Exploring the limits for passive indoor climate control

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Abstract

Passive climate control, using building materials to moderate variation in both temperature and relative humidity has been shown to work in archives, which have a small air exchange rate and can be allowed to get colder than humans find congenial. Extending the same principles to exhibition rooms containing people seems not to have been tried, but it should work if museum climate standards are relaxed from their present insistence on a stability that only mechanical air conditioning can deliver. The feasibility of passive climate control is determined largely by the outside climate. Some typical climate patterns are interpreted for their suitability for museum building.

Introduction

Passive climate control is well established in small enclosures such as showcases and transport cases. Can the principles be extended to ameliorate the climate in whole buildings? Temperature buffering of the daily cycle can be achieved in brick walls which are 60 cm thick. This is a massive wall by current architectural fashion but was quite ordinary in those times when buildings were basically stacks of stones held together by gravity. In a well ventilated room, this flattening of the temperature cycle will sometimes cause a reduction in the daily relative humidity (RH) cycle and sometimes magnify the RH variation beyond the fluctuations outside. Therefore, temperature buffering must be accompanied by RH buffering. This can be achieved by lining the room with porous water absorbent materials. This doesn't happen in the current style of architecture, where surface finishes form an impermeable layer even on the few water absorbent architectural materials in current use. RH buffering was a feature of ancient buildings, where interior surfaces were bare wood, earth plaster or lime plaster over earth. This article is an analysis of the changes needed in modern architectural practice that will allow the establishment of a moderate indoor climate without resorting to air conditioning. Mechanical ventilation systems are not excluded as aids to perfecting the climate, but the emphasis is on climate control that is resistant to mechanical, electronic and human failure.

Temperature buffering

The common mineral building materials, brick, earth, concrete and stone, have sufficiently similar thermal properties that one can generalise that a 60 cm thickness will attenuate and delay heat transmission so that the inside surface will experience a very small daily temperature cycle, displaced by 12 hours from the much larger outdoor cycle. This means that the heat leaking through the wall is a maximum in the middle of the night, which is often a convenient time to have it, since the air exchange is then bringing cool air into the room.

The pattern of temperature distribution resulting from a daily temperature cycle is shown in figure 1. A thicker wall will hardly improve the situation

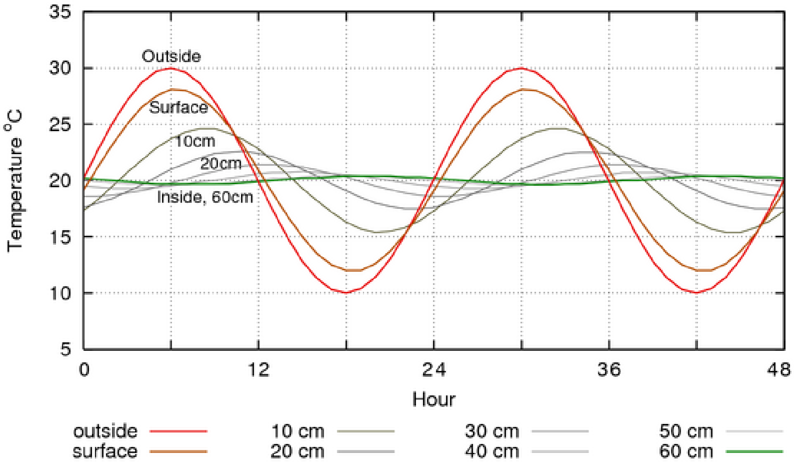

Figure 1: The course of the temperature at various depths from the outer surface of a brick wall, exposed to ambient air on the outside and placed against an infinite thickness of perfect insulator on the inside. The weak temperature cycle on the inside surface is approximately 12 hours behind the daily temperature cycle on the outside.[1]

further, because temperature patterns longer than the daily cycle cannot be predicted, or designed for. Only an underground room can even out the other reliable weather cycle: the full year.

The effect of temperature buffering on the relative humidity

The half time for the 60 cm wall to come to equilibrium with a sudden but lasting change of temperature is about two days (figure 2). A sudden change of outdoor temperature will cause a spike in the indoor RH, because of the temperature difference between the inside surface of the wall and the incoming air. This is a frequent cause of transient condensation on the walls of massive buildings.

Much of the daily cycle of RH is caused by the temperature cycle operating on air of fairly constant water vapour content. As the temperature rises, the RH automatically falls, because it is the ratio of the actual water vapour content, which is nearly constant, to the maximum possible water vapour content, which increases steeply with temperature. This process can be seen operating during period A in figure 3. At times the weather pattern becomes unstable, with air masses of different water vapour content following each other. Period B in figure 3 includes an episode where continental air, cool and dry, flowed over Denmark for four days, until the warm moist Atlantic air re-established itself. The thermal inertia of the wall caused a mismatch between inside and outside temperature for several days after these sudden changes. The interior RH therefore varied much more than the outside RH. There was condensation on the interior surface of the wall when the moist Atlantic air flowed in while the wall was still cool from the four preceding days of cold weather.

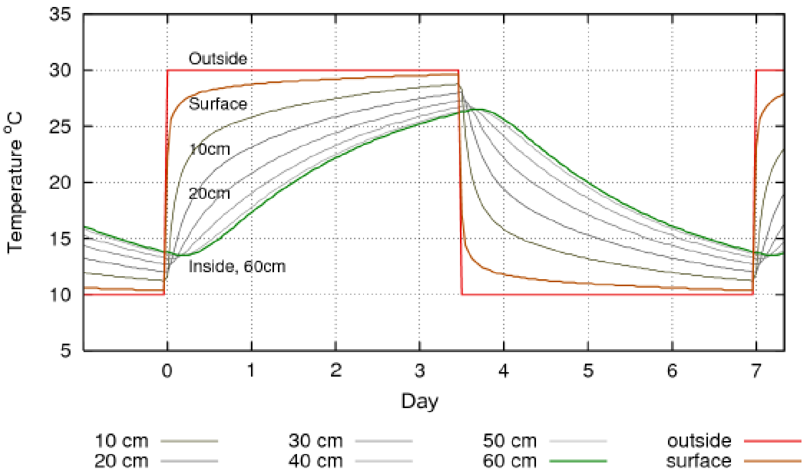

Figure 2: The course of the temperature at various depths from the outer surface of a brick wall when the exterior temperature is suddenly changed to a new steady value. The half time for the wall to come to a new equilibrium is about two days.

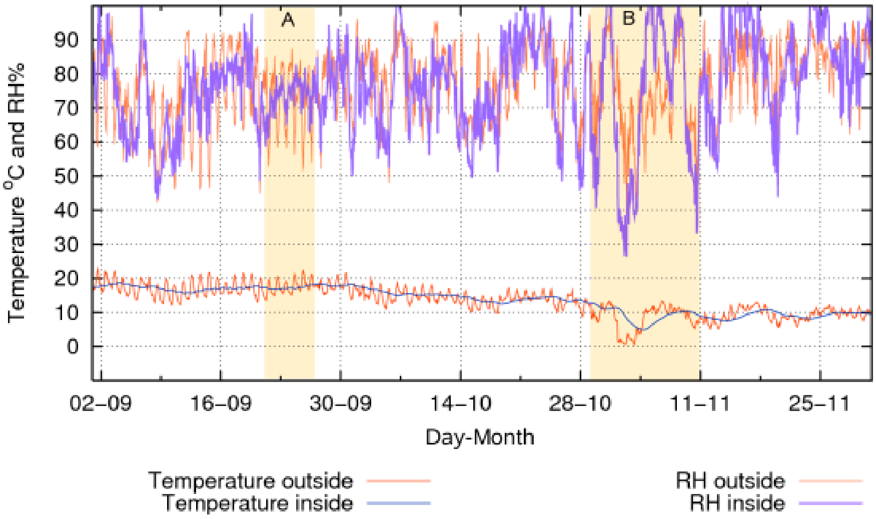

Figure 3: The RH and temperature within a well ventilated building exposed to the autumn weather of Copenhagen in 2006. In period **A** the weather is stable with a fairly constant water vapour content. The RH variation is largely caused by the daily temperature cycle. The RH variation within the building is reduced because of the relatively constant temperature. In period **B**, however, a sudden influx of continental air, cool and dry, combines with the thermal inertia of the building to drive the internal RH beyond the extremes of the outdoor values.

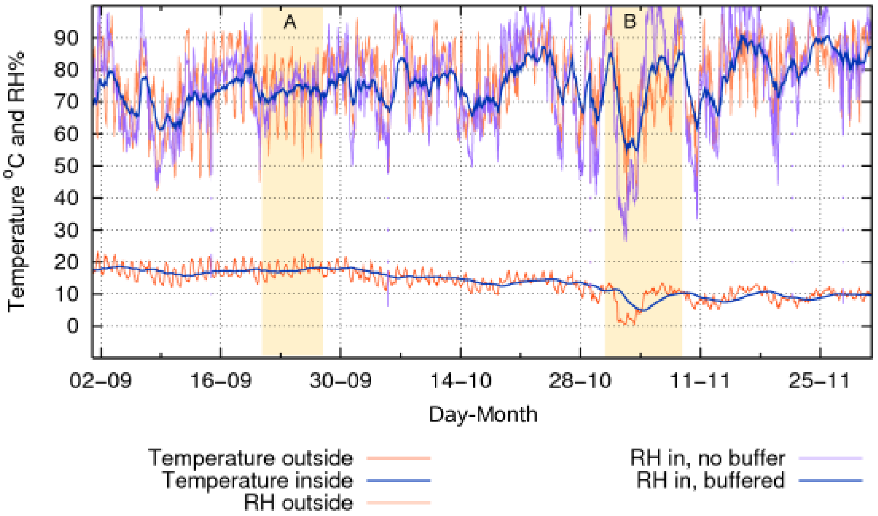

Figure 4: This diagram is the same as figure 3 but with an added trace for the interior RH after 20 mm of paper humidity buffer has been added to the inside surface of the wall. The air change rate is once per hour and there is one square metre of paper surface exposed for each cubic metre of room volume. The RH variation is much reduced by the moisture buffer and now never exceeds the extreme values in the outside RH.

The need for humidity buffering in massive buildings

Massive buildings with thermal inertia need some humidity buffering to bring the indoor RH variation below the amplitude of the outdoor cycle. Figure 4 shows the consequences of adding 20 mm of paper to the inside of the brick wall. The indoor RH is now quite stable, on a daily cycle, during the period of stable weather marked A. During period B the indoor RH variation is considerably reduced, though still disquietingly unstable in a conservator's eyes.

Further stabilisation of the indoor climate can be achieved either by reducing ventilation or by increasing the RH buffer capacity. One air change per hour is typical for a house, too little for a cinema and too much for an archive. The decision to minimise ventilation depends on the purpose of the room. An alternative, or additional, strategy is to increase the RH buffer capacity of the wall. This is surprisingly difficult. Figure 5 shows that the daily cycle of RH does not reach the deep layers of the paper buffer, so putting a thicker layer of paper on the wall will not help. The only solution is to corrugate the wall surface to give a bigger surface area. A close analysis shows that the process limiting the buffer capacity is diffusion within the paper; the resistance to moisture movement from the air to the paper surface is relatively small. A labyrinthine buffer such as a wall of vertical cardboard cylinders open to convective air circulation, would give a better buffer capacity. Another, more fire resistant possibility is a ventilated stack of perforated brick which has been dipped into a slurry of absorbent montmorillonite clay. None of these ideas has been tried in practice. The only labyrinthine RH buffer actually used in museum stores and archives is the collected items, many of paper, or enclosed in cardboard containers. It is quite effective, since all archives are well stuffed with cellulosic material.

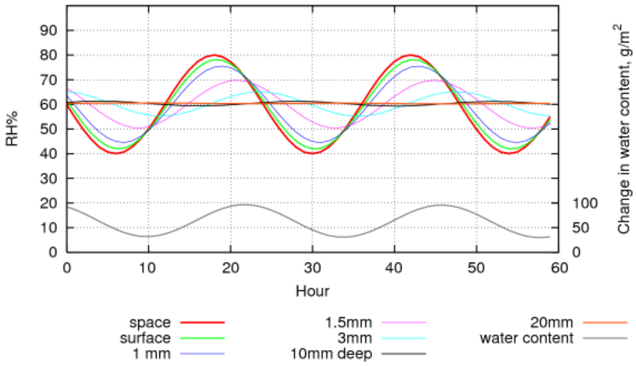

Figure 5: The RH within the pores of a 20 mm thick stack of paper laid on an impermeable surface and exposed to a sinusoidal variation in RH. The daily cycle of RH hardly penetrates to the base of the layers. This indicates that the lower layers are not changing in water content and are therefore not contributing to stabilising the RH.

Archives without air conditioning

An example of an almost natural archive climate is the military archive of the fortress of Segovia in Spain (figure 6). The archive is in the basement 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 when she comes to work. At point A in figure 7 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. 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. The principle of injecting outside air when it is of suitable water vapour content to drive the inside RH towards the ideal value is good, but humans are not naturally expert at estimating atmospheric water vapour content. The task is best left to automatic machinery which decides by measurement when to pump air. Since air is sometimes at its driest late in the night, after it has lost moisture to dew, a protected air inlet is more secure than an open window.

The Alcazar archive has no heating. Its average temperature is not far from the average temperature of the ground two metres below the surface, about 12°C. This accounts for the high relative humidity, also not far from the average outside, perhaps slightly increased by evaporation of water diffusing through the walls and floor.

Using unregulated heat to moderate the relative humidity

In maritime temperate climates, the average relative humidity can be reduced to a value tolerable to archivists by heating the air about five degrees above ambient. This is done to prevent biological decay in unoccupied historic buildings that are closed in winter, the most humid period in northern Europe. It is called conservation heating and is usually regulated by a hygrostat: the temperature is adjusted to keep the relative humidity constant. Using an electrical

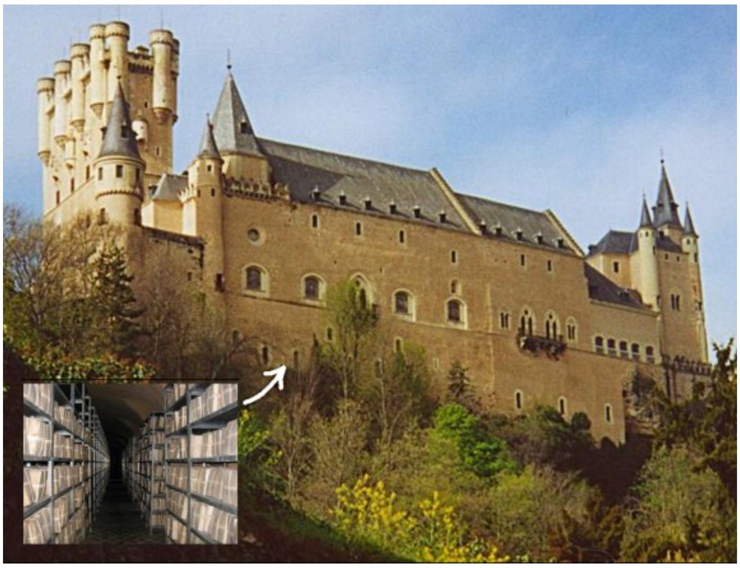

Figure 6: The north facade of the Alcazar of Segovia, Spain. The narrow windows just visible over the shrubbery illuminate the military archive. The insert, bottom-left, shows the interior of the archive.

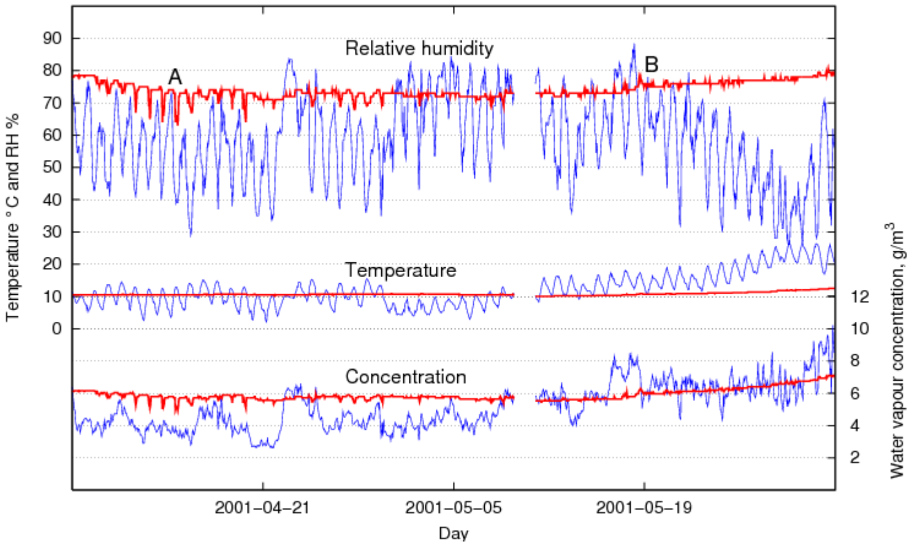

Figure 7: The climate within the Segovia archive during a period of two months in the spring of 2001 (the steadier trace of each pair) compared with the outdoor climate. At point A the RH dips regularly because the archivist opens the windows when she starts work. This tends to reduce the RH in slow steps. At point B the outside water vapour content is higher and the open windows increase the interior RH. Notice the very stable temperature (the middle steady trace).

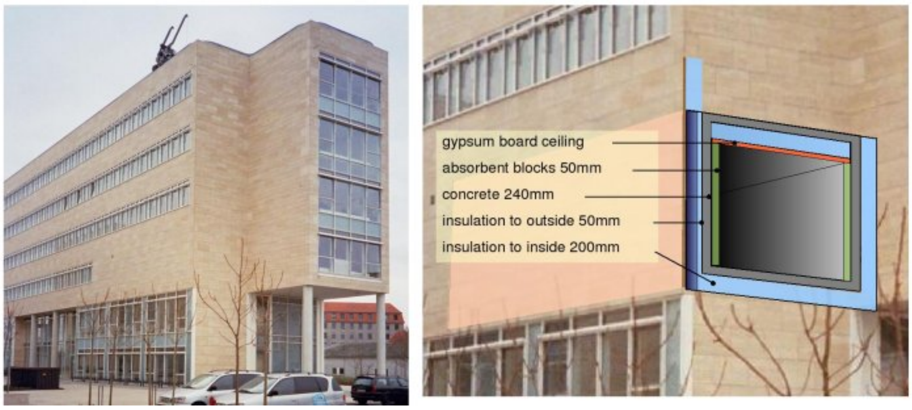

Figure 8: The Arnamagnaean archive of Copenhagen University lies behind the windowless section of the facade. The close up on the right shows a section through the archive. Notice the unusual placing of insulation against the interior of the building and the thinner insulation on the external wall. Humidity buffering of the empty room is provided by 50 mm of cellular concrete lining the interior. It is finished with porous silicate paint to prevent dusting.

regulating device brings the risk of breakdown. Furthermore, it brings the risk of runaway heating in an archive, where a rise in temperature will cause a rise in RH, because of the buffering characteristics of cellulose. The temperature excess in summer will accelerate chemical decay. However, if there is a large temperature and moisture buffering in the building, it is possible to avoid the summer temperature excess by using the humidity inertia of the room to tide over the period of high humidity. In winter the temperature can be allowed to drift down to a point about five degrees above the average outside temperature. This period can be used to re-establish the correct indoor RH by leaking in outside air of low water vapour content.

An example of this technique is the Arnamagnaean archive of medieval manuscripts in Copenhagen University, figure 8 (left). This is a small room, 10m x 4m, housing mostly paper objects. A cross section of the archive is exposed in figure 8 (right). The walls are of concrete, 240 mm thick, with an inner moisture buffer of cellular concrete 50 mm thick. An unusual feature of the construction is that the room is insulated on the inside wall dividing the room from the corridor of the university department, which is always warm. The insulation to the outside is thinner. Consequently, 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. That was the plan. In reality, the room is warmer than intended. Figure 9 shows the gentle annual cycle of the inside temperature, and the stable RH.

However, the building is new and the concrete slabs will take time to dry out. Furthermore, the design is unique, so a backup mechanical system was installed. This is a tube through the outside wall with a fan in it. When the outside water vapour content is, by chance, of a suitable value to drive the inside towards the specified ideal RH, the fan starts. The natural air exchange rate of the room is about one air change every ten hours. With the fan, the exchange rate is once every two hours.

The performance of the archive was tested by first running the ventilation continuously during a period when the outside water vapour content would force the relative humidity down. This is the shaded area from January to

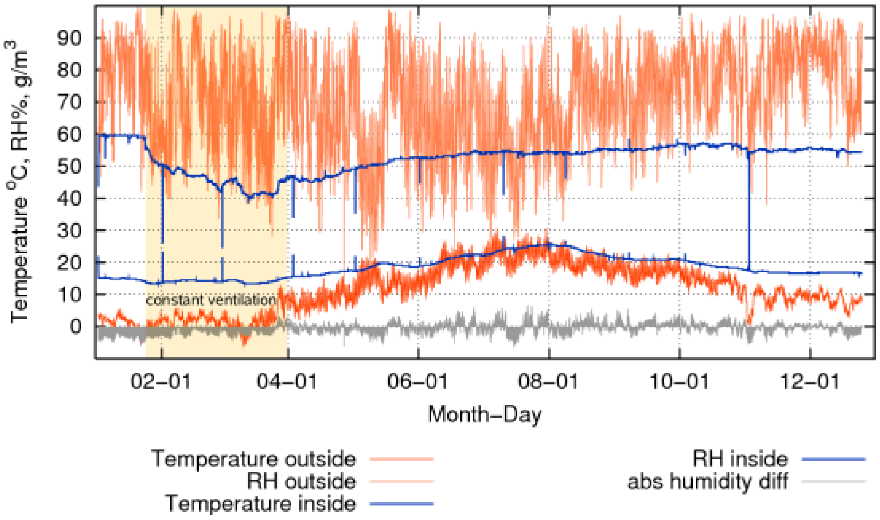

Figure 9: The climate in the Arnamagnaean archive during 2006. From late January to the end of March the ventilation was continuous at about one air change every two hours. Thereafter, the room was ventilated according to the suitability of the outside air to push the internal RH towards the set point, 55%. The grey band at the bottom of the graph shows the relative water vapour content of the outside air compared with the inside air. Grey fill above the zero line indicates a higher water vapour concentration outside. During such conditions pumping will raise the inside RH. [3].

April 2006 in figure 9. It shows how the archive would react to a mechanical or measuring error that locked the ventilator on for a long period. The shaded grey component close to the zero line on the graph shows the relative water vapour concentrations of outside and inside air. When the grey area is above the zero line, there is more water vapour in the outside air. During the late winter to spring period, the outside water vapour concentration was consistently below the inside value, even as the inside RH was moving down towards 40%. On the few occasions when the outside water vapour concentration was only just below the inside value, the inside RH rose, due to buffering from the archived materials. From June to mid-August the ventilation was stopped. The buffer capacity of the room and its contents was easily able to cruise over this period without significant deviation from the intended 55% RH.

The temperature in the Arnamagnaean archive was surprisingly resistant to being changed by the constant pumping of air into the room. The room was deliberately not heavily thermally insulated, so that there is a significant stream of heat from the building, through the room and then out to the outdoors. This prevents the ventilation air from affecting the room temperature, as would happen in a heavily insulated room. The air entering the room is only affecting the RH, and doing that quite slowly, because of the high moisture buffer capacity.

Temperature control

So far, I have coupled temperature with RH control, without checking that the temperature is always acceptable to humans. In the cool temperate climate of Copenhagen, RH control by semi-passive means is entirely compatible with a reasonable temperature for human activities but the control logic for the

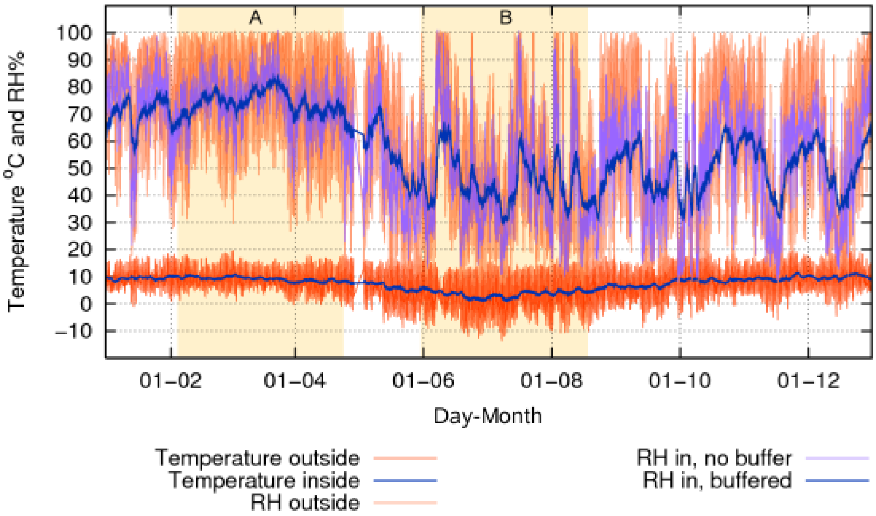

Figure 10: The climate at the ancient site of Tiwanaku near lake Titicaca in Bolivia. The well ventilated brick building with wallpaper, used in earlier simulations is modelled in this environment. During period **A** the weather is stable and the internal RH is very stable but during period **B** the varying outdoor water vapour content destabilises the interior RH. Note that the cold season coincides with a generally low but very unstable RH, wih a huge daily variation. [4]

Alcazar or the Arnamagnaean collections cannot automatically be extended to other climates.

Figure 10 shows the climate at Tiwanaku, the pre-Columbian ruin in Bolivia. Here the period of high outdoor RH coincides with the (relatively) warm season, while the cold weather brings generally low and variable RH. The climate control used for the Arnamagnaean archive would not work here and the cold dry period, averaging close to zero degrees, might provoke complaints from some people. However, during the cold period there is abundant dewfall, sometimes as frost, because of radiation cooling to the thin clear atmosphere. A deeper analysis of the local climate might support using condensed water to humidify a warmed interior.

The situation in Egypt (figure 11) is rather different. Here the problem is the temperature, rising to thirty degrees even after buffering the daily cycle. In this case the priority is to reduce the temperature, since the RH is very low in the hot period. A tall building designed to use the stack effect will have the interior wall surface at a nearly constant temperature. At night, cool air will be drawn in at the bottom by convection. During the heat of the day the low air inlets are closed so the cool interior air is trapped in the building by gravity.

Such semi-passive air conditioning, where mechanisms are only used to control air flow rather than condition the air, can be extended to any climate with a large daily range in temperature. A scheme for such control, which allows both cooling and reduction of RH is sketched in figure 12. In this strange device cool night air is pumped through a heat accumulator. During the day, hot air of low RH is pumped through a moisture absorbent buffer, drying it out. During the early morning hours these two accumulators are connected in series to introduce cool, dehumidified air to the building, using power only to work the fan. This reduction of the RH, against the tendency of cool air to rise in RH is due to the

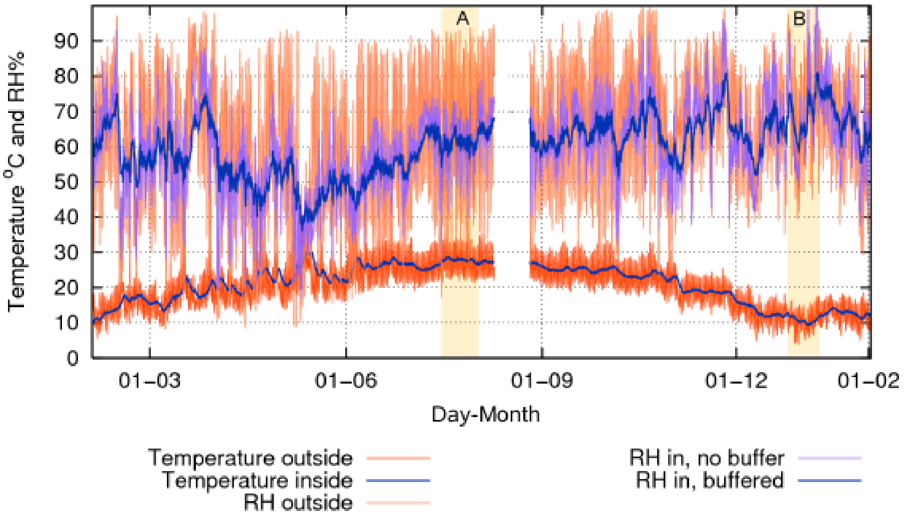

Figure 11: The climate at the Egyptian Sphinx. The well ventilated brick building with wallpaper used in earlier simulations shows the same climatic patterns with periods of stable and unstable weather. During period **A** the weather is stable and the internal RH is very stable but during period **B** the varying outdoor water vapour content destabilises the interior RH. Note that the outdoor temperature occasionally approaches 40°C while the buffered indoor temperature sometimes approaches 30°C. However the night minimum seldom rises above 23°C. [4]

temperature independence of the moisture sorption of materials. The material which has been dried out with the warm, low RH midday air will, on cooling, retain the same low equilibrium RH (to be precise the RH will fall further) and is therefore capable of dehumidifying a cool air stream.

Climate analysis

These actual and theoretical examples of climate control without air conditioning prompt the suggestion that a museum building project should start with a thorough analysis of the local climate, using hourly data rather than monthly averages. The wind can also be used to aid and even to direct ventilation, for example the reliable evening change of wind direction in a mountain valley or at the seaside. This enquiry about local conditions should be widened to a study of the local geology. Earth is a good thermal buffer, and has some interesting and barely researched interaction between heat flow and moisture movement, since it is unusually moisture active at moderate RH. A local subsoil with high montmorillonite content, characteristic of weathered volcanic soil, will make a good moisture buffer whereas a kaolinite clay, common in granite areas, is almost inert to moisture. Various hypothetical primitive structures can readily be modelled approximately, including designs using thermal insulation, which has hardly been discussed in this article. In this way the materials and structure of the building can be optimised for low energy use, by cunning adaptation to local conditions.

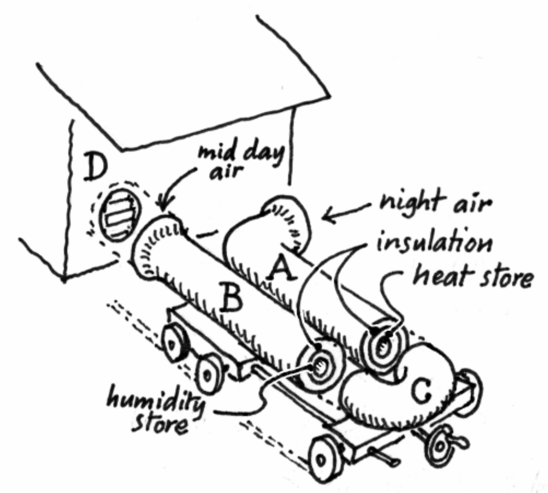

Figure 12: A schematic sketch for air conditioning a building in a climate that is both hot and humid, but has a considerable daily temperature cycle. During the night, cool air is drawn only through the heat accumulator tube A. During the hottest part of the day, when the RH is low, air is drawn only through the RH buffer tube B. During the early morning hours, the apparatus is rolled up to the air intake to the building and the coupling C is pressed up to connect the tube A in series to tube B. Air is pumped in, first being cooled at A, then dehumidified at B, before entering the building.

How to proceed from this analysis

The hypothetical buildings in this analysis have had quite a large ventilation rate - once per hour. The two real buildings have had slower ventilation rates, because they were uninhabited archives. In a museum gallery there has to be a careful balancing of ventilation rate with thermal and moisture buffering. The permeability of walls, and their ability to soak up pollutants are other factors that can be brought into the mix of properties. The passive air conditioning can be aided by intermittent injection of outside air and, in really difficult climates, aided by mechanical air conditioning, perhaps underdimensioned and acting only outside opening hours.

There is at present no museum gallery known to the author which was purposefully designed to have an entirely natural climate, moderated only by the materials and design of the building. Current fashion in museum design is exemplified by the Denver Art Museum by Daniel Liebeskind, which has walls leaning out at such angles that modern technology would be challenged to give them the thermal inertia of an old fashioned brick wall. There is a presumption that the architect designs an eye catching sculpture while the engineer puts in the necessary mechanical air conditioning, based on the specification by the conservator, who is well served by standards so cautious that mechanical air conditioning is the only way to achieve the specified climate. The whole industry is locked into this way of working, and its economic structure also encourages this pattern of large expenditure on the mechanical equipment with lesser priority to reducing the running cost, both in energy and in expert manpower, sleeping with a bleeper under the pillow, connected to the climate alarm system.

There is one major obstacle to designing buildings with both humidity buffering and a reasonable air exchange rate for human occupation. Although common and cheap structures, such as earth walls, have a large exchangeable moisture content, this moisture is so slowly made available from the depths of the wall that it is unable to compete with the flow of water vapour entrained by the ventilation air as soon as the exchange rate exceeds about once per hour. Some way of making the water available quickly must be devised, tested and made available as a standard product which an architect can specify with confidence.

The current public debate about global warming gives cause to hope that a mental revolution has begun - towards an architecture where cunning but simple methods both to save energy and to give a congenial indoor climate are found worthy of the consideration of architects and challenge the ingenuity of engineers.

Acknowledgements

I am greatly indebted to the work and good advice of my colleagues in the Conservation Department of the National Museum of Denmark: Poul Klenz Larsen, Morten Ryhl-Svendsen and Lars Aasbjerg Jensen.

References

[1] The thermal and moisture movement is simulated by a finite element program based on the description in Tim Padfield's 1998 Phd thesis, *The role of absorbent materials in moderating changes of relative humidity*: http://www.padfield.org/tim/cfys/phd/phd-indx.php. The moisture diffusion program assumes a constant temperature, which is not strictly correct. However, the temperature dependence of the sorption characteristics of materials is very small. The thermal diffusion program is almost identical to the moisture diffusion, since the same diffusion law is presumed to apply to both processes, though its validity in predicting moisture movement is only approximate.

[2] Data from Victoria Smith. The Alcazar measurements were funded by the EU 5th Framework MIMIC project.

[3] Data for the Arnamagnaean archive climate comes from Mette Jakobsen, Poul Klenz Larsen and Morten Ryhl-Svendsen. The initiative to rely on a largely passive climate control comes from Peter Springborg, Curator of the Arnamagnaean collection. Further information: *http://english.arnamagnaeansk.ku.dk/*

[4] Climate data for Tiwanaku and the Sphinx were provided by Shin Maekawa, Getty Conservation Institute.

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