The potential and limits for passive air conditioning of museums, stores and archives

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Abstract

The climate in unventilated stores and archives can be entirely passively controlled in temperate regions. Three actual and one simulated archive demonstrate the potential of variants of conservation heating. The heat and humidity buffering of the building and its content must be sufficient to allow the building to cruise through both summer and winter extremes on inertial guidance. This brings the passive climate quite close to the strict limits imposed by standards and guidelines. The increased chemical decay caused by internal pollution accumulating through lack of ventilation cannot be quantified because of a lack of research on the kinetics of gas-solid reactions in stores with multiple levels of enclosures. However, pollutant absorbers are effective in cleaning the air. Extension of passive climate control to exhibition spaces cannot provide a constant climate but is certainly capable of reducing variation in temperature and relative humidity to a useful degree and within the safe limits according to current scientific knowledge.

Introduction

Passive climate control has mostly been used for archives and museum stores in both historic and modern buildings. The extension of passive climate control to exhibition spaces is rarely found as deliberate design, though it frequently happens unintentionally. The fundamental requirement for natural climatic stability in a building is a large thermal inertia, usually provided by heavy walls. A second requirement is moisture absorbent surfaces able to stabilise the relative humidity (RH) against the variable water content of the ventilation air. A third requirement is that the building must provide natural temperature uniformity, with no cold corners.

Figure 1. "The environmental adviser said the library will have a more stable relative humidity if the open edges of the books are exposed."

An archive without climate control: the military archive of the fortress of Segovia

An example of an almost natural archive climate is the military archive of the fortress (Alcazar) of Segovia in Spain (figure 2). The archive is in the basement

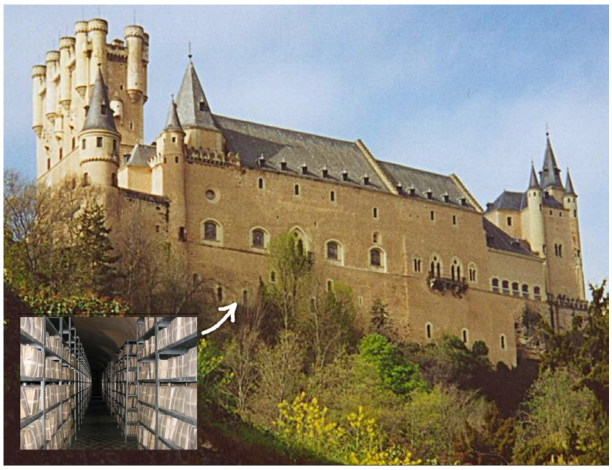

Figure 2. North facade of the Alcazar of Segovia, Spain. The narrow windows just visible over the shrubbery illuminate the military archive. The insert, bottom left, shows the interior of the archive.

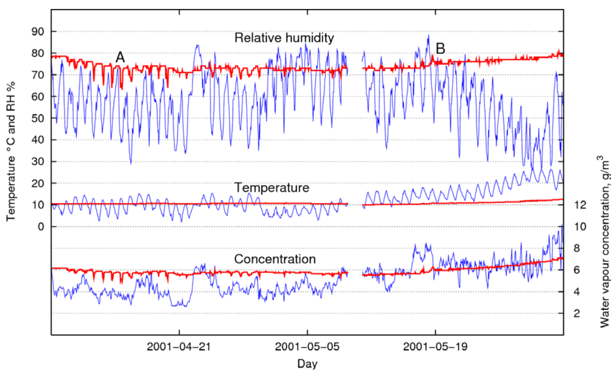

Figure 3. The climate within the Segovia archive, and outside.[1]

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of the building enclosed on one side by a stone wall with narrow windows. The other side of the room is formed by the massive limestone bedrock.

The climate in the archive is stable, but rather humid by conservation standards. The archivist fights the humidity by opening windows during working hours. At point A in figure 3 the downward pointing blips in the RH trace show the RH being forced down by the entry of outside air of low water vapour content, with the RH rebounding almost to its previous value when the window is closed in the afternoon. This intermittent ventilation clearly reduces the inside RH by small steps each day. However, the archivist still opened the windows later in the year, when the outside air is generally of higher water vapour content than the inside air. Humans are not good at estimating atmospheric water vapour. The task is best left to automatic machinery which decides by measurement when to pump air.

An archive which is heated in winter: The Suffolk Record Office

In temperate climates, heating will reduce the RH without significantly increasing the rate of degradation of the collection. This is known as conservation heating. If the room is also heavily buffered against RH change, summer heating can be avoided. The room will cruise through the summer period with a constant RH, far from water vapour equilibrium with the outside air. A good example of this approach is the Suffolk Record Office in Ipswich, UK (figure 4). The two storey building has narrow recessed windows. The wall is faced with 112 mm brick, then there is a ventilated cavity. Inside this is 110 mm of insulating block, then a second, unventilated cavity, then 300 mm of brick and a coat of 13 mm plaster on the inside. The attic space is ventilated. The building

Figure 4. The Suffolk Record Office, Ipswich UK. The walls are 630mm thick, half of which is brick. It was built in 1990. The architect was Henk Pieksma.

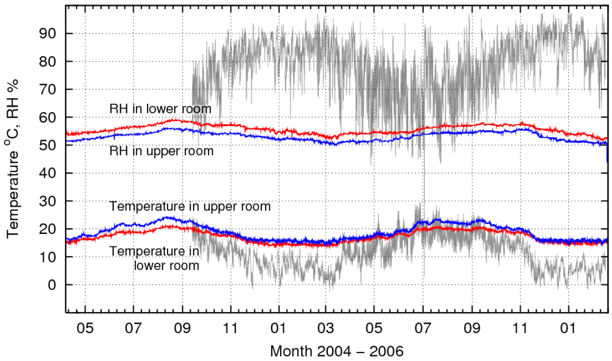

Figure 5. The climate within the Suffolk Record Office. The uneven grey traces are the outside temperature and RH [2]

is heated in winter, but there is no air circulation at all, and no active control of RH. The climate in the archive rooms is shown in figure 5, together with the outside weather. The winter heating reduces the RH sufficiently that there is no need for heating during the summer.

An archive which borrows heat from its surroundings: The Arnamagnæan archive

The standard version of Conservation Heating uses a hygrostat to warm to a constant RH. This does not work in a well filled archive, because the RH rises as the temperature rises, causing positive feedback and a runaway temperature. It is better to control the temperature according to the season, raising it well above ambient during the winter and holding it about ambient during the summer.

In the Arnamagnæan archive of Copenhagen University, Denmark [3], shown in figure 6, the temperature is raised pseudo-passively, by leaking heat in from the adjacent corridors and rooms, which are maintained at a temperature for human comfort. The winter temperature outside is allowed to influence the archive temperature through thin insulation on the two outside walls, with thicker insulation on the walls towards the interior. A

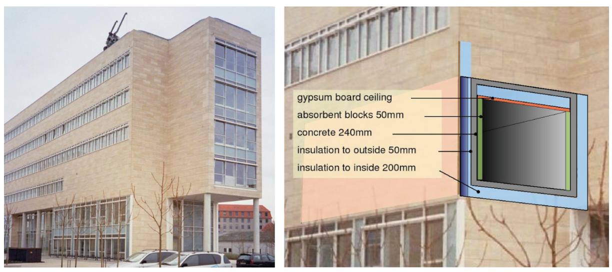

Figure 6. The building of Copenhagen University which houses the Arnamagnæan archive behind the windowless section of facade. On the right is a section through the archive. Note the thermal insulation against the interior of the building and the comparatively thin insulation of the outer wall. As a consequence, the archive temperature lies about midway between the outside temperature and the temperature of the core of the building.

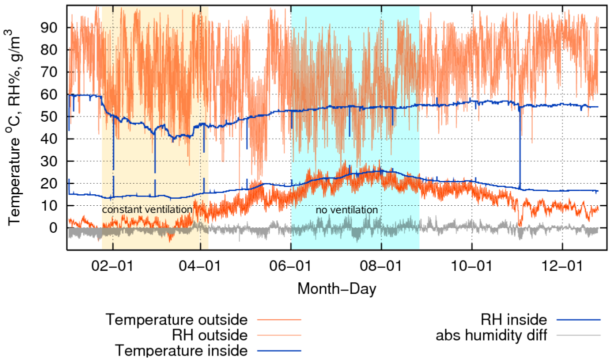

Figure 7. The climate inside and outside the Arnamagnæan archive during tests in 2006 of its resistance to malfunction of the air pumping system. The decrease in inside RH during February and March was caused by deliberately ventilating the room continuously, at 2 air changes per hour, to stress the humidity buffering. During July and August the room was completely unventilated, to test the resistance to the high RH expected in summer. The grey trace at the bottom shows the difference between outside and inside water vapour concentration. Shading above the zero line indicates a higher water vapour concentration outside. The sharp blips on the curves mark short periods when the data logger was withdrawn to the conservator's office for the data to be extracted. These brief retreats reveal the temperature and RH which surrounds six of the eight sides of the archive.

section through the archive is shown in figure 6. The temperature of the room hovers about midway between the inside temperature of the whole building, which is about 22°C, and the varying outdoor temperature.

The RH within the archive is usually controlled by pumping in outside air when, by chance, it has a water vapour content that will drive the room RH to the specified value. In figure 7, however, there are two periods when the pump was deliberately left on or off for long periods. The difference in water vapour concentration between the outside and the inside is shown as the grey shaded areas on the graph. During the winter there is nearly always a lower water vapour concentration outside. This means that the RH cannot be driven upwards by pumping in outside air. The archive has to buffer its own climate isolated from the outside weather. During the spring and autumn there are many periods when the RH can be driven either up or down by ventilation. After the concrete structure has dried, and with growing confidence in the self-buffering of the archive, it should be possible eventually to abandon the ventilation control altogether.

Modelling the climate within buildings with both thermal and moisture buffering

The Arnamagnæan archive takes heat from the surrounding building, so cannot be regarded as truly passive. It is, however, possible to use solar heating in summer and ground heat in winter to provide entirely natural heating to maintain a constant RH. We don't yet have a measured example but rely on simulation, using a structure similar to the storage building of the regional museums of southern Denmark, in Ribe.

Figure 8. The recently constructed building in Ribe, providing storage for the regional museums of southern Denmark.

We have used the Danish program Bsim[4]. The simulated building is 20 x 10 x 5 m high, with the long facade facing south and the roof ridge east-west. The walls are made of 240 mm light weight concrete with 250 mm of insulation on the outside. There is an air gap and then a 110 mm brick facing. The flat ceiling is 25 mm of cement fibre board covered by 300 mm of mineral wool insulation. The ventilated roof is steel panels supported by 22 mm fibre board. The floor is 150 mm concrete cast directly on the ground without any insulation. The air exchange rate is once every ten hours.

The course of the indoor climate is shown in figure 9. The temperature drifts from 5°C in winter to 16°C in summer, and the daily fluctuations are around 1°C. The RH is unstable, with 20% changes within the same week, and an annual drift from 40% in winter to 90% in summer. The predicted temperature is close to that measured in the real Ribe building in summer, but in winter the simulated temperature is 2-3°C higher than in the real building. The RH cannot

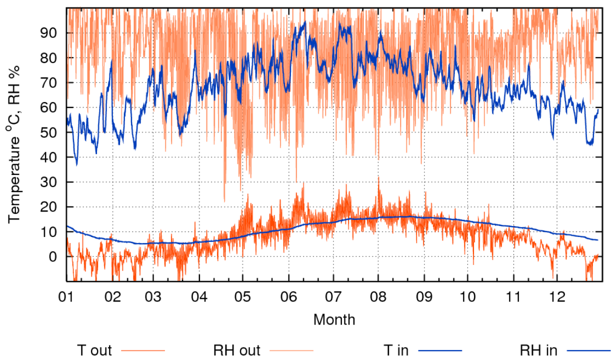

Figure 9. The course of the temperature and RH in the simulated store room.

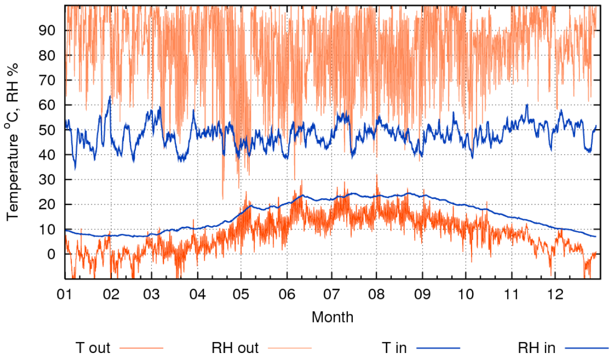

Figure 10. A simulation of the climate in the Ribe store if windows are placed in the roof and the solar heat allowed to warm the ceiling.

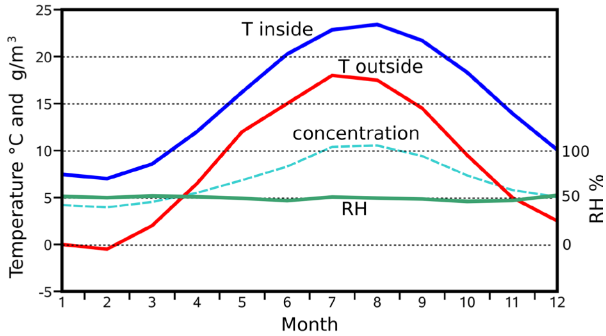

Figure 11. The curves in this graph are derived from the monthly average temperature and RH in Copenhagen over the last 30 years. A room has to be heated to lower the RH. The inside temperature is a sine curve, which gives a RH very close to a constant 50%.

be compared, because the real building is always dehumidified.

For the next simulation, figure 10, the building has south facing windows, covering about 10% of the roof. The glass is a low energy type, which transmits most of the sunlight from the outside, but reflects the long wavelength radiation from the inside. To get this solar energy down to the store room the insulation is moved up from the ceiling to the roof, and 200 mm of cellular concrete is substituted for the fibre board ceiling. The inside of the walls is covered with 100 mm of paper. These changes have a dramatic influence on the indoor climate. The annual variation in temperature is from 8°C in winter to 24°C in summer, which brings the RH down to 40-60% all through the year. The buffer effect of the paper lining reduces the daily RH variation from 20% to 10%. Heat from the sun warms the building to the right temperature in summer. During the winter heat is provided from the ground through the uninsulated floor. Some refinements are needed to ensure uniformity of the indoor temperature when the floor is colder than the air in summer, and the ceiling cooler in winter. In a real building, the RH would be further stabilised by the stored artifacts.

Minimal conservation heating

A defect of conservation heating is that the higher average temperature accelerates the decay of organic materials. However, in a heavily buffered building it is possible to impose a much smaller annual temperature cycle. The building continues on inertial guidance, holding a constant RH which is often out of equilibrium with the outside water vapour content.

Figure 11 shows the temperature inside varying from about 8°C in winter to 24°C in summer, to give 50% RH throughout the year. This is a large temperature cycle, way beyond what is advised by the current standards for museums and archives.

If we flatten the annual temperature cycle, the RH will automatically develop an annual cycle. This is shown in figure 12. The RH cycles from 38% to 64%, which is only just within the boundaries for avoiding mechanical damage at the dry limit and biological damage at the moist limit. However, the archives show an immense moisture buffer capacity, so it is worth exploring how this can be exploited to make the RH more constant.

There are two ways of ensuring a constant RH through the year. One is to ensure a sufficiently large buffer capacity and a slow air exchange, so the room simply holds the annual average RH without taking any notice of the seasonal change in the outside weather. There is alternatively the semi passive technique as used in the Arnamagnæan archive. Figure 13 shows that by the random variation of nature, the outdoor water vapour concentration does intermittently intersect the indoor water vapour concentration in a room at 50% RH subjected to the

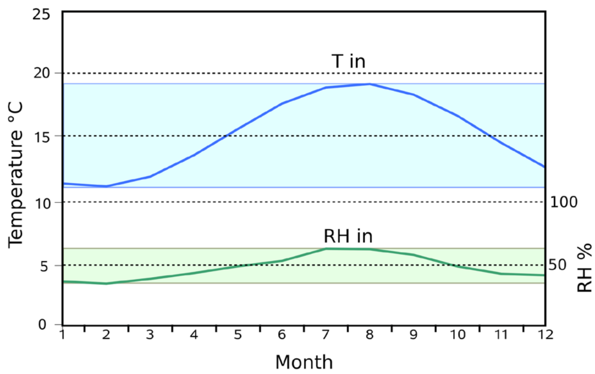

Figure 12. The consequences of flattening the temperature curve from the ideal for forcing 50% RH, as shown in figure 11. The RH cycle is only barely acceptable as a conservation climate but the temperature cycle is now 11°C to 19°C.

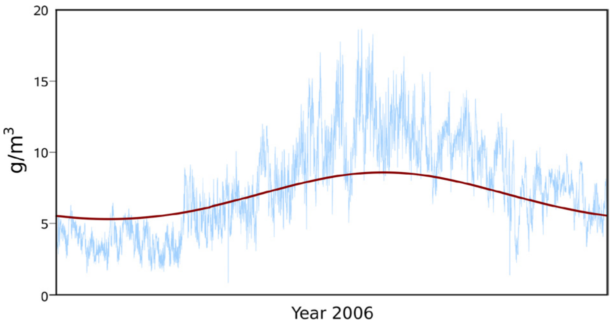

Figure 13. The flatter curve of indoor water vapour content, corresponding to 50% RH at the flattened temperature cycle of figure 12, is here compared with the actual water vapour content of outside air every hour in 2006. Random variation in the weather brings the outside water vapour concentration to pass through the inside value quite often, with not more than a month at a time when the outside concentration is consistently on one side of the inside curve. These intersections allow the inside RH to be changed in either direction by pumping in outside air at a suitable time.

flattened temperature cycle shown in figure 12. At these times, mostly in spring and autumn, outside air can be pumped into the room to correct the drift of the RH away from the set point. Happily, the more unpredictable and variable the weather, the greater the opportunity to correct the error in the indoor RH.

One could argue that air pumps and vapour concentration sensors are hardly passive climate control, but they don't use much energy, and in a room with reasonable thermal and moisture buffering, they are fail safe.

VENTILATION

Ventilation has been advocated for centuries as an inhibitor of fungal growth. Since any ventilation at all will reduce the performance of humidity buffering, and to a lesser extent the stability of the temperature, there is a serious apparent conflict here.

A trawl through the microbiological literature reveals little reliable information about the direct effect of air movement on microbiological growth. The controlling variable for fungal and microbial growth is generally accepted to be the RH, called the water activity by biologists, with some influence from the nutritional qualities of the substrate. The advice to ventilate surely arises indirectly, from the need to ensure temperature uniformity, and consequent RH uniformity, in all corners of the room. It is also true that there are many sources of water vapour indoors and no passive ways of removing water vapour except by diffusion through the outer wall. If one is designing a new building, which is the main focus of this article, temperature uniformity should be designed in from the start. Corners should be rounded and the external wall should be uniform in structure and porous to water vapour. There should be some lateral heat conductivity in the outer wall, which is easier if it is thicker. All these improvements are easy to incorporate if one is building in earth or massive brick, both of which are currently out of fashion among architects.

Keeping the air exchange low will retard outdoor pollutants from reaching the collection stored inside the archive, which, if the pollutants are reactive, will much reduce the indoor concentration. There will, however, be an increase in concentration of internally generated pollutants, of which the most feared is acetic acid. There is scant information on the chance of such molecules reacting within the object or its immediate container before escaping into the larger space of the room and eventually to the outside. The air circulation within a book is orders of magnitude slower than in a free air space, and the exposed surface for reaction is enormous as a proportion of the air volume. Even though a poorly ventilated archive may offend the human nose, we lack a scientific treatment of how dangerous the stagnant air is to the stored materials.

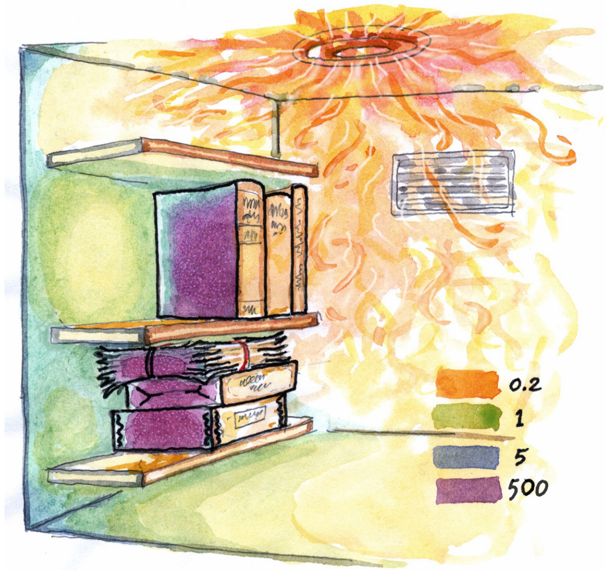

Figure 14. A schematic diagram of ventilation in an air conditioned room. The numbers give the approximate residence time in seconds of an air molecule within a 5 cm cube. The air functions as a heat transfer agent, forcing a uniform temperature in places directly affected by the air stream. Corners can maintain a considerably different temperature and consequently different RH, even if the water vapour concentration is uniform. Unventilated voids such as books and boxes, which are entirely enclosed by ventilated spaces, have the same temperature as the air and do not suffer biological attack more than exposed surfaces. The residence time for an air molecule within a book is assumed to equal that in the same volume of stagnant air.

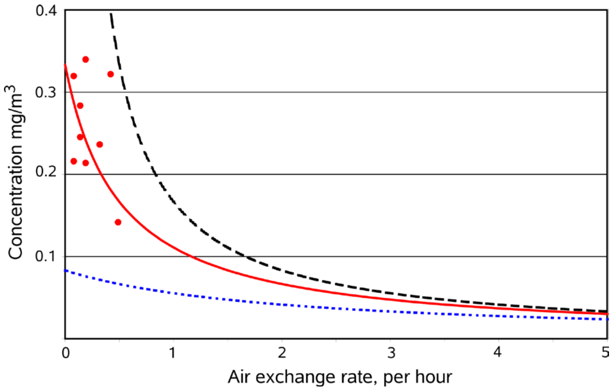

Figure 15. The concentration of an internally generated pollutant at different air exchange rates. The concentration is modelled for steady state conditions in a 120 m^3 room for a pollutant emitted into the room air at 20 mg/hour. The highest curve represents no re-sorption on inner surfaces. The middle curve represents a surface removal rate of 0.5 room volumes/hour. The bottom curve represents a surface removal rate of 2 room volumes/hour. The dots mark concentration measurements of acetic plus formic acids in the Arnamagnæan archive.

For mixed collections which consist of both objects that emit pollutants and other objects which are harmed by the same compounds, the simplest approximation is to assume that all pollutant molecules escape from their source into the room air, mix uniformly and are then available to attack susceptible materials. If pollutant removal must be carried out by dilution with fresh air only, the ventilation rate must be a couple of air changes per hour to have a significant effect. This is shown in figure 15 for a room similar to the Arnamagnæan archive.

The top curve in figure 15 shows the situation in an inert room, in which no re-sorption of the pollutants happens. The bottom curve shows the pollution concentration in a room with highly reactive surfaces. Most real rooms will be somewhere between these two extremes, as shown by the spot measurements from the Arnamagnæan archive. A passively controlled archive cannot have an air exchange rate much faster than once every ten hours. Ventilation that significantly reduces the pollution level will destroy the climatic stability. Pollutants can be absorbed by reactive walls but to match the dilution by ventilation would require every surface of a typical archive room to be lined with charcoal cloth. Alternatively, air can be pumped through a carbon filter at two air volumes per hour. This discussion assumes that all pollutant molecules emerge into the room, to be caught by reactive walls. It must be doubted that ventilation has any significant effect on the preservation of objects which themselves are the pollution source, such as stacks of acid paper, or decaying acetate film, because reaction within the immediate container cannot be significantly reduced by cleaning the room air.

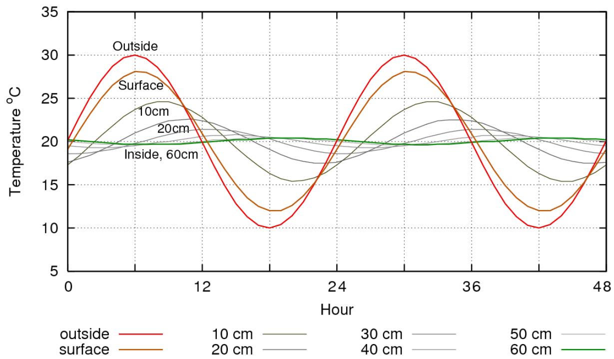

Figure 16. The heat flow through a 60 cm thick solid brick wall subjected to a daily cycle of outdoor temperature. The much diminished wave of heat reaches the inside surface of the wall about 12 hours later.

Buffering inhabited spaces

For rooms where people will spend some time, as visitors or occupants, ventilation with fresh air is necessary. People need approximately 10 litres per second, which equates to a ventilation rate of 0.5 air changes per hour for a typical work space. For the following discussion a ventilation rate of once per hour is assumed.

Figure 16 shows the variation with time of the temperature through a 60 cm brick wall exposed to a daily cycle on one side. The thermal inertia ensures that the inside surface of the wall is buffered against this daily cycle. Thermal insulation on the outside of the wall will further stabilise the temperature at the inside surface. This wall has a half time to reach equilibrium with a suddenly changed outdoor temperature of about two days. A thicker wall is not necessarily advantageous, as will be shown later. [5]

Quenching the daily temperature cycle sometimes has a moderating effect on the interior RH and sometimes destabilises it. When the incoming air adjusts to the interior temperature, the RH changes, sometimes to a degree that exceeds the variation in the outside RH (figure 17).

It is evident that thermal buffering must be combined with moisture buffering. Figure 18 shows the effect of coating the inside of the brick wall with 20 mm of paper. The moisture buffering effect of this layer depends very much on the air exchange rate and also on the ratio of the surface area of the buffer to the volume of the room. For this simulated building, the ratio of surface to volume is set to one square metre per cubic metre. This ratio is typical of an ordinary house. The indoor relative humidity is now moderated so that it is always less than the variation outside, and often much less.

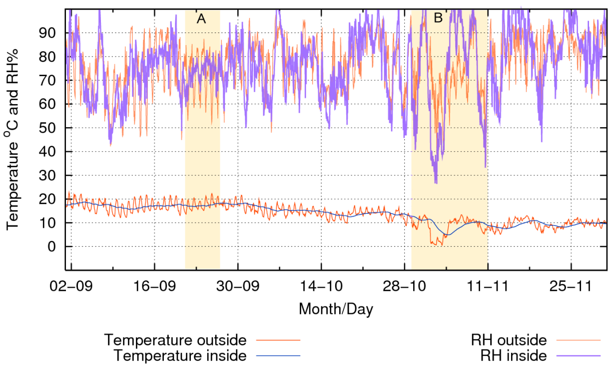

Figure 17. The simulated RH within a building which is well ventilated but has thick walls is sometimes more extreme than the outside RH, and sometimes more calm. During period A the weather is stable and the daily RH cycle is mainly caused by the daily temperature cycle, so the RH variation within the temperature stabilised building is smaller than outside. During period B, however, a sudden change of weather caused a drop in temperature which took several days to pull down the indoor temperature. During this, and the subsequent warming period, the indoor RH variation exceeded that outdoors.

The conservator will remark that the RH variation is still extreme, compared with the variation allowed by museum standards. A reason for this is that RH buffering by materials is feeble and short lived compared with temperature buffering when the air change rate is large. Figure 19 is the moisture analog to figure 16, showing the penetration of moisture, expressed as interstitial RH, through a 20 mm stack of paper. At 10 mm into the stack the influence of the daily RH cycle in the room becomes negligible. It is only the sorbed water in this first 10 mm that is exchangeable to buffer the daily variation in RH. Further progress in exhibition space climate buffering must wait on the development of absorbent walls with a high exposed surface area.

Conclusions

Passive climate control of archives and stores by increasing their cold season temperature above the temperature outside is so easy and reliable that it should always be applied in temperate climates. The

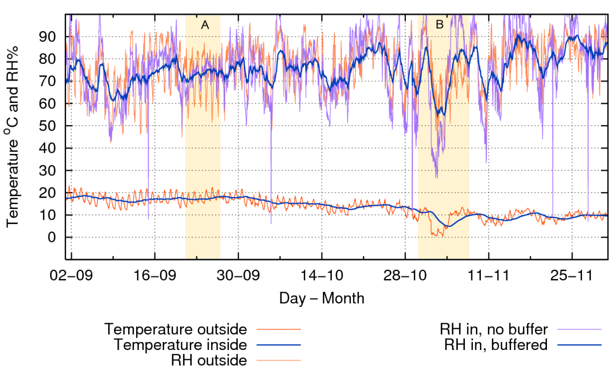

Figure 18. The simulated indoor RH is considerably stabilised by the RH buffer applied to the walls. Now, the inside RH variation never exceeds that outdoors.

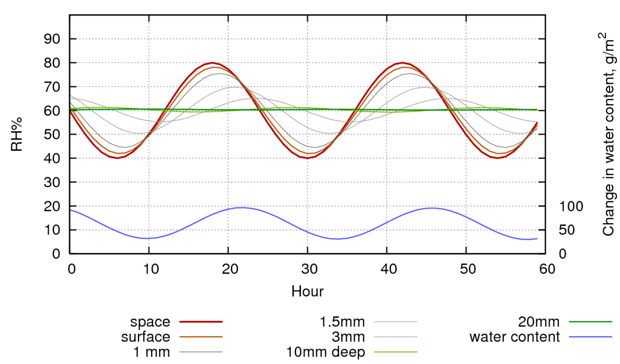

Figure 19. The penetration of water vapour into a 20mm thick stack of paper as the RH varies. The pattern of diminishing influence with depth closely follows the pattern of heat flow shown in figure 16 but the effect vanishes below 10 mm depth. The lowest curve shows the water vapour available for buffering RH in the room.[4]

RH inertia in a well packed store vastly exceeds that of the building itself: the half time for RH equilibrium can easily be extended to half a year.

The threat from internally generated pollutants lingering in an unventilated room can be averted by recirculating the air through a pollutant filter, but the rate of damage from mildly polluted room air has yet to be defined.

Passive climate control of museum exhibition rooms is limited by the large air exchange required by people. Thermal buffering merely requires a massive wall. The principal reason passive control has not been applied is lack of quantitative experiments with RH buffers of large active area to compensate for the slow diffusion of water through absorbent materials.

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References

1 The Segovia climate data were provided by Victoria Smith. The investigation was financed by the EU 5th framework MIMIC project.

2 Climate data were supplied by Dominic Wall, The Suffolk Record Office, Ipswich UK.

3 The Arnemagnæan archive was designed by HRAS Architects of Virum, Denmark. Climate data were provided by the conservator Mette Jakobsen. We thank the curator Peter Springborg for suggesting and then supporting this initiative in passive climate control.

4 http://www.en.sbi.dk/publications/programs_models/bsim (visited 2007/4/10)

5 The hygrothermal simulations are based on the computer program described in chapter 3 of Tim Padfield, "The role of absorbent materials in moderating changes of relative humidity". PhD thesis, 1998. Technical University of Denmark, Series R number 54 1999, ISBN 87-7740-256-1. Also available on the internet: http://www.padfield.org/tim/cfys/phd/phd-indx.php.