains almost constant. For a mineral surface with well attached paint layers and stable pigments the surface RH may not matter. But if the wall paintings are contaminated with salt, the RH is very important.

Salt	% RH
NaCl	75
NaNO <sub>3</sub>	74
NaSO <sub>4</sub>	82
KCI	85
KNO <sub>3</sub>	93
KSO <sub>4</sub>	97
KCO <sub>3</sub>	43
$CaCL_2(6H_2O)$	29
Ca(NO <sub>3</sub> ) <sub>2</sub> (4 H <sub>2</sub> O)	50

Table 3.A . The precipitation RH for different salts at 25 °C

#### **Panels and paintings**

Objects attached to the building structure have slightly different climatic conditions compared to the free standing objects. Panels and paintings are usually mounted on the wall or the ceiling with a gap of a few centimetres. In this position they are exposed to the interior climatic conditions on the one side, and to the climate of the air gap between the wall and the object on the other side. One can regard the air gap as an extended boundary layer, where both temperature and relative humidity may differ significantly from the room conditions in general. This may, or may not be an advantage. On the one hand it may improve the thermal stability for the painting or the panel. On the other hand there may be high RH, or even condensation, in the air gap due to the temperature difference, or because of evaporation from the wall. It is usually recommended that the air gap be ventilated in order to overcome such problems. It is a common practice to place wooden blocks or corks between free hanging paintings to ensure sufficient air movement. But it is a delicate matter to decide how much ventilation is needed. Some authors even report that a small gap gives better climatic stability. A further complication arises in the situation where heating elements are located behind a panel or just below a painting. The climatic conditions depend entirely on the geometry of the arrangement, and should be evaluated in each specific case.



*Fig. 3.4. The climatic conditions for the panel painting is influenced both by the electric heating elements and the window.* 

Wooden panels are sensitive to variations in RH, because the moisture content of the porous wooden structure depends upon the RH in the surrounding air. The moisture uptake and release makes the wood expand and contract, which can lead to deformation and eventually failure, either of the wood itself or of the paint layer. The climate induced strain leads to mechanical stress, which may exceed the strength of the wood. Cracks may develope if the wood is not allowed to swell or shrink. Polychrome panel paintings are particularly sensitive to climatic variations, due to the different response of the paint layers and the wood. The expansion or contraction of the wood makes the paint crack, loose adhesion and flake off. The range of +/- 15 % RH is safe for most types of wood, glues, grounds and paints, but this is reduced if the object is kept at a high or low RH.



Fig. 3.5. A crack in a panel painting caused by contraction of the wood due to drying.



Fig. 3.6. Painting on canvas with extensive cracking caused by variations in RH.

The duration of the RH fluctuations is an important parameter, because it takes some time for the wood to reach equilibrium. Slow variations such as annual cycles allow the whole object to acclimatise evenly, which prevents bending and cracking of the wood, but may be harmful to the paint layers. Fast fluctuations (in hours) have little effect on the objects due to thermal inertia, and are not considered dangerous. This is an argument for recommending intermittent heating in churches but many (thousands) repeated cycles of RH variation may cause failure at smaller amplitude. This is known as fatigue. The limit for reversible strain is within the interval quoted above.

The strain caused by temperature variations is small compared to the hygroscopic response. But temperature has an influence on the rate of water vapour diffusion which is reduced at low temperature, so the response to RH changes is slower than at high temperatures.

Some paints become brittle below 8 °C, and therefore are more sensitive to fluctuations in RH. This aspect is relevant for those heritage buildings which are not heated to comfort temperatures in winter.

Canvas paintings are also susceptible to mechanical damage induced by RH variations, but the dynamics are slightly different due the material composition. They respond faster than wooden panels to variations in RH,

but the dimensional change within the range 30-70 % RH is less. This is because most canvas fibres are rather inert to moderate moisture content. If RH reaches 80% or more the hide glue gets soft, and there is a risk of delamination of the paint layer. At low RH, the glue causes problems due to shrinkage and stiffening. A further complication is that the paint has different mechanical properties depending on the type of pigment. Paper, parchment, leather and textiles also respond to RH variations, but they are in general less sensitive to low RH if the object is allowed to move freely. An important exception for historic buildings is guilt leather, which is suspended on wooden frames like a canvas painting.

#### Furniture

The furniture of a historic house or a church is exposed to the climatic conditions of the individual room. The microclimate may vary considerably from one end of the building to the other, and even be different within the same room. It is usually recommended that furniture be moved away from outer walls so the air can circulate freely, and thereby avoid cold and humid areas. This will improve the heat distribution and give a more uniform temperature in a building with large thermal inertia and poor thermal insulation. This is a reasonable practice for houses with conservation heating, where the heating elements are often unevenly distributed. The temperature behind a cabinet against a cold outer wall can be several degrees lower than in the proximity of the radiator. The problem is not the temperature difference itself, but the dampness it will cause. Furniture is at risk of biological degradation, if the climatic conditions are damp. Most chairs, tables and cabinets consist of a combination of organic materials such as wood, textiles and leather. The main agents of degradation for these materials are mould, pests and insects.



Fig. 3.7. Attack by woodworms in a chair.

#### Mould

Mould is very common in historic buildings. The spores originate from nature and enter the houses with natural infiltration of air. Mould grows on the surface of most organic materials in damp environments. There are a large variety of species, each with specific climatic limits for germination and growth. The growth condition for mould is outlined in the so called isopleth system (Sedlbauer, 2001). The lower limit for mould growth is 80 % RH at 20 °C for most species, rising up to 90% RH at 5 °C and 100 % RH at 0 °C. The RH limit at 20 °C is lowered to 70 % RH if the surface is treated with oil, wax or other nutrients favourable to mould infestation. The germination of the mould spores depend on the duration of appropriate

climatic conditions. A minor violation of the risk threshold value leads to infestation after only a week or more, whereas a sudden warm and humid environment can cause mould growth in a day. It is a common belief that stagnant air is favourable for mould growth, but there is no scientific evidence for this assertion. The reason is more likely that stagnant air will maintain temperature differences, and therefore higher RH in cold areas.



Fig. 3.8. Climatic limits for mould growth and insects. The solid line indicate the limit for mould growth on a typical surface and the dashed line indicate the limit for mould growth on a nutrient substrate.

#### Pests and insects

The climatic conditions for pests and insects to breed and thrive differ from species to species. All insects need water to survive. Some get it from the water absorbed by the host material and others produce water by the metabolism of dry food. A few species can absorb water directly from the water vapour in the ambient air. The general recommendation is that 60% RH is safe for all materials and types of biological degradation, but 70% seems to be acceptable in some situations. Temperature is an important parameter for the insects to move around and to breed. Many insects can survive down below 0 °C but they hibernate at temperatures below 10 °C. Most insects need 20 °C or more to reproduce. A low temperature is always a good precaution against insects.

#### **Books and documents**

A collection of historic books and documents is an important part of the original interior of many heritage buildings. In some cases the collection is kept in a few cabinets, whereas others fill up an entire room to form a library or archive. If the books are tightly stacked, each individual page is protected against the ambient climate by its neighbors. It takes time for a temperature change to penetrate into the centre of a 1000 page volume. The RH inside a book is even more stable. This is because paper is a very good humidity buffer, . Many book cabinets have glass doors to protect the books against dust. A closed cabinet filled with books or documents has a more stable RH, because the air exchange is low. But a closed book cabinet tends to smell

due to the release of acetic acid and other VOC's from the paper. This may be harmful to any corrosive metal objects stored with the book. Another worry is mould growth due to the stagnant air, but this unjustified myth is not an argument for keeping the door open or to remove the glass.

#### Chemical degradation

The main cause of degradation for paper, parchment and other organic materials is chemical reactions such as oxidation and hydrolysis. The speed of chemical degradation rises exponentially with temperature. For chemical processes involving water (hydrolysis), the reaction rate also depends on the relative humidity. The combined effect of relative humidity and temperature is used to predict a relative lifetime of paper. The isoperm was defined as a curve joining points of equal permanence for different combinations of temperature and relative humidity (fig. 3.10).



Fig. 3.9. Diagram with isoperms indicating the relative lifetime of materials exposed to hydrolysis.

The isoperm was set to 1 for the combination of 20 °C and 50 % RH. Any combination of T and RH on the same isoperm will give the same lifetime of the material. If the temperature is raised to 25 °C, the isoperm will be 0.5, indicating only half the lifetime. A temperature at 15 °C gives an isoperm of 2, which doubles the lifetime. A change of permanence is also achieved by raising or lowering the relative humidity, but this parameter has less influence than temperature. Low temperature and low RH will slow down the chemical decay by hydrolysis and increase the lifetime. This is valid for any organic material such as paper, leather and textile.

#### **Church organs**

A church organ is a complicated instrument made of many different materials and therefore exposed to most of the climate induced decay agents mentioned above. But the climate does not only influence the preservation of this instrument, it also has a major influence of its function. The sound of an organ comes from the vibrations when air is blown through the pipes. The frequency of this vibration relies on the density of the air, which in turn depends on the temperature and the relative humidity. An organ will therefore only play in tune, if the temperature and relative humidity is equal to the conditions at the time it was tuned. If the temperature is only a few degrees different it will play false. This physical fact is sometimes used as an argument for keeping a church heated to constant comfort temperature. But a constant temperature will give a low RH in winter, which is not a benefit for the organ, because all the wooden elements respond to the dryness. In extreme situations the wind chest may suffer irreversible damage by bending or cracking. The situation is sometimes aggravated if the organ is raised above floor level on a pulpit, where the temperature is higher and the RH therefore lower.

The metal pipes of a historic organ are sometimes made of lead or a tin alloy. Lead is exposed to corrosion which is enforced by high RH and a high concentration of acetic acid released by the wood. This problem is inherited by the manufacture of the instrument and is difficult to prevent. Pure tin may suffer from tin pest, which is a transformation of the element tin at temperatures below 13 °C. The silvery, ductile metal changes to a grey, brittle substance and eventually to powder. The process looks like metal corrosion but is not dependent on moisture or any other external component. The transformation is inhibited by impurities and is slow to initiate due to high activation energy. It is therefore a quite rare phenomenon, and the risk of tin pest should not be an argument for heating a church if it is not otherwise needed.



Fig. 3.10. A church organ on a pulpit is often exposed to higher temperatures and lower RH.

#### **General recommendations**

The appropriate ranges for temperature and relative humidity depend on the composition and the condition of the collection. Many collections have a variety of objects made of different materials, and even a single object may consist of two or more components. Each group of materials has specific safe intervals for temperature and humidity. It is sometimes difficult to find a compromise that meets all demands. One should also take into account the history of the objects. If a wooden object has acclimatised to a humid environment it may not be safe to lower the average RH to museum standards. Contaminants or conservation treatments may have altered the sensibility of an object and thereby introduced other limits for acceptable climate. An overview of safe ranges of relative humidity and temperature for a selection of materials is given in figure 3.11.

The main objective for controlling the relative humidity in historic buildings is to prevent biological degradation caused by high relative humidity and mechanical damage due to low RH. The lower limit for

mould growth is around 70% RH, but some insects can survive at lower RH. An appropriate set point for historic buildings is about 60% RH, which will be acceptable for most items.

The risk of mechanical damage due to low RH depends on the amplitude and frequency of the fluctuations. The general agreement is that small and rapid fluctuations are less harmful than large and slow variations, but this also depends on the type and quality of the objects. Variations of +/-10% RH is on the safe side for most materials.

Degradation caused by metal corrosion or salt contamination has other limits to RH. A few materials demand a permanently lower RH, for example historic glass with alkaline salt content.

Preservation conditions are affected also by the temperature, which governs the speed of many chemical processes. Generally, a cold environment is better than warm conditions. An important example is modern materials such as photographs and plastics that require lower temperature for the long term preservation. However, some paints and polymers become brittle at low temperatures.

RH%	10	20	30	40	50	60	70	80
Paper in sheets, textiles								
Books								
Leather and parchment								
Paintings on canvas								
Paintings on wood								
Art matured in a damp environment, church art								
Wall paintings and stone with salt contamination								
Metal with active corrosion or salt contamination								
Weeping or crizzled glass								
Photographic film, magnetic and optical media								
Temperature °C	-20	-10	0	10	20	30		
Paper in sheets, textiles								
Books								
Leather and parchment								
Paintings on canvas								
Paintings on wood								
Art matured in a damp environment, church art								
Wall paintings and stone with salt contamination								
Metal with active corrosion or salt contamination								
Weeping or crizzled glass								
Photographic film magnetic and optical media								

Fig. 3.11. Safe ranges for temperature and relative humidity for a selection of materials and objects.

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# 4. The building envelope

# Introduction

The building envelope is continuously exposed to the climatic conditions produced by the natural environment. It is the outside temperature and humidity that governs the loss and gain of heat and moisture in buildings. The ability of the building to shield the interior climate against the exterior influence depends on the location, the architectural design and the materials and thickness of the structure. Of particular importance is the size and orientation of the windows, because they are important sources of heat gain and loss by radiation. The air tightness of the building also has a significant influence on the climatic stability, because heat and humidity is exchanged by infiltration of air.



*Fig. 4.1.* The glass porch only screens against wind and rain. The natural stability of temperature and humidity is small compared to the solid masonry tower behind.

Many historic houses and their interiors have survived for centuries without any active climate control. One such building from the 17th Century is the Skokloster Castle near Stockholm that holds a large mixed collection of furniture and artifacts (Brostrøm 2010). Another example is the Linderhof Palace near Munich, a 19th Century royal summer residence with generous interior decorations (Bichlmaier & Kilian, 2011). These buildings have relied entirely on the natural stability provided by the structure and the contents. This is known as passive climate control as opposed to active climate control that requires machinery and energy. Any active solution for climate control in historic buildings should be based on an understanding and utilisation of the passive function of the building. A thorough analysis and understanding of the hygrothermal performance of the building envelope is always required to select the right measures and to understand their consequences.

This chapter gives a brief introduction the building physics that explains how the building envelope influences the indoor climate through heat and moisture transport as well as ventilation.



Fig. 4.2. Exterior view of Skokloster Palace located in Sweden.



Fig. 4.3. Exterior view of Linderhof Palace located in the Bavarian Alps.

# Heat transfer in buildings

Heat is energy transferred from one location to another due to a temperature difference. Heat flows in and out of a building by radiation, conduction and convection. The building envelope will reduce or enhance the heat flow and thereby influence the inside temperature. The heat transmission is either imposed by the outside climate or by the supply of heat from a heating device.

# Radiation

Heat radiation or infrared heat is a fraction of the electromagnetic spectrum between visible light and microwaves. Heat radiation passes through vacuum or atmospheric air without loss of energy. This is the reason that the Sun can heat up the Earth at long distance. Another reason for the Suns ability to keep us warm is its very high surface temperature. The radiation intensity increases rapidly with temperature, and the heat transfer is proportional to the temperature difference in the fourth power.

The heat transfer also depends on the emissivity of the surfaces. A dark and rough surface will emit and absorb much more thermal radiation than a reflective surface. The surface properties are particularly important for the roof of a building, which will heat up through radiation from the sun during daytime. The hot roof radiates heat further down into the attic, which then becomes warm. At night the roof emits some heat to the open sky, but at a lower temperature, so the total heat gain keeps the building above the daily average. This may increase the need for ventilation or even cooling during daytime.

The windows of a building are also highly exposed to the solar radiation. South facing windows or skylights, in particular, let in solar heat to the building and play an important role for the thermal equilibrium of any house. The solar heating is a benefit in cold climates but inconvenient in warmer locations. Some types of modern glass have a coating that will reflect part of the radiation. This can be used either to reduce heat losses or reduce incoming solar radiation. Curtains or shutters can be used in the same way. To reduce incoming solar radiation, shutters are most efficient when placed on the outside.



*Fig. 4.4.* The heat gain and heat loss by radiation, conduction and convection affects the thermal equilibrium of the building.

#### Conduction

Conduction is heat that moves through a medium by molecular vibration. Dense materials such as metals and minerals have a high conductivity, whereas porous materials such as wood have low conductivity. When standing with bare feet on a stone floor, it appears to be colder than a wooden floor even if the temperature is the same. This is because the heat conduction in stone is faster, so the temperature of the foot sole is quickly reduced. The heat loss through a wood wall of a house is less than through a solid stone wall of the same thickness. A stone house is therefore less comfortable and more energy consuming than a wooden house in a cold climate.

Materials intended for thermal insulation have very low heat conductivity. Thermal insulation is a way to reduce heat losses through the building envelope given that that is permissible from a conservation point of view. In most historic buildings, insulation of the walls is not an option. If there is an open attic or space under the roof, this allows the installation from above without supplementary construction work. Thermal insulation may be considered for buildings with permanent heating. In buildings with intermittent heating there is not much energy saved, but insulation may reduce cold

drafts from the ceiling and thereby improve thermal comfort. There is no advantage to having thermal insulation in unheated buildings.



Fig. 4.5. The walls of a stone house has high heat conductivity.



Fig. 4.6. The walls of a wooden house has low heat conductivity.

Apart from saving energy insulation will also change the climatic conditions at the interior surface. In winter the surface temperature will be higher, which in turn will reduce the risk of soiling through thermoforesis. In summer the temperature will be lower, because the influence of solar heating of the attic is reduced. This may be a benefit if the building suffers from high temperature in summer. On the other hand many houses need this free supply of summer heating to keep the RH moderate.



*Fig. 4.7. Thermal insulation in the ceiling reduces heat loss in winter and heat gain from the attic in summer.* 

#### Convection

Convection is heat that moves with a stream of gas (often air) or a liquid (often water). The driving force is a pressure gradient, which is either externally enforced by wind, or internally by a pump or a fan. The pressure gradient can also be imposed by a temperature difference. Warm air or water is lighter than cold air or water, and it will rise by its own force when heated. This effect is used for heat distribution in convective heating systems.

Heat convection in a building is mainly related to air movements. Heat is distributed horizontally within a building by air flow through open doors and vertically through staircases. Convective air movement in a room or between rooms is often generated by heating in winter. When warm air rises from a heating element in one part of a room, it will be cooled down by the walls and ceiling and may generate a colder air stream in another part of the room. It is perceived by the users as cold draughts and can be misinterpreted for air leakage through windows or doors. Convective air circulation caused by heating is mainly associated with tall rooms or buildings with large windows.

#### Thermal inertia

Thermal inertia is a combination of the thermal conductance and the heat capacity of a material. Heat capacity is the amount of heat required to change the temperature of a material by a given amount. Heat capacity is almost proportional to the density of the material, whereas heat conductivity is inversely proportional to the density. A stone wall has a large thermal capacity and thermal conductance, whereas a wooden wall has small heat capacity and thermal conductance. Because the two thermal properties combine, a stone wall has the same thermal inertia as a solid wooden wall of the same thickness.

The thermal inertia of a house depends mainly on the thickness of the building components and their composition. Ordinary buildings have enough thermal inertia to even out daily variations in temperature. A stone house is often more inert to short term temperature variations, because the walls

are thicker than a wooden house. But only very heavy structures like underground spaces can even out the annual variation. They maintain a stable temperature which is close to the annual average of the ambient temperature above ground. Likewise the floor of a building can act as a heat sink, which will moderate the temperature. To have any benefit of the thermal inertia of the ground, the floor should not have a crawl space or be insulated.



*Fig. 4.8. The daily variation in temperature is large in the attic due to solar heating and heat loss by radiation at night. Heavy walls reduce the variation.* 



*Fig. 4.9. The annual variation in temperature inside an unheated building is equal to that outside. Only underground spaces have almost constant temperature.* 

#### Moisture transport in buildings

The building envelope is exposed to moisture from external sources like rain and humid air. Humans are the main internal source of humidity by breathing and transpiration or by cooking and cleaning. Water vapour moves by diffusion through porous walls or ceilings, or by infiltration of outside air. Liquid water moves by capillary flow due to driving rain or rising damp from the ground. The building envelope exchange water with the interior climate by evaporation, absorption or condensation.



Fig. 4.10. The gain and loss of humidity through the building envelope.

#### Humidity

Humidity is the amount of water vapour in the air. The water vapour is invisible and without any smell. Unlike with temperature, the human body is rather insensitive to humidity. It is therefore difficult for humans to determine humidity, unless the air is very dry or very humid. We need instruments to decide for us. There are four main expressions of humidity: vapour pressure, relative humidity, absolute humidity, specific humidity.

Vapour pressure is the partial pressure exerted by the water molecules. The unit for vapour pressure is pascal (Pa). The pressure depends on the amount of molecules and the temperature. More molecules and higher temperature will give a higher pressure at a fixed volume. The vapour pressure is not influenced by other ideal gases, such as atmospheric air. The vapour pressure is the same whether there is air pressure or not. There is a limit to the amount of water vapour in a fixed volume at any temperature, called the saturation vapour pressure. The relative humidity is defined as the ratio of the partial pressure of water vapour to the saturated vapour pressure at the same temperature. The unit is percent RH ranging between 0 and 100. The relation between vapour pressure, temperature and RH is given by the vapour pressure diagram.

Absolute humidity is the mass of water vapour per unit volume. The absolute humidity at saturation is shown in the second axis in the vapour diagram. Absolute humidity ranges from zero to roughly 30 grams per cubic metre when the air is saturated at 30 °C. At ordinary room temperature there is not much more than a teaspoon of water in a cubic metre of air. Absolute humidity is a useful unit when calculating the loss or gain of moisture by condensation or evaporation, and through air infiltration at the same temperature. But if the air is heated or cooled, one needs to use the specific humidity.

Specific humidity is the ratio of grams of water vapour to kilos of dry air. It is also called humidity ratio or mixing ratio with the unit g/kg. This definition takes into account the effect of temperature on the air density. Air expands when it is heated, whereby the density is reduced. This is included in the psychrometric diagram, similar to the vapour pressure diagram, (see appendix).



Fig. 4.11. Water vapour pressure diagram.

#### Diffusion

Water vapour moves through a porous material by diffusion. The driving potential for water vapour diffusion is a difference in vapour pressure within the pore system. The rate of diffusion through a dry building component is proportional to the vapour pressure difference between inside and outside.

An example is diffusion thorugh a ceiling with gypsum plaster on a wooden support. In winter the diffusion is mainly from the inside into the attic, but in summer it is mainly in the opposite direction. The amount of water vapour lost or gained by diffusion is in general small compared to the water vapour transported by air infiltration (see next section).

#### Condensation

If the absolute humidity reaches saturation, the vapour condenses and there will be fog or mist, which is small water drops (aerosols) held up by air movements. Sometimes condensation takes place on a cold surface, which has reached the dew point. Single glazed windows are highly exposed to condensation on the inside if the building is heated in winter. For buildings with large thermal capacity, there is a risk of condensation in spring and early summer. At this time of year the ambient absolute humidity is rising with the rising outside average temperature. But the rise in floor or wall
temperature inside the building is delayed due to the thermal inertia. Outside air entering the building is cooled and water droplets form on the surface, if it is impermeable to water. This also happens on a permeable surface, but the water is absorbed by the porous structure and may not be visible.



*Fig. 4.12. Condensation at the tiled floor occurs in spring when warm, humid air enters the courtyard, while the solar gain is still too little to raise the ground temperature.* 

## **Evaporation**

Evaporation, the phase transition from liquid water to water vapour takes place inside a building at all times of year. There is no need for a pool of water for this to happen. A damp floor or wall releases moisture to the inside by evaporation. The water is held by capillary force in the pores of the materials, and the water molecules need energy to escape. The surface temperature will therefore drop due to evaporation, and rise in the case of condensation. The temperature effect is usually small and has little effect on the total heat balance of a building. But evaporative cooling can be used to chill a room in very dry and warm climates. The evaporation from a solid brick masonry wall can be significant. An investigation in Kippinge Church indicated an addition of 1500 litres in a year, or one litre per cubic metre space. (Larsen 2011). This passive humidification can be a benefit in heated buildings, because it maintains a moderate relative humidity in winter. But uncontrolled passive humidification may give much too high relative humidity in buildings with little ventilation or heating.



*Fig. 4.13. Condensation below the glass cover in the floor occurs at all times of the year due to evaporation from the ground through the old tiled floor below.* 

## Humidity buffering

Some building materials have the ability to moderate or buffer the relative humidity in a room or a building. Porous materials such as brick or wood absorb water vapour inside their structure. Wood can absorb much more water than brick, and it is therefore potentially a better humidity buffer. The actual buffer capacity also depends on the rate at which the water vapour diffuses in and out of the material which in turn depends on the pore structure of the material and on the surface properties. The diffusion coefficient for brick is much higher than for wood, so brick and wood are equally good (or bad) humidity buffers. A thick layer of oil paint will prevent exchange of moisture though the surface, but even a thin coat of wax or oil retards vapour diffusion. Only few materials will be able to release enough water vapour to have any significant influence on a long term stability. In general the humidity buffer effect can only ameliorate diurnal fluctuations in RH caused by intermittent heating, or human generated humidity peaks during social events.

#### Driving rain

Rain is a major source of moisture in any building. Controlling the rain water is an important part of interior climate control. Gutters and drains must be inspected and cleaned regularly. Mortar joints in stone walls must be well maintained in order to reject driving rain. Lime washed walls need frequent maintenance to be water repellant. Outside water proofing by hydrophobic chemicals is proposed by many suppliers, but such intervention is not recommended. Inside water proofing with a tar layer used to be very common practice, but is now considered to be wrong. Old plaster with tar is often removed during restoration, letting moisture evaporate into the building.



*Fig. 4.14. Gutters and drains must be well maintained. Fail safe details that need little attention are preferred.* 

If driving rain is absorbed by the facade it migrates by capillary suction though the wall to the inside. The suction pressure is generated inside the material due to the formation of water menisci in the small pores (< 100 nm). The transport can be horizontal across a wall or vertical inside the wall when the capillary force is larger than the gravitational force. The maximum height of capillary rise depends on the pore size of the material. The rate of transport is restricted by the permeability of the pores and the rate of evaporation. The evaporation can contribute significantly to the moisture content of the inside air. It has the potential to increase the absolute humidity by 1-3 g/m<sup>3</sup> above ambient and thereby maintain a moderate relative humidity in heated buildings.

## **Rising damp**

The ground is an important source of moisture, particularly in buildings with a tiled floor laid directly on the soil. Such constructions allow a constant evaporation of moisture into the building, and a vapour barrier may be needed. A concrete slab or impermeable sandstone tiles will reduce the evaporation significantly. If there is a wooden floor with a crawl space to the ground, the situation is more complex. The cavity is usually more or less ventilated to allow water vapour escape. But natural ventilation is often not enough to remove the moisture, so the space may reach high levels of RH. In summer the warm and humid air may condense in the cooler space below the floor, and mould may develop in a few days. If the floor has a crawl space with openings to the outside, natural ventilation driven by wind is stronger. But this construction has the same risk of mould infestation in summer. Crawl spaces should be monitored, and active climate control such as dehumidification may be needed to keep RH below risk levels for mould and insects.



*Fig. 4.15. A moisture membrane is installed below the floor tiles to prevent evaporation of ground moisture into the church.* 

## Air movement in buildings

Air exchange through infiltration or natural ventilation has an important affect on the indoor climate in general and relative humidity in particular. Infiltration is the random air leakage through cracks and openings in the building envelope. Natural ventilation is the intentional intake of outside air through open windows and doors or through vents or ducts. The infiltration of outside air into a building is governed by the climatic variations. The wind creates a pressure difference around the building, which generates air movements through the building envelope. With strong winds and a leaky building, the inside climate will be almost similar to the outside. An air pressure gradient also develops due to different temperatures. Warm air has less density than cold air and will therefore be lighter and move upwards. In tall rooms this 'stack effect' will enhance the infiltration in winter.



*Fig. 4.16. Gain and loss of air through the building envelope is driven by pressure gradient caused by wind or temperature differences.* 

For any building with a controlled indoor climate, it is important to keep the building envelope as air tight as possible. Historic buildings are usually rather leaky, but the infiltration can be reduced by keeping the chimneys closed and installing double glazing in the windows. Some houses have built in shutters, which excludes most of the daylight, but give little improvement of air tightness. Modern buildings can be made very air tight thanks to elastic sealants and plastic foils. The air tightness is expressed by the air exchange rate (AER) and quoted in air changes per hour ( $h^{-1}$ ). This is the volume of inside air that leaves the volume of the building (or room) in one hour. The natural infiltration is usually somewhere between 0.1  $h^{-1}$  and 1.0  $h^{-1}$ 



Fig. 4.17. Duct for natural ventilation installed in a church wall.

Wooden ceilings or floors can be very leaky, because the joints between the boards tend to open. It is quite invasive, and not always practical, to tighten the individual joints. An air membrane can be installed instead to prevent air infiltration. This is usually a layer of tar paper, which is water repellant,

but open to vapour transport. Gypsum board is a good alternative, which also provides some fire resistance. It is generally not recommended to use a vapour barrier, i.e. plastic foil. The argument is that the moisture load due to human activity in a cultural heritage building is often small compared to the natural ventilation rate and that the moisture diffusion may be reversed during the year.

## Windows

The windows are often the main source of air leakage, so better sealing or adding an extra pane will reduce the leakage rate. This intervention will also reduce the intrusion of outside pollutants, dust and particles. The heat loss is reduced by double glazing, depending on how much the building is heated. The main benefit for thermal comfort is that cold draught below the windows is limited. Double glazing is usually installed on the inside of the original windows. The new frames must be well sealed, whereas the original frames must allow for some ventilation of the space in between. The new frames must be designed with respect to the original window. Tailor made frames can be made in wood as well as metal.



Fig. 4.18. Double glazing reduces air leakage, heat loss and cold draft.

## Climatic separation

In some situations it may be difficult to comply with specifications for comfort (temperature) on one hand and for conservation (RH) on the other hand. Another problem is conflicting conservation requirements. In a medieval church with salt contaminated wall paintings, it is required to keep the RH as high as possible, usually above 70% RH. Such a high level of RH may encourage woodworms to attack the wooden furniture. These paradoxes can be solved by a climatic separation, which enables two levels of RH within the same building. The partition must be as air tight as possible and impermeable to water vapour, whereas thermal insulation is less important. Transparent or translucent partition walls are suitable for this purpose, because they have little visual impact to the room. There are a few examples of a glass wall or glass door mounted in an arch to act as climatic protection for wall paintings in Danish churches.



Fig. 4.19. A glass partition wall mounted in the arch in a church.

# Climatic enclosure

Climatic enclosure, for example showcases, is a useful way to protect sensitive objects or materials with special needs. This is particularly relevant in museums, where most objects on display are kept in showcases anyway. It is only a minor effort to make the sealing so airtight that a constant level of RH can be maintained inside the showcase. A humidity absorbent material is able to control the RH at the specified set point, regardless of the RH in the room. This kind of humidity control will ameliorate the daily variations in RH and keep a steady RH over weeks or even months. From time to time, depending on the leakage rate of the showcase, the absorbent must be conditioned to the specified threshold value. Sometimes the object on display is able to buffer itself. If the showcase is well sealed, and there is sufficient quantity of material, the humidity buffered showcase may be able to even out the annual variation in RH. The disadvantage of airtight showcases is that internally generated pollutants may accumulate to such high concentrations that metal objects will suffer from corrosion.



Fig. 4.20. The display of fragile objects made of textile, wood, bone and lead in a showcase. The objects were excavated from archbishop Absalons grave in Sorø klosterkirke (DK).

# Examples

# Museum of Rudolf Tegner (Zeeland, DK)

The collection of the works of the Danish sculptor Rudolf Tegner is housed in a solid concrete building from 1935. It is located in a nature reserve without any external energy supply. The museum is only open to the public in summer, so there is no need for comfort heating. The building has one level and concrete walls and floor without thermal insulation. The concrete structure reduces the daily fluctuation in temperature, but not the annual variation, which is -5 - 30 °C. There is no artificial light, only daylight through the glass roof. The solar gain in summer raises the inside temperature above ambient, reaching a maximum of 30 °C in midsummer. The spaces have a high ceiling to provide a reservoir of air required for human health. Natural ventilation is sufficient to assure good air quality. The annual variation in relative humidity is from 40 % RH in summer to 90 % RH in winter. The daily fluctuation is small, possibly due to a low infiltration rate. The painted concrete walls have no humidity buffer capacity. In this case the objects on display are robust, but not all museums can be run safely without any climate control.



Fig. 4.21. Rudolf Tegners Museum is a solid concrete building located in a nature reserve.



Fig. 4.22. The solar gain through the glass roof has a large impact on the interior climate in summer.



*Fig. 4.23. Climate record 2011/2012. The high temperature in summer is due to solar heating through the skylights.* 

## Skokloster Castle

Skokloster castle is a heavy stone and brick building located on Lake Mälaren north of Stockholm. It houses a large and diverse collection of artefacts shown in their historic environment without any showcases. The castle is open for visitors mainly during the summer

In many rooms there are open fireplaces and ovens, but the upper floors have had practically no heating for 300 years. Nowadays, some rooms in the ground floor are heated all year round, but apart from this, there is no active climatisation in the castle. Temporary electric heaters have been used after outbreaks of mould. On the upper floors, the doors are closed and opened to control air exchange and curtains are used to control solar radiation.



Fig. 4.24. Record of RH from room 2A compared to the outside RH.



Fig. 4.25. Temperature record from room 2A compared to the outside temperature.

An analysis of the variations in temperature and RH shows that the variations inside are significantly reduced as compared to the outdoor climate and that there are considerable differences among the rooms. Furthermore it was shown that the variations in RH in the rooms can be reduced by enhancing the effective hygrothermal inertia of the building through a reduction of the air exchange. Even so, some kind of active humidity control conservation heating or dehumidification, would be needed in order to eliminate the mould risk.

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# 5. Heating

# Introduction

Most historic buildings have been heated during their lifetimes, but usually not to the comfort temperature we expect today. Heating was needed for human comfort, and should still mainly be used for this purpose. Constant heating is only needed in buildings with permanent occupation. Otherwise, the heating should vary in time or space depending in the use of the building.

The building and the objects do not need heat for preservation, but heating helps keep the building dry, which is a benefit in most situations. However, too much heating can cause trouble if the climate becomes too dry. Heat is a powerful drug which must be used in small doses.



*Fig. 5.1. Conservation heating by a moveable electric heater on the floor in front of the old ceramic stove. Salsta castle, Sweden.* 



*Fig. 5.2.* A warm air heating system for conservation heating is installed in the old chimney pipes. The inlet and outlet grates are visible behind the old cast iron stove.

# Heating systems

# Traditional heating systems

Many historic houses have traditional heating systems with iron stoves or open fireplaces, which have a documentary value in themselves. For centuries these installations may have served the purpose of providing thermal comfort for the inhabitants. Today an open fire is generally not recommended for heating a historic house due to poor efficiency and the risk of fire. Instead fireplaces and stoves may be used to house new heating installations. Old cast iron stoves can be retrofitted with electric heating elements or water pipes. This installation is invisible if the installations are mounted through the chimney. It is even authentic in the way it recreates the radiant heat and original temperature distribution of the room, although this may not be an advantage for conservation.



*Fig. 5.3.* A new heating element made of copper pipes is installed in the old cast iron stove. The coal bucket remains empty.

# Warm air heating

Warm air heating systems use air as a conveyor of heat to the rooms in a building. The warm air is distributed through ducts which connect to a unit with a fan to recirculate the air through a heat exchanger and dust filters to remove particles from the returned air. Sometimes an air heating system is integrated with ventilation, and a portion of outside air is mixed into the air stream. Some systems also have humidification to prevent dryness in winter.

The inlet temperature should not be more than 40 °C in order to avoid large temperature differences within the room. Still the warm air tends to rise up fast and develop a vertical temperature gradient in rooms with high ceilings.

Air has poor thermal capacity, so a large amount air needs to be circulated in order to bring enough heat into the room or building. The ducts therefore need to be quite large. Usually the ducts are installed in the attic, in the basement or below the floor. Old chimneys are sometimes reused for vertical distribution. Warm air heating systems are powered by electricity, hot water from a boiler or by heat pumps.



Fig. 5.4. Warm air heating systems force air movements within the room which may cause draft and discomfort.



Fig. 5.5. Duct for warm air heating in the attic of a church.



Fig. 5.6. The inlet of warm air is through small holes in the top of the vault.

### **Radiant heating**

Radiant heating elements transfer heat by radiation to the surface of a person without heating up the air. The purpose is to heat the persons directly and avoid convective air movements. Radiant heat is also used to counter balance the heat loss by radiation to cold surfaces, like walls or windows. The energy transfer depends on the temperature difference, the area of the radiator and the distance to the target. Infrared heaters that reach temperatures above 200 °C are used for fast and focused heating. Infrared heaters are often mounted high up on the walls or below the ceiling, but this is in many cases too invasive in a historic building.

Low temperature radiant heaters are mounted low on the walls or in the pews in churches. The surface temperature should not be above 70 °C to protect against injury and fire. Radiant heating elements should be placed as close to the user as possible to get the best utilisation of the heat radiation. Radiant heating elements should not be hidden behind panels for the sake of the visual impact, because this will also prevent the radiation from reaching the target. The heating elements can be camouflaged by colour or shape to fit the interior of the building. An elegant solution is transparent heating elements made of glass, which are less visible than solid ones.

Floor heating solves the problem of visual impact, but the intervention may not be acceptable with respect to conservation. Floor heating is commonly used both in wooden floors and tiled floors. It provides good comfort and an even vertical heat distribution. The surface temperature of a warm floor should not exceed 28 °C. Radiant heaters are often powered by electricity, but can also be hot water systems. Radiative gas heaters emit water vapour and carbon dioxide, and are not recommended for historic buildings.



Fig. 5.7. Radiant heating system with low temperature elements prevents convective air movements.



*Fig. 5.8. Low temperature radiant heating panel mounted on the chancel wall. The panel consists of a white concrete element with electric heating wires embedded.* 



Fig. 5.9. Infrared heating element suspended from the roof.

# Convective heating

Convective heating elements transfer heat to the air. A convector heated by hot water has ribs or fins to enlarge the surface area and maximise the heat transfer. A convector powered by electricity works like a toaster with filaments inside a metal box, open at the top and at the bottom. The air is moved by the buoyancy forces caused by temperature difference and distributed within each room.

The convective heating elements are mounted low on the walls or below the seats in a church. It is also quite common to install convectors below the floor, covered by a grate to allow air movement. The heat dispersion depends on the air circulation, so there has to be free space both below and above the convector. This is particularly important for under floor convectors, which tend to be mounted in spaces that are too narrow for proper air circulation to take place. Convective heaters can be used to compensate for cold draughts below windows or along outer walls. As compared to radiators, convectors tend to be smaller for a given heating power. Some convective heaters have built in fans. It should be pointed out that whereas the fan provides a more efficient distribution of the warm air, it does not increase the heating power. The main disadvantage is the soiling of the walls above a convective heatent.



Fig. 5.10. Convective heating systems create air movements in the room and may cause drafts and soiling.



Fig. 5.11. Convective heating element mounted below the seat in a pew.



Fig. 5.12. Convective heating element on a wall may cause soiling.

# **Conservation Heating**

Conservation heating is used not mainly for comfort but to reduce the relative humidity below risk levels. The temperatures needed are much lower than that which is required for human comfort. As a consequence the heating power is less than for conventional heating systems.

Conservation heating has been used for many years to reduce relative humidity in historic houses in the winter. It is a simple and robust climate control strategy, but the stability of RH depends on the air infiltration rate and the temperature control. A leaky house with high thermal stability will experience large variations in RH. A peculiar aspect of conservations heating is that it is sometimes required in summer in order to keep the RH at an acceptable level. This is relevant for medieval churches where the windows are often too few or too small to give enough solar gain. Conservation heating may also increase evaporation from damp walls or floors. As the air temperature rises to reduce the RH, the air can hold more water vapour, which will then give a lower RH.



*Fig. 5.13. Conservation heating with a portable electric fan heater controlled by a hygrostat.* 



Fig. 5.14. An air to air heat pump integrated in the furniture in Garda church, Gotland.

In spite of the low temperatures, conservation heating of historic buildings has a considerable energy demand. The heat loss is larger from historic buildings than from modern houses due to poor thermal insulation of walls and ceilings. Leaky doors and windows further increase the heat loss even at reduced temperature. In a case study on three historic buildings owned by The National Trust, the annual energy consumption for conservation heating was 39 - 53 kWh/m<sup>3</sup> (Blades et al, 2011).

Generally conservation requires more energy than dehumidification. The energy demand can be significantly reduced by the use of heat pumps. Heat pumps are particularly well suited for conservation heating, because they perform better when the temperature difference is small. Conservation heating with heat pumps can even be more efficient than dehumidification in large buildings with reasonably good thermal insulation.

#### Example

The energy consumption for conservation heating is calculated for a generic building exposed to similar climatic conditions as in South Scandinavia. The building is empty and has no internal or external sources of heat, so the inside temperature follows that outside. The only source of humidity is the outside air, which flows through at a constant rate, defined by the air exchange rate (AER). The RH is maintained at a constant all year by heating. The calculation uses the monthly averages of temperature and relative humidity in Denmark. For every month the temperature, at which the RH is 60%, is determined.

The energy needed for heating buildings with different U-values as a function of the AER is shown in the diagrams below. The energy consumption for conservation heating is proportional to the AER for any U-value. The intersection of each line with the y-axis represents the heat loss by transmission. The heat loss also depends on the size of the building. Small buildings are less energy efficient than large buildings, because the surface to volume ratio is larger for small buildings (fig. 5.8). This means that conservation heating is more relevant for large buildings than for small houses.



Fig. 5.15. The annual energy consumption for conservation heating to 60 % RH for a building with a volume of 500  $m^3$ . Each line represents an average U-value of the building.



Fig. 5.16. The annual energy consumption for conservation heating to 60 % RH for a building with an average U-value of 1.0 W/m<sup>2</sup>K. Each line represents the volume of the building as indicated.

When designing a new system for conservation heating, one should not aim for the standard design temperature. This will give a much too high capacity. A temperature difference of 5-10 degrees between inside and outside is usually sufficient to keep a moderate relative humidity. The appropriate power depends on the size and shape of the building, the average U-value of the building envelope and the air exchange rate. A rectangular building with a 20 m x 10 m floor and 6 m to the ceiling, a U-value of  $1,0 \text{ W/m}^2$  K and an AER at  $0.1 \text{ h}^{-1}$ , needs a heating power of 6 kW for conservation heating. The heating power for comfort temperature in the same house is 20 kW.

# **Intermittent Heating**

Intermittent heating is used to provide comfort for a limited period of time. This heating method is typically used in rural churches, but can be applied in any kind of building, which is used occasionally for receptions or events. The heating time must be as short as possible to limit the stress to heritage objects and to minimise energy consumption. The required heating power is therefore larger than for conventional heating systems. Localised heating can be used to focus the heat input in specific areas of a building or a room. Radiant heaters are most efficient for intermittent heating because they heat up the body of a person rather than the air.

When designing a heating system for intermittent heating, the heating power should be larger than for constant heating to comfort temperature. Exterior thermal insulation is of minor importance, because most of the energy is absorbed by the walls, floor and ceiling. It is the thermal capacity of the building envelope that matters. Therefore, the heating power cannot be calculated the same way as for constant heating. It depends on the building size and structure, the temperature rise and the heating time.



*Fig. 5.17. The relation between heating power, heating time and energy use for intermittent heating of a generic building.* 

The relation between heating power and heating time is not linear: If the heating power is doubled, the heating time decreases with a factor four. Thus changes in the heating power or requirements for heating time will have a stronger impact than one would think.

The energy demand for intermittent heating increases with heating time. Quick heating is the most energy efficient. The energy demand can be estimated by computer modeling. A generic building has been used, similar in size to the one described above, with a volume of  $1200 \text{ m}^3$ . It has solid brick walls, a wooden floor and an insulated, wooden ceiling. The heating system is designed for a temperature rise of 10 °C. The heating power is 20 -50 kW and the heating periods range from 3 to 46 hours. A heating power of 40 kW is reasonable, giving a heating time of 4 hours and an energy use of 180 kWh. The air only needs 4.2 kW to heat up, so the majority of energy is absorbed in the building structure. A higher heating power will not save much energy, but a lower heating power enforces results in a heating time and uses more energy



*Fig. 5.18. Local radiant heating in a Lau Church (S). The heating elements are integrated in the chandeliers and in the pews.* 

# **Local Heating**

Local heating is used to heat only designated parts of a building or a room in order to provide either comfort or better preservation conditions. While achieving the desired heating effect locally, unwanted climatic disturbance in the building or room as a whole can be limited. The basic technical solution is to place a number of low-temperature radiant sources in the room to heat designated zones. Local radiant heating is particularly useful for intermittent heating and is commonly used in churches. Typically heaters are placed in the pews to focus heat input where the visitors are. Compared to warm air heating, electrical radiant heating panels mounted under the bench seats provide the best thermal comfort for a moderate air temperature. Radiators can also be placed overhead but the visual impact should be considered.

It is possible to heat the person without heating the building, but there is a limit to how much radiant heat a person can tolerate without discomfort.

# Examples

# Gl. Estrup Manor house

Gammel Estrup Manor house is a museum with both permanent and temporary exhibitions. It is open all year, but the winter temperature is kept lower than usual for human comfort. The exhibition rooms are heated by portable electric panels located in the window niches. The heating power is adjusted so the inside temperature follows the average outside temperature with a constant difference of 8 °C. The temperature is 12-14 °C in winter and the RH is 40 -60%. The building has a high thermal stability due to the thick walls made of brick masonry, but the heat loss is never the less considerable. The windows are double glazed to reduce heat loss and improve air tightness. The annual average energy consumption is 80 kWh /m<sup>2</sup> or 20 kWh/ m<sup>3</sup> with a 4 m ceiling height.



Fig. 5.19. Gammel Estrup Manor house is used as museum all year.



*Fig. 5.20. Conservation heating with moveable electric heaters controlled by the outside average temperature.* 

# Kippinge church

Kippinge church is a 13<sup>th</sup> century brick building in a rural environment. The nave and chancel have a rectangular floor plan 10 m x 20 m, and the total volume is approximately 1200 m<sup>3</sup>. The walls are solid red brick and lime mortar, with lime plaster and lime wash on the inside. The floor is limestone tiles and wooden planks without any thermal insulation. The nave has a wooden barrel vault with a vapour impermeable membrane and 50 mm of mineral wool on top. The wooden framed windows are double glazed. The average infiltration rate is 0.07 h<sup>-1</sup>, both in summer and winter. The heating system consists of electrical radiant heating elements mounted in the pews and on the chancel walls. The church was heated intermittently to a basic temperature of 8°C, and to 18°C for services every second week. The radiant heating system allowed short heating episodes and a low basic temperature, which had little influence on the relative humidity. Dehumidification was needed to keep the RH at an acceptable level. The annual energy consumption for heating was 16 MWh, measured from July 2009 to July 2010, and 17 Mwh measured from July 2010 to July 2011. The heat loss by infiltration was 1.5 MWh, and the rest was lost by transmission through the walls and ceiling.



*Fig. 5.21. Kippinge Church has radiant heating in the pews and on the walls in the nave. Radiant heat is advantageous for tall rooms.* 



Fig. 5.22. The radiant heating elements are mounted below the bench seats.

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# 6. Dehumidification

# Introduction

Dehumidification is the concept of extracting water vapour from the air in order to reduce the RH inside a room or a building. It is used in buildings where the relative humidity is too high, either permanently or seasonally. This chapter explains the function and limitations of different types of dehumidifiers and gives an overview of their application.



*Fig. 6.1. A condensing dehumidifier temporarily installed in the aisle of a church. It is removed during services.* 



*Fig.* 6.2. *The principal function of a dehumidifier permanently installed in the attic of a building. The dehumidifier is controlled by a sensor in the room.* 

# Experience

Mechanical dehumidifiers have been used for decades by the military, industry and by private or public buildings owners to control the RH in damp environments. Dehumidification is an energy efficient way of controlling the RH to a specific set point in buildings, where heating is not needed for human comfort.

An early example of permanent dehumidification in a historic house is Läckö Castle, where a centralised system was installed (Holmberg, 2000). The dehumidifiers were placed in the attic, and dry air was distributed through the flue pipes of the old chimneys. The effort was only partly successful because of a high infiltration rate, and because there were too few inlets to give an even RH in all rooms. Dehumidification was also adapted for museum stores, where low temperature is actually a benefit for preservation (Ryhl-Svendsen et. al, 2010). In recent years dehumidification has been introduced for energy efficient climate control in cultural heritage buildings in Denmark (Larsen & Brostrøm, 2011) and in Sweden.



Fig. 6.3. An absorption dehumidifier temporarily installed in a doorway.

# Different types of dehumidifiers

### Condensing dehumidifier

Condensation takes place when the temperature is below the dew point of the air. This process involves the phase change of water vapour into liquid water or ice. In a condensing dehumidifier, the air is forced over a cooled surface where the water vapour in the air condenses.

Condensing dehumidifiers are available in numerous shapes and sizes, but they all contain the same basic elements: A compressor and a reservoir for the cooling liquid, a heating unit and a cooling coil,

and an electric fan to move the air through the assembly. The simple types only have an on/off switch, whereas the more advanced models are controlled by a built-in humidistat. Some have a meter to count the number of working hours. The condensed water drips into a pan or is led to a drain. Some suppliers offer a built-in pump, which may be convenient if the water has to be led to a drain in another room.



*Fig. 6.4. A condensing dehumidifier contains a cooling element, a heating element and fan to move the air through the assembly.* 

#### Absorption dehumidifier

Absorption is the uptake of water vapour in a desiccant (a hygroscopic material). The water molecules are released again as water vapour, so this process does not involve liquid water. By exposing the desiccant to a sequence of ad- and desorption by different air flows, it will gradually dry out a room or a building.

The absorption dehumidifier passes the air through a desiccant, usually a silica gel, which absorbs the water vapour from the air. A separate flow of heated air removes the water vapour to the outside. The most simple device contain the desiccant in a box, and the two processes takes place in successive intervals Some products contain a rotating desiccant wheel, where the silica gel is integrated in a perforated metal cylinder. In this the accessible surface is enlarged to facilitate the fast uptake and release of the water vapour. The process air is led through one segment of the cylinder, whereas the regeneration air passes through a different segment. As the cylinder slowly revolves both processes take place at the same time. In most models, the warm and humid air is released to the outside.



Fig. 6.5. An absorption dehumidifier contains a desiccant, sometimes mounted in a revolving unit. The process air and the regeneration air pass though different segments of the desiccant.

### Heat condensing dehumidifier

The heat condensing dehumidifier combines the principles of absorption and condensation. It contains a desiccant with an integrated heating element. It is mounted in a steel box with a fan and valves for inlet and outlet of air. The apparatus works in two stages. First the humidity is extracted by absorption as the air is led through the desiccant. Secondly the desiccant is dried by heating it to a temperature far above ambient. As the moisture evaporates from the desiccant it condenses on the inside of the metal enclosure. The liquid water is collected at the base and led to a drain. This device does not contain any moving parts and is therefore maintenance free. This type of dehumidification was introduced recently and experience is therefore limited.



Fig. 6.6. A heat condensing dehumidifier works in two stages. First the water vapour is absorbed by the desiccant. Secondly the water evaporates from the heated desiccant and condenses on the inside of the colder metal enclosure.

#### Performance

The capacity of a dehumidifier in a given room or building depends on the air exchange and the moisture sources in the building. Most suppliers offer diagrams of performance for each model, which may be useful when choosing the appropriate type and size. But if the infiltration rate of the room or the building is not known, it may be difficult to come up with an estimate of the excess moisture. Likewise, evaporation from walls or floors is not easy to determine. Usually the choice is made on a rough estimate. The volume of the building or room multiplied by the air exchange rate gives the volume of air, which needs dehumidification. This volume is then multiplied by the difference in absolute humidity between inside and outside to give the amount of water in grams. The difference in absolute humidity is estimated by climate measurements inside and outside. The capacity of the dehumidifier depends on temperature. Less water is extracted at lower temperature, but this is compensated by the fact that the water vapour content is lower at low temperature.

The energy use of a dehumidifier depends on the temperature and relative humidity. Both condensing and absorption dehumidifiers perform best at normal comfort temperature and high RH. Empirical data for the condensing dehumidifier give an energy consumption of 0.5- 2.0 kWh/kg at 20 °C and 60% RH (Andersson et al, 2003). This energy input is retained as heat within the building.

The condensing dehumidifier is less efficient below 8 -  $10^{\circ}$ C, because ice is generated on the cooling unit, so intermittent defrosting is required. This method is appropriate for buildings with some basic heating or where dehumidification is used mainly when the ambient temperature is above 10 °C.

An absorption dehumidifier uses more energy than a condensing dehumidifier per kg of water removed from the air. The energy use is 1,5-2,5 kW/kg at 50% RH in the temperature range 0-20 °C. Of the energy used, the heat of evaporation for water is 0.67 kWh/kg, This energy is lost, unless the dehumidifier has heat recovery or a condensing unit.

The absorption dehumidifier works at low temperatures, even below zero, but at a higher cost. This method is therefore favourable in houses without human occupation, or in buildings which are closed in the winter season. The heat condensing dehumidifier uses around 2 kWh/kg at 50% and 0-15  $^{\circ}$ C.



Fig. 6.7. Annual energy consumption for dehumidification to the RH indicated for each line. It is assumed that the dehumidifier uses 1 kWh to remove 1 kg of water vapour.

As an example, the annual energy consumption for dehumidification is calculated for a generic building with a volume of 500 m<sup>3</sup>. The building is assumed to be empty and has no internal or external sources of heat, so the inside temperature follows that outside. The only source of humidity is the outside air, the air exchange rate (AER) is assumed to be constant. The RH is maintained as a constant all year by dehumidification. The calculation uses the monthly averages of temperature and relative humidity in Denmark. For every month the excess moisture to be removed by a dehumidifier is determined. The energy needed for dehumidification to different target levels of RH as a function of the AER is shown in the diagram above. The energy consumption for dehumidification is proportional to the AER for any RH set point. If the building is completely airtight, and there is no internal moisture source, there will not be any need of dehumidification, so all lines radiate from the origin.



*Fig.* 6.8. An absorption dehumidifier installed in the attic of a historic house. The air is recirculated through the chimneys.



Fig. 6.9. The dry air is let through the old stove into the living room, located in the centre of the house.

### Installation

It is usually quite easy to implement dehumidification in a historic interior. For temporary solutions it may be acceptable to use a portable device. If the water is collected into a bucket, there should be a ballcock switch to prevent flooding from the bucket. For winter use, the water should not be led to an outside drain with a hose, because it may be congested by ice. In any case it is always a good idea to place a tray below the apparatus to collect any spill over. For buildings with many rooms it is often more convenient to have a central dehumidifier installation in the basement or in the attic. In such a case, the dry air is distributed by ducts through inlets in the floor or ceiling. Sometimes chimneys or ventilation ducts integrated in the walls can be reused for this purpose.

#### Examples

#### Kippinge church

The medieval church in Kippinge is located in a rural area on the island of Falster in Denmark. 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 the few hours of use but kept at around 8°C most of the time. The winter temperature is a few degrees higher than assumed for the

calculations, so the need for dehumidification is less than predicted in winter. The RH was controlled to 70 % by a condensing dehumidifier located in the isle between the nave and the chancel. A total of 1500 litres was removed in one year. The AER was measured to  $0.1 \text{ h}^{-1}$ . The annual energy consumption for dehumidification was 1900 kWh or 1.5 kWh/m<sup>3</sup>. The energy use for the condensing dehumidifier was therefore around 1.3 kWh/litre.



Fig. 6.10. The medieval church in Kippinge has permanent dehumidification to keep 70% RH.



Fig. 6.11. The condensing dehumidifier is located in the central isle, and removed before services.

# Liselund country house

The country house in Liselund dates back to 1800. The building is situated by a small pond in a romantic park on the island of Møn in the Baltic Sea. 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, located in the basement. The dry air is distributed by ducts into each room through small inlets in the floor. The air is returned through a duct located in the centre of the building. The RH was in the range 55-65 % all year, while the temperature was drifting from around 0 °C in winter to 20 °C in summer. The air exchange rate was 0.4 h<sup>-1</sup>. The annual energy consumption for dehumidification was 14 kWh/m<sup>3</sup> per year. This is much more than calculated according to the diagram (figure 6.7). The 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 occurs occasionally.



*Fig. 6.12. The country house in Liselund Park has permanent dehumidification with a sorption dehumidifier, located in the basement.* 



*Fig. 6.13. The dry air is supplied to each room through inlets in the floor and extracted through central duct.* 

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# 7. Ventilation

#### Introduction

Ventilation is the deliberate intake of 'fresh' outside air and removal of 'used' air from the interior. Ventilation is usually controlled only by the interior conditions, assuming the outside air is always a benefit. It is mainly used to ensure human health and comfort by removing a surplus of heat, moisture, pollutants or bad smells. Depending on the outdoor conditions, ventilation can either have a positive effect or a negative effect on the inside relative humidity. Adaptive ventilation is the concept of controlling the relative humidity by intake of outside air. It takes advantage of the natural diurnal and seasonal variations in the outside absolute humidity. The outside air is ventilated into the building only when the water vapour content is favourable for raising or lowering the inside relative humidity.



*Fig. 7.1. Principal diagram of an adaptive ventilation system. The operation of the fan is controlled by a small computer connected to the inside and outside sensors.* 

#### Experience

In Scandinavia, adaptive ventilation is a common and well established method to control RH in attics and crawl spaces (Hagentoft et al, 2008). In historic buildings there is a limited experience from the use of adaptive ventilation (Brostrøm et al, 2011). Adaptive ventilation in historic buildings is more common in central Europe. The concept was implemented in the Torhalle in Lorsch, Germany, where condensation on the wall paintings was avoided by mechanical fans controlled by indoor and outdoor climate sensors (Reiss & Kiessl, 1993). In the church in Zillis, Schwitzerland, controlled ventilation was used to stabilise RH in favour of the painted wooden ceiling. The effort was not very successful due to a large infiltration rate and the fact that ventilation was turned off in winter to reduce heat loss. (Bläuer-Böhm et al, 2001). A seasonal use was tested in the Antikentempel in Potsdam-Sanssouci Park to prevent mould growth on the walls and ceiling. From May to September there was adaptive ventilation by a fan mounted in the skylight (Brockmann, 2010).



Fig. 7.2. Outlet valve for controlled ventilation installed in a window.

## Performance

Adaptive ventilation is mainly relevant for unoccupied buildings with little need of heating for human comfort. The ventilation system can operate at all times of the year, because there is no need to consider the heat loss. In permanently heated buildings adaptive ventilation should be used only in summer. Adaptive ventilation is particularly useful when there are internal moisture sources in the building resulting in absolute humidity levels higher than outside. Since the outdoor climate sets the operating conditions, ventilation itself cannot guarantee a moderate RH at all times, thus auxiliary climate control such as dehumidification or heating may be needed. The outdoor absolute humidity correlates with temperature, so the air may be more humid on a warm and sunny summer day than on a cold and rainy day. This paradox is difficult to accept for most humans, because the body is sensitive to temperature and not to absolute humidity. Another effect of the correlation between outdoor temperature and absolute humidity is that adaptive ventilation often operates in the night when it is colder outside. This introduces an unwanted cooling effect, which will raise the relative humidity.



*Fig. 7.3. Duct for natural ventilation installed in a window niche. Natural ventilation does not ensure a moderate relative humidity inside a building.* 



Fig. 7.4. Many churches have 'summer doors' with metal mesh to increase natural ventilation in order to dry out the interior. It has the opposite effect on days, when the outside air is warm and humid.

## **Technical solutions**

In theory adaptive ventilation can be achieved by opening windows and doors as a simple way of controlling the intake of outside air. This type of ventilation is free of energy use, except for the heat loss in case of heating. However, it is difficult for a person to decide when the climatic conditions are suitable for adjusting the indoor climate, and when it will have the opposite effect. It is also impossible to know if the flow rate is large enough, because it relies entirely on the random air movements. Manually controlled natural ventilation is therefore not recommended for climate control. In practice, mechanical ventilation should be used. For adaptive ventilation one should aim for an air exchange rate of one time per hour. This will enable the system to benefit from even short periods of favourable outside conditions. Given proper control, the energy demand is marginal in relation to other kinds of humidity control.

Adaptive ventilation is used in several commercial control systems, which is intended for attics and crawl spaces under houses. It is sold as a standard plug and play assembly or as a custom design, including a control unit with sensors, a fans and valves. This equipment can be used in a historic building with little intervention. The control unit should have an indoor and outdoor sensor for temperature and relative humidity, and calculate the mixing ratio to decide when to operate the intake fan. The electric fan can be installed in the attic or in an adjacent space, and existing ducts or chimneys reused for the extraction of air. Many historic buildings have old vents in the outer walls, which can be reused with little effort. The outlet of air should be controlled by a valve, which opens due to the overpressure build up by the intake fan. Apart from the air intake and the outlet, the space must be reasonably air tight to have any benefit from adaptive ventilation.



Fig. 7.5. The intake fan for adaptive ventilation can be located in the attic.



Fig. 7.6. Old vents can be reused for air outlet by adaptive ventilation.

## Examples

## Country house, Klints

A country house in Klints on Gotland had controlled ventilation installed in the basement (Broström et al, 2009). The house was built in the early part of the 18th century. It is a limestone construction with 60 cm thick walls. The walls are covered with lime plaster both inside and outside. The windows are single glazed. The building is naturally ventilated, mainly through fireplaces. The building, which is

listed, has severe moisture problems; furniture and wooden floors show signs of woodworm and there are algae growing on the walls.

In summary, the results showed that controlled ventilation has had a significant drying effect removing some 1600 kg of water in year. The mould risk was kept at an acceptable level with the exception of two short periods. Installation costs are low and energy costs are negligible in relation to alternative measures. In this case, the effect of the ventilation could be improved by increased fan capacity and improving air tightness to reduce leakage when the fan is not in operation. Heating or dehumidification would be needed as an auxiliary measure to reduce mould risk, but only for short periods of time.



Fig. 7.7. Exterior view of the farmhouse in Klints, Gotland.



Fig. 7.8. The fan for adaptive ventilation is installed in the open fireplace of the farmhouse.

## Hangvar church

As mentioned above, the covariance of temperature and MR is a limitation to the effectiveness of adaptive ventilation in historic buildings. In Hangvar church, located on the island of Gotland in the Baltic Sea a solution was implemented using preheating of the inlet air through an integration of solar energy and adaptive ventilation. The concept operates as follows:

1. In the day time, solar energy is collected and stored.

2. At night, when the outside air is generally drier, the inlet air is preheated using the stored energy.
This case study shows that adaptive ventilation has improved the indoor climate in the church. During one year, some 1100 kg of water has been removed from the building resulting in significantly lower RH level and reduced mould risk. The members of the parish have felt that the indoor air quality has improved, mainly in the elimination of bad smells. The annual energy consumption for the operation of the fan was 250 kWh. Overall this gives an efficiency of 0,22 kWh/kg which is an order of magnitude smaller than for conventional dehumidifiers.

The preheating of the inlet air has counteracted the cooling effect that was reported in previous studies. During one year, the contribution from the solar panels was 2000 kWh. This is economically viable only if the solar panels are subsidised. In this case, adaptive ventilation is not sufficient to eliminate mould risk throughout the year, however it does significantly reduce the operational time and energy demand for auxiliary measures such as dehumidification.



Fig. 7.9. Exterior view of Hangvar Church. The electricity produced by the solar panels was used to run a fan for adaptive ventilation and for preheating the intake air.

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# 8. Decisions

#### Introduction

Experience has shown that knowledge and experience are necessary, but not sufficient, conditions for the selection and design of climate control systems. The message of this chapter is that a well planned and systematic decision process is crucial in order to find good solutions and eliminate bad ones. This chapter introduces a systematic and generic framework for decision making about indoor climate control. The situations and conditions where such decisions are made vary widely, hence decision processes will also vary. It is up to the reader to think about and adapt the suggested steps presented here to come up with a decision process suited to the conditions at hand.

From a sustainability perspective, it is desirable to strive for solutions that take into account a wide set of assessment criteria, preferably from a life cycle perspective. The chosen indoor climate control strategy and technical systems will be a compromise between the requirements related to the use of the building, risk reduction and resource use. The balancing between these factors has to be made in relation to the long term objectives for the management of the building. The more unclear these objectives are, the more difficult it will be to determine a suitable compromise. As indoor climate issues are of critical importance for long term management, it is important that all affected aspects are brought to the discussion table in the negotiation phase. This will require an inclusive and interdisciplinary decision process which also inovolves the users.



Fig. 8.1. The indoor climate control strategy and technical system will be a compromise between the requirements related to the use of the building, risk reduction and resource use.

#### Levels of decision making

The decision making process and the level of expertise needed has to be suited to the complexity of the task. Generally decisions about indoor climate control are made at three levels of management. There are strategic decisions at the policy level, for example regarding guidelines for a set of buildings sharing similar characteristics. At the level of the individual building, there are decisions made related to the introduction of new technical systems or when existing control strategies have to be changed.

These decisions are often, but not always, made in parallel with renovations or a changed use of the building. At this level there is also a need for re-evaluation during the maintenance phase. Relevant indicators for use, risk reduction and resource use should be measured and evaluated regularly, not only at the end of the technical lifetime of the system. Finally, there are decisions made during the operation phase regarding the use of the existing system or minor modifications to it. These three levels differ in terms of the extension of the decision making process, the need for expertise and the frequency of decision making as summarised in table 1.

Type of decision	Level	Aim	Expertise needed	Frequency
Policy	Building stock	Guidelines	Indoor climate control	Decennial
-	-		Preservation	
New system or major	Individual building	Specifications	Indoor climate control	Decennial
strategy change	_		Preservation	
Re-evaluation	Individual building	Specifications	Indoor climate control	Annual
	_		Preservation	
Daily operation	Technical system	Optimisation	None (technical skills	Daily
			when necessary)	-

Table 8.1. Levels of decision making.

## A generic decision process

The following account of a generic decision making process is targeted toward a situation where a new technical system is considered, or a major change in climate control strategy is needed. Again, it is important to use this framework as a starting-point, which has to be adapted to suit the case-specific conditions. The process is based on the European standard *EN 15759-1 Conservation of cultural property - Indoor climate - Part 1:Guidelines for heating churches, chapels and other places of worship.* This is an iterative step by step procedure as shown in the flow chart below.

More general directions are given in the British guidelines PAS 198:2012 Specification for managing environmental conditions for cultural collections.



Figure 8.2. A generic decision process.

## **Building** survey

This includes the technical condition of the building (see chapter 4) as well an assessment of cultural heritage values.

## The present indoor climate

The present (near past) indoor climate of the building must be determined through measurements over at least one year. (Se chapter 2)

# Define objectives

The objectives in terms of future use of the building, energy use, economics and preservation have to be defined and specified as far as possible.

## Specification for the indoor climate

This is a critical step. An appropriate solution cannot be defined without clear specifications for the desired indoor climate. As mentioned above, the chosen indoor climate control strategy and technical system will be a compromise between the requirements related to the use of the building, risk reduction and resource use. General requirements for indoor climate in historic buildings are presented in chapter 3. It should be noted that in most cases the climate specifications are negotiable and may have to be adjusted if the consequences in terms of costs and technical installations are not acceptable.

## Select a solution for climate control

The difference between the present indoor climate and the climate specifications determine the need for change, if any. The different strategies and technical solutions are discussed in chapters 5, 6 and 7.

#### Assessment in relation to the objectives

The proposed solutions must be assessed in relation to the objectives as defined above. If the solution is not in agreement with the objectives iterations will follow:

- 1. Change or adjust the strategy and/or technical solution.
- 2. Revise the climate specifications
- 3. Revise the objectives

# Implementation and evaluation

Finally, it is important to evaluate and optimise the control system after implementation following standard engineering practice. The system should also be monitored and evaluated for a prolonged period of time, preferably with a permanent monitoring system. Such monitoring should be a part of the daily maintenance of the control system in order to evaluate if it performs in accordance with the demand specification.

Even if the system performs according to its specifications (i.e. doing things right), it is recommended that performance should be regularly assessed on a more strategic level (i.e. doing the right things) with respect to the use of the building, energy use, cost, damages etc.